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IMPACTS TO WILDLIFE OF WIND ENERGY SITING AND OPERATION IN THE UNITED STATES

Taber D. Allison, Jay E. Diffendorfer, Erin F. Baerwald, Julie A. Beston, David Drake, Amanda M. Hale, Cris D. Hein, Manuela M. Huso, Scott R. Loss, Jeffrey E. Lovich, M. Dale Strickland, Kathryn A. Williams, Virginia L. Winder

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SUMMARY

Electricity from wind energy is a major contributor to the strategy to reduce greenhouse gas emissions from fossil fuel use and thus reduce the negative impacts of climate change. Wind energy, like all power sources, can have adverse impacts on wildlife. After nearly 25 years of focused research, these impacts are much better understood, although uncertainty remains. In this report, we summarize positive impacts of replacing fossil fuels with wind energy, while describing what we have learned and what remains uncertain about negative ecological impacts of the construction and operation of land-based and offshore wind energy on wildlife and wildlife habitat in the U.S. Finally, we propose research on ways to minimize these impacts.

TO SUMMARIZE:

1. ***Environmental and other benefits*** of wind energy include near-zero greenhouse gas emissions, reductions of other common air pollutants, and little or no water use associated with producing electricity from wind energy. Various scenarios for meeting U.S. carbon emission reduction goals indicate that a four- to five-fold expansion of land-based wind energy from the current 97 gigawatts (GW) by the year 2050 is needed to minimize temperature increases and reduce the risk of climate change to people and wildlife.
2. ***Collision fatalities of birds and bats*** are the most visible and measurable impacts of wind energy production. Current estimates suggest most bird species, especially songbirds, are at low risk of population-level impacts. Raptors as a group appear more vulnerable to collisions. Population-level impacts on migratory tree bats are a concern, and better information on population sizes is needed to evaluate potential impacts to these species. Although recorded fatalities of cave-dwelling bat species are typically low at most wind energy facilities, additional mortality from collisions is a concern given major declines in these species due to white-nose syndrome (WNS). Assessments of regional and cumulative fatality impacts for birds and bats have been hampered by the lack of data from areas with a high proportion of the nation's installed wind energy capacity. Efforts to expand data accessibility from all regions are underway, and this greater access to data along with improvements in statistical estimators should lead to improved impact assessments.
3. ***Habitat impacts*** of wind energy development are difficult to assess. An individual wind energy facility may encompass thousands of acres, but only a small percentage of the landscape within the project area is directly transformed. If a project is sited in previously undisturbed habitat, there is concern for indirect impacts, such as displacement of sensitive species. Studies to date indicate displacement of some species, but the long-term population impacts are unknown.
4. ***Offshore wind energy development*** in the U.S. is just beginning. Studies at offshore wind facilities in Europe indicate some bird and marine mammal species are displaced from project areas, but substantial uncertainty exists regarding the individual or population-level impacts of this displacement. Bird and bat collisions with offshore turbines are thought to be less common than at terrestrial facilities, but currently the tools to measure fatalities at offshore wind energy facilities are not available.

The wind energy industry, state and federal agencies, conservation groups, academia, and scientific organizations have collaborated for nearly 25 years to conduct the research needed to improve our understanding of risk to wildlife and to avoid and minimize that risk. Efforts to reduce the uncertainty about wildlife risk must keep up with

COVER PHOTOS: a) Golden eagle b) Judith Gap Wind Energy Center in Montana c) Mexican free-tailed bats exiting Bracken Bat Cave in Texas d) Greater sage-grouse. *PHOTO CREDITS:* a) Susanne Nilsson b) Credit-Invenergy LLC, National Renewable Energy Laboratory c) Ann Froschauer, U.S. Fish & Wildlife Service d) Jeannie Stafford, U.S. Fish & Wildlife Service the pace and scale of the need to reduce carbon emissions. This will require focusing our research priorities and increasing the rate at which we incorporate research results into the development and validation of best practices for siting and operating wind energy facilities.

We recommend continued focus on (1) species of regulatory concern or those where known or suspected population-level concern exists but corroborating data are needed, (2) research improving risk evaluation and siting to avoid impacts on species of concern or sensitive habitats, (3) evaluation of promising collision-reducing technologies and operational strategies with high potential for widespread implementation, and (4) coordinated research and data pooling to enable statistically robust analysis of infrequent, but potentially ecologically significant impacts for some species.

INTRODUCTION

Electricity from wind energy is a major contributor to reducing greenhouse gas emissions from fossil fuel use and thus to reducing the impacts of climate change. Wind energy, however, like all power sources, can have adverse impacts on wildlife, including injury and death of birds and bats from turbine collisions, and the loss and fragmentation of species' habitat.

Awareness of the impact of wind energy production on wildlife in the U.S. arose in the late 1980s when attention focused on turbine collision fatalities of raptors, notably golden eagles and red-tailed hawks, at one of the nation's first large-scale wind energy facilities in California's Altamont Pass Wind Resource Area. As wind energy development has expanded to other parts of the country, research has extended to include habitat impacts as well as fatalities, and concerns have emerged regarding impacts to the habitat of grassland songbirds and grouse species in the Great Plains, forest interior bird species on ridgelines in the East, and terrestrial vertebrates including ungulates and desert tortoises.

Although some bat fatalities had been observed in early studies, research related to bat-wind interactions increased dramatically after 2003 when 1,400 to 4,000 bat fatalities were estimated to have occurred in a six-week period at the Mountaineer Wind Energy Center in West Virginia. In some regions, such as the eastern and mid-western U.S., estimated bat mortality from collisions has been substantially higher than that of birds. With the introduction of offshore wind energy development in the U.S., the list of potentially affected wildlife has expanded to include seabirds, marine mammals, sea turtles, fish, and other aquatic taxa, and considerable efforts are underway to understand, and avoid and minimize potential impacts.

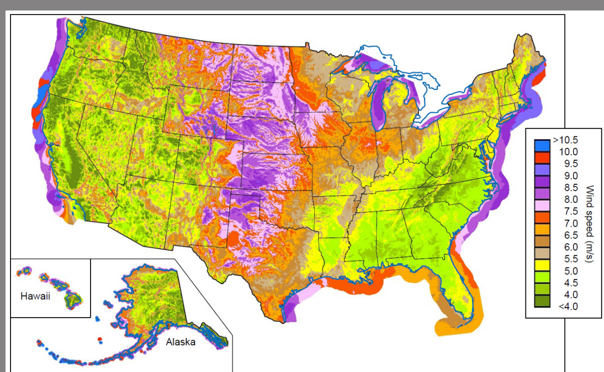
The pace and scale of wind energy development over the past 15 years *(see Box 1)* has generated concern about the risk that wind energy development presents to wildlife. This concern has led to increased investment in research. Since the early 1990s, in a partnership unique among energy industries, the wind energy industry, state and federal agencies, conservation groups, and scientific organizations have collaborated to promote and conduct research to address the concerns about wildlife impacts. Collaboration has been motivated by the desire to balance wildlife conservation with the need for rapid and deep cuts in greenhouse gas emissions to prevent the predicted, substantial impacts of anthropogenic climate change to the physical, human, and biological systems of the planet.

This *Issues in Ecology* is intended to further this collaborative spirit by reviewing the benefits of wind energy and evaluating what is known and what remains uncertain about the negative ecological impacts of the siting and operation of land-based and offshore wind energy on wildlife and wildlife habitat in the U.S. We begin with a brief review of the potential benefits of electricity from wind energy; evaluate negative impacts resulting from siting, construction, operation, and maintenance of wind energy facilities in the U.S.; and propose research to reduce uncertainty and minimize the adverse impacts of wind energy on wildlife. A detailed comparison of the ecological effects of electricity generation from different sources is beyond the scope of this Issue, as are the full life cycle impacts of the wind energy industry (e.g., the manufacturing of turbine components).

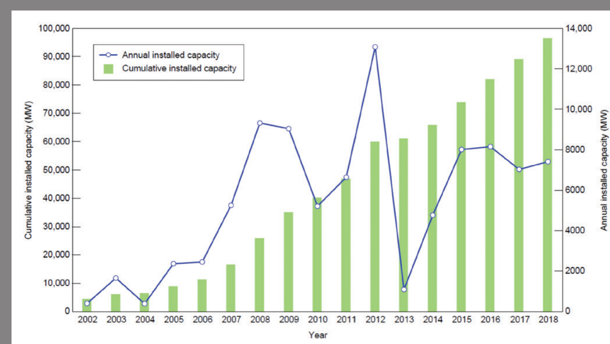
BOX 1. SOME BASIC FACTS ABOUT WIND ENERGY

Wind energy potential varies substantially within the U.S. (Box 1 Figure 1), and installed capacity also varies regionally, reflecting a variety of factors affecting economic viability of wind energy projects. Installed wind energy capacity in the U.S. has grown substantially from approximately 4,000 megawatts (MW) in 2001 to more than 97 GW at the end of March 2019, most of which are installed at more than 1,000 utility-scale projects in 41 states (Box 1 Figure 2). Wind energy accounted for approximately 7% of the total electricity generated by all energy technologies in 2018 in the U.S. and along with solar energy represents the fastest-growing source of electricity in the U.S. (https://www.eia.gov/todayinenergy/detail.php?id=38053). Almost all the growth in wind energy is occurring at land-based facilities. The first offshore wind energy facility in the U.S. began operation off Block Island (Rhode Island) in 2016, and other offshore projects are proposed for the East and West Coasts, the Great Lakes, and Hawaii.

The towers of most modern land-based turbines range in height from 60 to 80 m (200 to 260 feet), and individual turbine blades range in length from 38 to 50 m (125 to 165 feet) resulting in a maximum potential height of approximately 130 m (425 feet) and a rotor-swept area of 0.45 to 1.34 ha (1.1 to 3.3 acres). Due to advances in technology to expand power output and efficiency, turbine tower heights and rotor diameters are increasing; since 2016 more than 5,000 turbines have been installed with a combined height of more than 500 feet. Relative to earlier models, the number of blade revolutions per minute has decreased from 60 to 80 rpm to 11 to 20 rpm, but blade tip speeds have remained about the same, ranging from 230 to 300 kph (140 to 180 mph) under normal operating conditions. Turbines in modern wind energy facilities are spaced hundreds of meters apart, with larger turbines typically having wider spacing.



Box 1 Figure 1. Land-based and offshore annual average wind speed at 80 m above ground level across the continental United States. Source: Wind resource estimates were developed by AWS Truepower LLC. Web: http://www.awstruepower.com. Map developed by National Renewable Energy Lab. Spatial resolution of wind resource data is 2.0 km.



Box 1 Figure 2. Growth in the electricity produced by wind energy over time. Source: American Wind Energy U.S. Wind Industry Fourth Quarter 2018 Association Market Report, Released January 30, 2019, www.awea.org

ENVIRONMENTAL BENEFITS OF WIND ENERGY

Generation of electricity from wind has several environmental benefits that represent important drivers for the expansion of wind energy capacity in the U.S. *(Figure 1)*. These include (1) zero carbon emissions; (2) reduced air pollution including nitrogen oxides, sulfur oxides, and mercury; (3) no or little water withdrawal, water consumption, and impacts to water quality; and (4) the long-term availability of the wind resource. Further, there is the reduced potential for catastrophic events associated with other sources of electricity, such as nuclear accidents, which can have enormous ecological impacts.

A major ecological benefit of wind energy is the near-zero greenhouse gas emissions (e.g., CO_2, emitted when fossil fuels are burned, and CH_4 emitted when mining and burning natural gas) from wind energy facilities while generating electricity. Increasing greenhouse gas emissions are projected to raise global average surface temperatures by 3˚ to 4˚ Celsius

(C) above preindustrial age averages within this century. Predictions about the severe consequences to human society of increasing greenhouse gases are well described, and there is scientific consensus that rising global temperatures substantially increase the risk of species extinctions and major disruption of terrestrial and marine ecosystems across the globe.

Limiting the magnitude of warming and its impacts on humans and biodiversity will require deep reductions in greenhouse gas emissions. Various modeling efforts indicate that a large proportion of these reductions can come from wind-generated electricity. For example, the Western Wind and Solar Integration Study showed that achieving 33% wind and solar-generated electricity in the Rocky Mountain and West Coast states could avoid 29% to 34% of power-sector CO_2 emissions from the Western grid.[13] In 2015, installed wind energy in the United States was estimated to have reduced direct power-sector CO_2 emissions by 132 million metric tonnes, more than 6% of U.S. CO_2 emissions from fossil fuel burning.[28] Various scenarios indicate that meeting U.S. emissions reduction goals will require expansion of land-based wind energy from the current 97 GW (as of the end of March 2019) to approximately 320 GW by 2050.[28]

Reductions of other common air pollutants from wind energy generation can also have substantial benefits for human and ecosystem health. Wind energy produces no particulate matter or mercury and other toxins that directly affect human and wildlife health. In 2015, electricity generated by wind was estimated to have avoided 176,000 and 106,000 metric tonnes of sulfur dioxide and nitrogen oxide emissions, respectively.[28]

In contrast to nearly all other electricity sources, including some forms of solar energy production, wind energy facilities withdraw, divert, and consume little or no water when generating electricity. Wind energy facilities, therefore, can be located in areas of the country where there is limited water availability, or where there are concerns about drought and water scarcity. Wind power generation in 2013 is estimated to have reduced power-sector water consumption by 73 billion gallons, or roughly 226 gallons per person in the U.S.[28] Thermal power plants withdraw more fresh water than any other industry in the United States, and water withdrawals can have additional impacts, including the destruction of aquatic organisms by trapping or entraining. Water use in hydraulic fracturing to mine natural gas can range from 2 to 7 million gallons per operation.

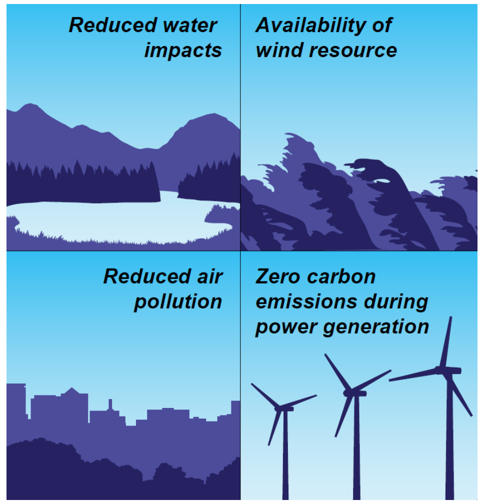


Figure 1. *Four main benefits of wind energy relative to fossil fuels.*

Wind is the result of incoming solar radiation that is converted to kinetic energy, and therefore the production of electricity from wind is assumed to be sustainable indefinitely as long as the sun shines. Scientific studies suggest that there are theoretical limits to the amount of energy that can be extracted efficiently from wind, but there is no "fundamental barrier" to obtaining the world's current power requirements and achieving emission reduction goals to mitigate the effects of climate change on humans and wildlife.

ADVERSE IMPACTS OF WIND ENERGY ON WILDLIFE

This section reviews what we have learned about the impacts and potential impacts of wind energy development on wildlife including:

- Bird and bat fatalities resulting from collision with turbines at land-based facilities
- Impacts to species' habitat
- Impacts related to offshore wind energy development

We first describe estimates of bird and bat collision mortality and assessments of population-level effects.

BIRD AND BAT FATALITIES AT LAND-BASED WIND ENERGY FACILITIES

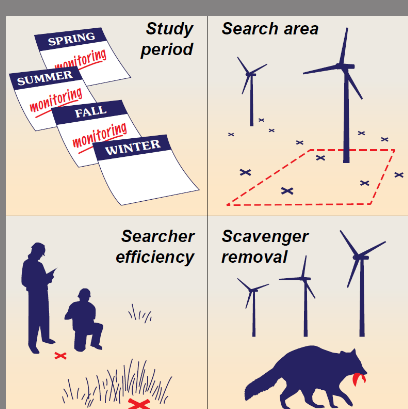
Fatalities of birds and bats from collisions with wind turbines have been documented at nearly every wind facility where studies have been conducted, and possibly the most commonly asked question about wind energy impacts on wildlife is—how many fatalities are there?

National average adjusted fatality rates *(as defined in Box 2)* reported in recent peer-reviewed national reviews vary from approximately three to six birds and four to seven bats per MW of installed wind energy capacity per year. The range of reported fatality rates can vary substantially among projects both within and among geographic regions. For example, reported adjusted fatality rates of small passerines vary across avifaunal regions in the U.S. ranging from about 1.2 to 1.4 fatalities per MW per year in northern forests, to 2.6 to 3.8 in the eastern U.S.[11] Some of the highest bat fatality rates have been reported at projects in eastern forests and the forest-agricultural matrix

BOX 2. ESTIMATING BIRD AND BAT COLLISION FATALITIES AT WIND ENERGY FACILITIES

Collision fatalities are estimated based on carcass searches conducted under operational wind turbines. Raw counts from searches underestimate the number of collision fatalities and must be adjusted for four primary sources of detection error described below. Standardized protocols are widely used to estimate these four sources of error and develop less biased estimates of collision fatalities.

- **Study period.** Many fatality-monitoring studies in the U.S. are not conducted during the winter because the activity of many species is reduced due to hibernation or migration; nonetheless, fatalities can occur. To compare annual fatality rates, estimates for some studies must be extrapolated beyond their period of monitoring.
- **Search area.** Search plots are usually centered on an individual wind turbine, but often terrain and vegetation cover prevent searching of the entire plot. Models of carcass densities at different distances from the turbine can be used to estimate the fraction of carcasses landing outside the search area, allowing researchers to adjust for unsearched area. Typically, only a sample of turbines is searched requiring extrapolation to the entire facility, although variation among turbines could occur.
- **Scavenger removal.** Animal scavengers can remove carcasses from the search area before searchers can find them. Bird and bat carcasses are placed within search plots and checked periodically over a set time period to determine how long a carcass will remain present and recognizable by a searcher. Results are used to estimate the probability of a carcass persisting between one carcass search and the next.
- **Searcher efficiency.** Searcher efficiency measures the proportion of carcasses present at the time of a search that a searcher can find. Carcasses of different sizes are placed within areas assumed to differ in detection rates. The proportion of placed carcasses found by searchers estimates searcher efficiency for combinations of carcass size and visibility class.



Box 2 Figure 1. Sources of detection error when estimating fatalities from collisions with wind turbines.

Fatality estimators: These are statistical equations that calculate an estimate of the total number of fatalities from raw carcass counts and information from trial carcasses used to estimate the different sources of detection error. A new generalized estimator (Gen-Est) uses data collected during carcass searches and estimates of detection rates to more accurately estimate the number of fatalities and to provide an accurate measure of precision associated with that estimate.

Adjusted fatality estimates are reported as fatalities per turbine or per MW installed capacity per season or year and are often reported for different groups, such as small birds, raptors, or bats, each of which may have different searcher efficiencies, scavenger removal rates, and spatial and temporal distributions. Possible sources of errors generally not accounted for in calculating fatality estimates include background fatalities (birds and bats dying from causes other than collisions) and fatally injured birds and bats that are able to fly beyond the limits of the search area.

of the upper Midwest, but there is also substantial variation in reported bat fatalities within those regions. For example, fatality rates of 40 to 50 bats per MW per year have been reported for projects along forested ridgelines of the central Appalachians, substantially higher than those reported at other projects in the northeastern U.S.[2]

Using adjusted fatality rate data from publicly available studies, estimates of average cumulative annual bird fatalities in the continental U.S. published in 2013 and 2014 ranged from approximately 230,000 to 600,000 birds per year,[15] estimates of cumulative bat fatalities published during that same period ranged from 200,000 to 800,000 bats per year.[2]

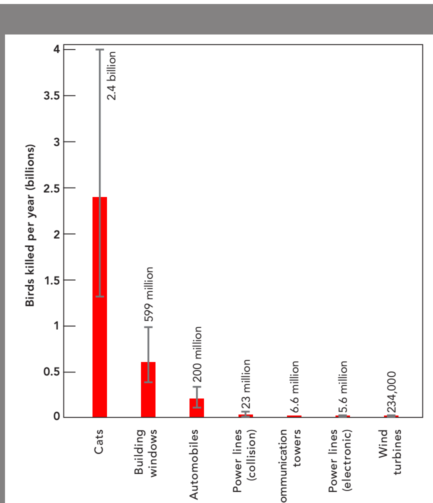
The accuracy of these estimates is uncertain for several reasons. For example, results from fatality-monitoring studies are only available for a subset of all wind energy facilities in the U.S. Some regions with high installed wind energy capacity, such as Texas, have relatively few available studies. Thus, national estimates may not be accurate unless they adequately account for regional variation in levels of bird and bat fatalities. Further, although survey methods are becoming more standardized, older studies included in cumulative estimates varied more widely in methods and may have had insufficient sampling intensity, leading to questions about the validity of aggregating estimates from different studies. Collaborative efforts continue to increase access to fatality studies and to improve the accuracy of project-level fatality estimates.

Like wind energy, substantial uncertainty exists around estimates of fatalities caused by other anthropogenic sources such as poisoning or collisions with buildings. However, our best estimates suggest total bird fatalities at wind turbines are low relative to other sources of anthropogenic mortality *(see Box 3)*. For bats, wind turbines and white-nose syndrome (a fungal disease) cause high numbers of fatalities in the U.S.

These overall comparisons mask important differences in the types of birds and bats killed by different anthropogenic sources. For example, wind turbines kill raptors in greater proportions than are killed by cats, and cats kill more passerines than are killed by turbines. For the golden eagle, a well-studied raptor, more individuals die from illegal shooting than from collisions with vehicles and wind turbines. Species-specific levels of fatality at wind energy facilities are more useful for regulatory decisions and conservation planning related to wind energy than the cumulative national estimates that garner more attention.

BOX 3. WIND ENERGY IN CONTEXT OF OTHER ANTHROPOGENIC SOURCES OF BIRD AND BAT FATALITIES

There are several well-known anthropogenic causes of fatalities of birds and bats. The magnitude of these fatalities has been estimated for birds in the U.S.; bat fatalities from anthropogenic sources may be substantial but have not been quantified to the same extent. Major sources of bird mortality include domestic cats, collisions with communication towers, vehicles, and building windows, collisions and electrocutions at power lines, and exposure at oil pits. Predation by the domestic cat is estimated to be the largest direct source of bird mortality by far, causing between 1.4 and 4.0 billion fatalities in the U.S. each year.[18] Collision deaths from sources other than wind energy number in the hundreds of millions (Box 3 Figure 1). Poisoning by agricultural pesticides and other toxins is another direct source of bird and bat mortality, but no reliable estimate exists for this source of mortality in the U.S.; a Canadian study estimated 2.7 million birds killed annually by these chemicals.[6] More detailed analysis reveals important species-specific differences among the different mortality sources. For example, oil spills and fisheries bycatch (incidental catch of non-target species) affect seabirds and waterfowl, while the fatalities caused by cats consist primarily of small song birds and terrestrial game birds.



Box 3 Figure 1. Comparison of total annual bird mortality in the U.S. and Canada from different direct mortality sources. Reprinted from Loss et al. (2015) with permission.

BIRDS

Three-hundred species of birds have been reported as collision fatalities at U.S. wind facilities for which data are available. Most of the observed fatalities (approximately 57%) are small passerines such as the horned lark or red-eyed vireo. Diurnal raptors constitute about 9% of total observed fatalities, and these percentages are higher in the western U.S. where these species are more abundant. To date, fatalities of water birds and waterfowl (e.g., ducks, gulls and terns, shorebirds, loons, grebes, and others) have been observed infrequently at land-based wind energy facilities. Differences among species in the number of observed fatalities should be interpreted with caution. Raptor carcasses, and large birds in general, are more likely to be found during fatality searches than smaller birds.

Birds, particularly night-migrating songbirds, collide in high numbers with tall stationary objects such as communication towers and buildings. Lighting, particularly in periods of low visibility, is thought to be a factor attracting migrating birds to communications towers and buildings. However, the lighting currently approved by the Federal Aviation Administration and typically used at wind turbines does not appear to contribute to bird fatalities.

It seems likely that the abundance and behavioral characteristics of a bird species influence its risk of collision, although the relative importance of these factors for determining collision risk of different species is poorly understood. Abundance may be one of the most important predictors of collisions for raptors,[26] and raptors as a group appear to be among the most vulnerable to collisions. Conversely, crows and ravens, large and conspicuous birds, are among the most common birds seen flying within the rotor-swept area of wind turbines, but they are found infrequently during fatality surveys. Landscape features (e.g., woodlots, wetlands, and certain landforms) may also influence collision risk. For example, these features influence raptor abundance by concentrating prey or creating favorable conditions for nesting, feeding, and flying. While landscape features may influence the abundance of other bird species, no clear relationship between bird abundance and fatalities of most other bird species has been shown.

Technological advances that increase turbine height and rotor-swept area are expected to increase the power generation capacity and efficiency of wind turbines enabling wind energy to expand to regions of the country where relatively little wind energy development exists today. Radar studies indicate that 90% of avian nocturnal migrants fly above the height of the current rotor-swept zone of turbines (140 m; 460 feet) in most operating wind energy facilities. Land-based wind turbines have been developed that extend almost twice the height of existing turbines reaching higher into the space used by nocturnal migrants, and there are concerns that this will increase bird collisions.

The few published studies have been contradictory in their findings regarding the effects of increased turbine height or increased MW capacity on fatality rates of birds. For raptors, however, repowering at Altamont Pass, where smaller turbines have been replaced by fewer, taller turbines, may decrease fatalities in this group. Given the trend toward larger, more powerful turbines and uncertainty about their impacts on the number of fatalities, further analysis of this relationship for birds is warranted.

BATS

Twenty-two of the 47 species of bats that occur in the continental U.S. have been recorded as fatalities at U.S. wind energy facilities. Three migratory tree-roosting species (hoary bat, eastern red bat, and silver-haired bat) constitute approximately 72% of the reported fatalities in available fatality monitoring studies at U.S. wind facilities. The species composition of bat fatalities varies regionally depending on the available pool of bat species. For example, in southwestern U.S., the Mexican free-tailed bat can constitute 50% or more of the bat carcasses found at facilities that overlap this species' range. Relatively high proportions of cave-hibernating bat fatalities (e.g., big brown bat and little brown bat) have been observed at some wind energy facilities in the upper Midwest compared to facilities in other regions in the U.S. Studies generally have shown a peak in bat fatalities in late summer and early fall, coinciding with the migration and mating season of tree-roosting bats, and a smaller peak in fatalities has been observed during spring migration.

Numerous hypotheses have been proposed for why bats, especially migratory tree-roosting bats, are killed in large numbers at some wind energy facilities in some regions of the U.S. Some of these hypotheses suggest that bats are attracted to turbines, perhaps by the sounds produced by rotating turbine blades, the possible concentration of insects near turbines, or because of bat mating behavior. Infrared imagery has shown bats exploring the nacelles, towers, and blades of wind turbines from the leeward direction, especially at low wind speeds.[8] It has been hypothesized that some bat species perceive wind turbines as trees and are attracted to the turbines for roosting, foraging, or mating. Analysis of bat carcasses beneath turbines found large percentages of mating-ready male hoary, eastern red, and silver-haired bats, indicating that sexual readiness coincides with the period of high levels of fatalities in these species. Bats rarely collide with stationary anthropogenic structures, and there are no reported fatalities at stationary wind turbines or meteorological towers. Bat fatalities have shown a positive correlation with tower height, but there are few analyses of this relationship with large datasets.

The hypothesis that bats may suffer fatal internal injuries, such as hemorrhaging in the lungs (barotrauma), when they experience a rapid drop in air pressure as they pass between rotating turbine blades, gained rapid public awareness when first proposed. More recent studies involving detailed analysis of bat carcasses have suggested that the proportion of fatalities that can be solely attributed to barotrauma as opposed to collisions may be much lower than originally thought.

EFFECTS OF COLLISION MORTALITY ON THE STATUS OF WILDLIFE POPULATIONS

Assessing the population-level effect of collision fatalities is difficult because the potential for this effect depends on multiple factors, including a species' population size, other sources of mortality, and the species' reproductive potential. As discussed previously, the uncertainty around existing fatality estimates leads to uncertainties around the potential for population-level effects. While recognizing these limitations, several studies have attempted to assess the potential for population declines from wind turbine collisions. Demographic models, such as population viability analyses designed around the biology of specific species, suggest the population size or dynamics of some species may be negatively affected from increases in mortality from collisions at wind turbines, particularly as more turbines are placed within the species' range.

For most songbirds in the U.S. for which data are available, cumulative collision mortality at wind energy facilities has been estimated to represent less than 0.01% of estimated population size.[11] In North America, most small songbird species have relatively high natural annual mortality, even as adults, and high reproductive potential indicating that population impacts from collisions at wind turbines are unlikely at current levels of installed wind capacity.

Long-lived species, including most raptors, that have higher adult survival and fewer offspring each year, may be more susceptible than short-lived species to population-level effects from collisions with wind turbines. Few peer-reviewed studies in the U.S. have investigated population-level effects of wind energy on any raptor species. Studies of the unusually high fatalities of golden eagle at the Altamont wind facility in California indicated that increased mortality from collisions did not cause a decline of the local population although recent research indicates that these fatalities are offset by immigration of young eagles into the area.[16] In Europe, where raptor numbers tend to be lower than in the U.S., a local decline attributed to the Smøla wind energy facility in Norway has been observed for white-tailed eagles,[9] and modeling results have suggested that some raptor species in Europe are at risk of population declines due to collision fatalities at wind turbines.[22]

Most species of bats have low reproductive potential and high adult survivorship. Little is known about population size or trends in migratory tree-roosting bats, the group of bats with highest reported turbine-related fatalities across the U.S., but modeling results suggest some of these species are at risk of population decline due to collision fatalities.[12] The ecological consequences of turbine-caused mortality of cave-dwelling bats such as the little brown bat, northern long-eared bat, or Indiana bat may be significant because of already high mortality and recent population declines caused by white-nose syndrome (WNS). At some facilities in the Northeast and Midwest little brown bats accounted for up to 60% of detected fatalities. Once common, this species has declined substantially due to WNS. Northern long-eared bat, recently listed as federally threatened due to population declines from WNS, and the federally endangered Indiana bat have also been recorded as fatalities, albeit rarely. The declining status of many cave-dwelling bat species raises concerns about the ecological consequences of any additional mortality.

ADVERSE IMPACTS TO SPECIES' HABITAT

Wind energy facilities can extend over thousands of acres, although the actual amount of land changed by project-related structures, including access roads and turbine pads, constitutes only a small fraction of that area. The magnitude of adverse impacts due to land transformation and the spatial extent of facilities will vary with each project, landscape, and species (see Figure 2). Wind energy facilities constructed on previously undisturbed landscapes may have a greater impact than projects built on land that has been transformed by human activity. For example, facilities installed in agricultural lands can take advantage of the existing road networks and use approximately one-sixth of the available land per MW compared to facilities placed in forested areas.

The total amount of land transformed by the development of a wind energy facility varies substantially from 0.11 to 4.3 ha/MW of installed capacity, which may constitute 5% to 10% of the total project area.[10] Some of the land transformation is temporary, for example, from burying cables or building staging areas. These disturbed areas can be restored or may recover naturally. Roads, which constitute approximately 40% of the transformed land area, and turbine pads are permanent through the life of the facility, but, theoretically, these could also be restored when a facility is decommissioned.

Land transformation associated with development of a wind energy facility has the potential to remove or fragment habitat for one or more species. Habitat fragmentation is the loss and separation of habitat into smaller segments. Individuals in the remaining habitat segments may exhibit decreased survival, reproduction, distribution, or use of the area. Construction, operation, and maintenance of a wind energy facility also results in increased human activity, and this activity may disturb sensitive species and cause displacement from otherwise suitable habitat. Disturbance from the operation of a wind energy facility may also disrupt movement or migration patterns. Development and operation of a wind energy facility may have differential effects on predators, prey, or competing species, thus affecting ecological interactions among species.

Figure 2. *Wind energy facilities located in different landscape types: a) flat, agricultural lands (photo credit: Emily Zink, West Inc). b) turbines along a ridgeline (photo credit: Tom Walsh, CC by-SA 3.0), and c) turbines following a hilltop in deciduous forest (photo credit: Dhaluza at English Wikipedia, CC by 3.0).*

Detailed studies evaluating these potential effects are limited, because sufficient testing of effects may require expensive studies

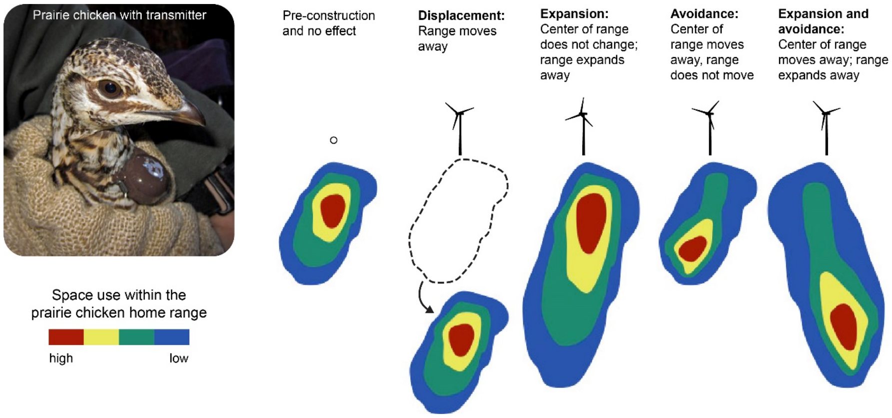


Figure 3. *Possible responses of prairie chicken and sage grouse before and after construction of a wind facility. Studies show responses are not consistently observed across species or locations. See text for further discussion of results (photo credit: U.S. Geological Survey, adapted from Winder et al. 2014)*[29]

that run for several years, and because such studies need to be replicated at multiple wind energy facilities. Many of the available studies have focused on grassland and shrub land birds, whose populations already appear to be declining with large-scale transformation of their habitat to agriculture, range management, or other types of energy development. These studies consistently show species-specific responses. For example, a 10-year study of nine grassland songbird species at three wind energy facilities in the Dakotas indicated that seven of these species declined but the effects were delayed until a few years after construction.[23] Two species showed no effect or experienced a temporary increase in abundance. Adverse and positive effects were not consistently observed across the three wind energy facilities.

A multi-year study comparing response of greater prairie-chickens to development of a wind energy project in Kansas versus a control site also showed mixed effects. Female survival significantly increased in proximity to the wind energy facility between pre-construction and post-construction periods, and no negative effect from proximity was observed on nest site selection or nest survival. Female greater prairie-chickens increased the size of their home range and avoided areas close to wind turbines within their home ranges after wind energy development *(Figure 3)*. Persistence of leks, which are male displaying and breeding areas, may also decrease in proximity to wind turbines. In a Wyoming study, female greater sage-grouse utilized areas farther from disturbed areas around a wind facility for brood rearing and summer habitat use, but otherwise no significant negative effects of wind energy on this species were detected.[17]

Bat acoustic activity is higher in forest gaps and edges than in interior forest. Wind turbine installation increases both the amount of forest edge and the number of forest gaps, and it is hypothesized that these changes result in increased bat activity potentially explaining the higher bat fatalities reported at some projects in forest regions. There has been little evaluation of this hypothesis. There are a few studies evaluating potential habitat impacts for other terrestrial vertebrates. Long-term studies on Agassiz's desert tortoises at a wind facility near Palm Springs, California indicated that adult females survived at higher rates near turbines, but fewer tortoises were utilizing the area around the facility suggesting displacement may not be apparent without almost 20 years of monitoring.[20] A study of a transplanted elk population during construction and operation of a wind energy facility in Oklahoma found turbines did not affect elk use of the surrounding area before and after construction. Winter survival of pronghorn was not affected by proximity to a wind energy facility in Wyoming.

Wind energy facilities can affect downwind microclimates by mixing different thermal layers in the atmosphere.[25] Observed effects include higher near-surface air temperatures at night and lower temperatures during the day *(Figure 4)*. Computer simulations suggest these effects extend downwind of the facility, but the distance depends on wind speed and topography. Whether the microclimate changes resulting from the operation of wind facilities affect wildlife, positively or negatively, is unknown.

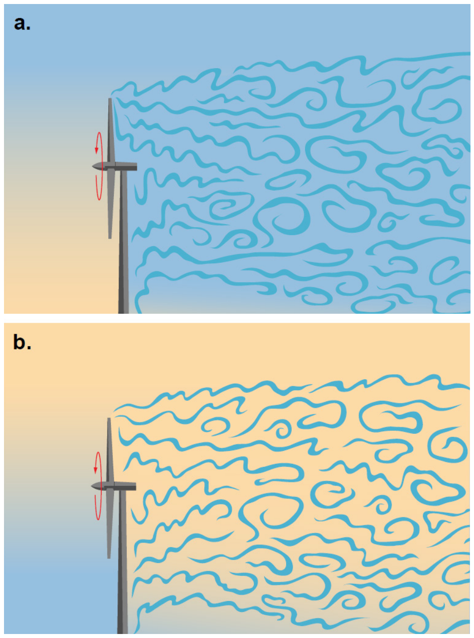


Figure 4. *Depiction of how turbulence from wind turbines can affect air temperature. When cool air (blue) is over warm air (tan) (a), turbulence mixes cool air down and warm air up, cooling the surface. The opposite can happen when warm air is above cool air (b).*

OFFSHORE WIND ENERGY DEVELOPMENT

Only one offshore wind facility is operating in the U.S. off Block Island, RI. However, offshore wind energy appears poised for major expansion with numerous leases for development in state and federal waters. The scope and degree of impacts to wildlife from offshore wind energy facilities are less understood than land-based wind energy development, but research collaboratives are being formed to reduce that uncertainty. Concerns about potential wildlife impacts are based on inferences drawn from impacts documented at wind facilities from northern Europe and from other offshore development activities, the latter of which inform questions on the potential impacts to sea turtles and large cetaceans, which are not well represented in studies at European offshore wind facilities.

Offshore wind energy facilities present similar concerns as land-based wind energy regarding ecological impacts, primarily collision mortality of birds and bats and displacement of birds. Additional concerns have focused on species found in the marine environment, such as mortality and injury, displacement, and prey-mediated impacts on fishes, marine mammals, and marine reptiles. Artificial reef effects from the hard surfaces provided by turbine installations may also affect the composition and distribution of ecological communities, with variable effects to individual species. Underwater noise, particularly from seismic surveys and construction activities, has the potential to cause physical injury to acoustically sensitive species at close range and a variety of behavioral changes farther away from the noise source.

INJURIES AND FATALITIES

There is limited documentation of bird and bat fatalities due to the challenges of conducting fatality monitoring in the offshore environment. Alternative approaches such as cameras and visual observations have limitations that have prevented their widespread implementation, including a narrow field of view (for cameras) and poor species detection or species identification capabilities, particularly for smaller-bodied species. Efforts to infer collision risk in the U.S. have thus largely focused on evaluating avian and bat activity offshore. Siting and permitting decisions for many European offshore wind facilities are informed by collision risk models, which have been created to predict the number of avian collisions for offshore wind energy facilities. However, these models are highly sensitive to uncertainties in input data. The few empirical studies at land-based wind facilities that have compared model-estimated collision risk to actual mortality rates found only a weak relationship between the two, and due to logistical difficulties, the accuracy of these models has not been evaluated in the offshore environment.

Offshore avian activity appears to vary with distance from shore, submarine topography, time of year, and weather conditions. Recent offshore surveys and subsequent modeling in the eastern U.S. have indicated that seabird abundance and species diversity generally decrease with increasing distances from shore, though the distributions of individual species vary widely. Both seabirds and many land birds migrate over open water, and some water bodies such as the Great Lakes are crossed by large numbers of terrestrial migrants during migration. Bird fatalities have been reported at offshore oil and gas structures under certain weather conditions and when such structures are brightly lit. However, the lighting used at offshore wind farms in the U.S. for marine navigation and to mark an aviation hazard may be less likely to attract birds.

Visual and acoustic surveys in the U.S. show bats forage and migrate over the ocean at distances > 40 km from shore, although the magnitude of this activity is unknown. In Europe, bats have been recorded foraging and roosting 15-80 km offshore on wind turbines and oil and gas platforms in the North Sea. It is unknown whether bats are attracted to offshore wind turbines, but their presence at offshore structures indicates a potential for collisions.

Sound from human activity propagated underwater can affect marine mammals and acoustically sensitive fishes. The magnitude of these effects depends on a variety of factors, including the frequency, intensity, and duration of the sounds, water depth, the species being exposed, and the animal's life history stage and behavior at the time of exposure. Potential injurious effects from exposure to high intensity sound such as naval sonar include death and temporary or permanent hearing loss. No evidence of such effects has been found for pile driving (during installation of turbines) at offshore wind facilities to date, and the potential for auditory injury from pile driving noise has been estimated to occur within a fairly small radius (100 m in one study). A variety of mitigation measures have been proposed to minimize sound impacts, including the use of Marine Mammal Observers to halt potentially harmful activity when animals are observed and scheduling construction activity when sensitive species are absent.

Collisions with vessels are a primary source of mortality for some large whale species, and there is some potential for collisions with vessels during construction and operation activities for offshore wind facilities. Potential mitigation approaches include reducing vessel speed during locations or time periods when species of concern may be present.

AVOIDANCE AND DISPLACEMENT

Several species of seabirds have been shown to fly around offshore wind facilities and individual turbines, and it is estimated that over 95% of individual seabirds flying by offshore wind energy facilities do not approach turbines closely enough to be at risk of collision.[7] The degree of avoidance behavior likely is species-specific and dependent on the situation. Available studies suggest it is unlikely that resulting increased flight times and energy use lead to negative impacts to migrating birds, at least at current buildout scenarios. Avoidance of wind turbines may represent a more significant burden to individuals making multiple, daily trips between feeding and roosting or nesting areas.

Offshore wind facilities may also displace waterfowl and seabirds from use areas (e.g., feeding and roosting grounds). Some species are displaced only by construction activities, or for just a few years after operation begins, while species such as red-throated loon and northern gannet experience displacement for several years, and possibly indefinitely. Other species may be attracted to perches on structures or increases in food availability. Displacement may have population-level impacts for at least a few species, but efforts to model these effects are just beginning.

Acoustic disturbance from pile driving was recently determined to be the highest impact of all offshore wind energy development activities on marine mammals in Europe.[5] One study indicated that harbor porpoises could hear pile-driving noise over 80 km away,[27] and several studies have estimated that reductions in local activity and potential displacement during installation of monopoles occurred up to 20 km from the noise source. Construction noise may also affect acoustically sensitive fish species, particularly during sensitive life history periods.

Operational turbines emit low levels of underwater noise. Harbor seals have displayed little or no long-term displacement during operations. Harbor porpoises have displayed a high level of variability in observed displacement responses, which has been hypothesized to relate to local food availability or pre-existing levels of underwater noise at the development sites. Turtles can hear low-frequency underwater noise emitted during seismic surveys, pile driving activities, and wind turbine operations, but the effects are poorly understood. Some fish species may hear noise of operating turbines from 25 km away, but physiological or avoidance responses would be predicted at much closer ranges, perhaps in the <10 m range.[1]

Vessel activity associated with construction and maintenance of offshore wind facilities may also displace or attract animals, depending on the species and the intensity of the disturbance. Bottlenose dolphins, for example, may be attracted to and "bowride" near vessels, while many large whales, sea turtles, and some waterfowl such as scoters may avoid areas of high vessel activity.

HABITAT/PREY IMPACTS

Displacement or other behavioral impacts to prey fish during the construction period may influence seabird distributions and reproductive success. Underwater structures also change local habitat, by attracting benthic organisms that attach to the underwater structures and form artificial reefs, which have the potential to attract foraging marine mammals, sea turtles, and fishes, among other taxa. It is not fully understood whether these artificial reefs increase the carrying capacity of ecosystems to support predator populations or aggregate individuals already present. Recent evidence suggests that wind farms in the North Sea may support increased populations of blue mussels, which are a key species for local food webs,[24] but it is likely that a range of site-specific factors influence the degree to which artificial reef effects support productivity at higher trophic levels.

Electromagnetic fields (EMF) are generated by cables that carry electricity from wind turbines. Many species of fish, bottom dwelling elasmobranchs (sharks, rays and skates), and possibly sea turtles are sensitive to EMF, though there appear to be little or no observed effects for most taxa. Bottom-dwelling species sensitive to EMF have been shown to be attracted to cable routes along the sea bed, though it is unclear whether such attraction is a biologically significant effect. Recent research from the Pacific offshore environment indicated that this effect dissipated quickly with distance, and there was a lack of response detected in both fish and invertebrates.[19]

STRATEGIES TO AVOID AND MINIMIZE ADVERSE IMPACTS

In this section, we describe strategies currently in use or in development to avoid and minimize adverse impacts to wildlife from wind energy construction and operation. In the U.S. these efforts are focused almost entirely on land-based wind energy facilities.

AVOIDANCE: SITING

Avoidance of adverse impacts is typically addressed through siting practices, which can be further defined as:

- Macro-siting—locating individual projects within a landscape, or
- Micro-siting—locating individual turbines and associated infrastructure within a project boundary

Many states and federal agencies have developed guidelines for siting practices intended to avoid adverse impacts of wind energy development to wildlife for both land-based and offshore wind. These guidelines include identifying areas with high conservation value, such as wetlands, unique or rare natural communities, major avian migratory routes, or critical habitat for endangered species that could be avoided either by macro- or micro-siting. Effective guidelines require a clear understanding of the species of concern and evaluation of the risk posed to these species.

Several decision-support tools are available to aid wind project developers and permitting agencies in the early planning stages of project siting by providing searchable spatial data layers that identify areas of conservation concern. Published models identify areas of overlap of wind energy potential and landscape use by some species. In addition, recent publications have provided detailed recommendations on field protocols and study designs for risk assessment consistent with most state and federal guidelines. The voluntary U.S. Fish and Wildlife Service Land-Based Wind

Energy Guidelines provide a tiered approach to risk assessment and recommendations on how to site wind facilities and mitigate risk to wildlife, primarily birds and bats. The Bureau of Ocean Energy Management has identified offshore wind lease areas based in part on an evaluation of available wildlife survey data and has developed wildlife survey guidelines for offshore wind energy facilities.

There is interest in predicting collision risk to birds and bats, and it is logical to assume that collision risk is related to activity and exposure, in other words, the time a species spends within the rotor-swept area. Land-based siting guidelines therefore have recommended collecting activity data to support the prediction of collision fatality risk for birds and bats. Bird activity at land-based projects is typically estimated from visual surveys and radar, and bat acoustic activity is typically used to estimate relative bat activity. There is some evidence that raptor activity is correlated with raptor collision fatalities, but for most other groups of birds and bats there has been a lack of success in relating activity data to the observed level of fatalities.

Estimating avoidance behavior is also important in evaluating collision fatality risk both at land-based and offshore wind energy facilities, and estimation has been attempted for some bird species, notably raptors and seabirds. Except for a few species, such as golden and bald eagles,[21] in the U.S. there is a lack of guidance regarding how to use estimates of bird and bat activity to make siting decisions.

Siting of wind energy facilities and individual turbines can also be designed to reduce impacts of habitat loss or fragmentation or to avoid disturbing unique plant community types or habitat for an endangered species. The U.S. Fish and Wildlife Service's Land-Based Wind Energy Guidelines describe a path for estimating habitat fragmentation risk, and a process for identifying species that may be sensitive to habitat fragmentation. Project siting intended to avoid impacts to species' habitat is often hampered by lack of knowledge about how individual species will respond to the project. For some species, the response to roads or other disturbances may be well known, while for other species this information may be entirely lacking.

IMPACT REDUCTION: TURBINE SHUTDOWN

Shutting down of turbine operation, often referred to as curtailment or operational minimization, is intended to reduce bird and bat collision fatalities at wind turbines by "feathering"—changing the angle of turbine blades to slow blade rotation during periods where risk of collisions is high.

TURBINE SHUTDOWN TO REDUCE BAT FATALITIES

Several studies evaluating the effect of turbine curtailment at low wind speeds have documented significant reductions in bat fatalities. For example, curtailing blade rotation when wind speeds are below 5.0-6.5 meters per second (m/s) reduced bat fatalities by 50% or more.[4] Fatalities of individual bat species typically are not frequent enough to determine whether shutting down turbines is more effective for some species than others.

Turbines are designed to begin generating power above a certain wind-speed threshold, or "cut-in speed," typically set by the manufacturer at 2.5 to 3.5 m/s, but turbine blades rotate even when wind speed is below the manufacturer's cut-in speed—thereby presenting a collision risk to bats, although electrical power is not being generated. Recently, member companies of the American Wind Energy Association agreed to voluntarily reduce or "curtail" turbine blade rotation below the cut-in speed at night during fall migration to reduce bat-collision fatalities. Some states have instituted threshold levels of bat fatalities, which if exceeded would require curtailment of turbine operation below "designated" wind speeds at the wind facility.

Restricting turbine operation at low wind speeds reduces power production and that reduction increases with wind speed. The amount of reduction depends on the wind speed chosen for curtailment and the wind-speed characteristics of the project location. Because of concerns about reduction in power production, research is underway to evaluate whether incorporating bat activity and environmental variables, such as temperature or changes in barometric pressure, can be used in addition to wind speed to optimize reductions in bat fatalities while minimizing the reduction in energy production.

TURBINE SHUTDOWN TO REDUCE BIRD FATALITIES

The effectiveness of turbine shutdown in reducing bird fatalities has rarely been evaluated experimentally. For example, there is no published experimental evidence that stopping turbines reduces collision fatalities of songbirds, the largest group of bird collision fatalities reported at wind turbines. Turbine shutdown has been implemented to reduce raptor fatalities. Turbine shutdown at the Altamont Pass Wind Resource Area was implemented between 2005 and 2011 to reduce fatalities of four target raptor species—golden eagle, red-tailed hawk, American kestrel, and burrowing owl—during the period of highest raptor activity (November through February). The target reduction of 50% was not achieved, but fatalities of red-tailed hawk did decline significantly.[14] Fatalities of golden eagle also declined, but low numbers of fatalities made interpretation difficult. Kestrel and burrowing owl fatalities appeared to increase following implementation of turbine shutdowns, suggesting the fatalities of these species are due to causes other than collisions at wind turbines.

Wind energy companies have employed human observers to detect target species and to signal for shutdown of specific turbines or turbine strings, a process called "informed curtailment" that aims to reduce the amount of time that turbines are not generating power. Automated detection technologies are being used to track California condors with GPS transmitters, detect and shut down turbines with camera-based systems to reduce eagle collisions, and detect large raptors with ground-based radar.

MINIMIZATION: FOR BIRDS AND BATS

Because of concerns about power loss and the practicality of implementing curtailment in low wind regions, there has been substantial investment in developing technologies that reduce fatalities of birds and bats while allowing turbines to operate normally. One approach being tested is to use sound to deter birds and bats away from turbine blades (Figure 5). For example, all bat species in the U.S. echolocate by emitting high-frequency (ultrasonic) sounds and interpreting the reflected echoes from objects in their surroundings. These sounds allow bats to orient, capture prey, and communicate in the dark. Bat scientists have hypothesized that broadcasting ultrasound from wind turbines may "jam" a bat's ability to perceive its own echoes and cause bats to avoid wind turbines.

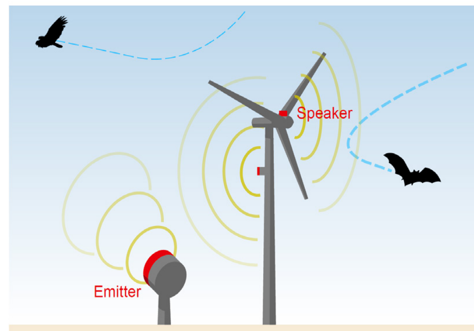


Figure 5. *Deterrent devices installed on the ground or on turbines are intended to reduce collision risk by keeping birds and bats away from turbines.*

Several tests of ultrasonic acoustic deterrence were being completed at the time of publication of this issue, but results were not yet published. Preliminary results are promising, suggesting an effectiveness approaching that of curtailment for some bat species.[3] One wind company is installing 2nd-generation acoustic deterrents at its facility in Texas. Research is ongoing to improve effectiveness, including understanding species-specific differences in response and the optimal placement and orientation of speakers on turbines. In addition to ultrasonic deterrence, research is underway to investigate ultraviolet light as a bat deterrent and to develop surface materials that reduce the attractiveness of wind turbines to bats.

Acoustic deterrents for birds, particularly raptors, have been used at European wind energy facilities and are undergoing testing in the U.S. Experimental evaluation of the effectiveness of this technology in reducing golden eagle fatalities is underway, and preliminary results indicate the deterrent affects eagle behavior reducing collision risk.

Acoustic deterrence also is under consideration to minimize impacts in the offshore environment. The approach, referred to as "ramping up," involves gradually increasing intensity of construction noise so that sensitive aquatic species will avoid the construction area and will no longer be present in the area by the time noise reaches levels that could cause harm. The approach is controversial; however, there is no clear evidence of effectiveness and the practice results in longer periods of construction noise overall. It is also a common practice to curtail some types of offshore construction activities when certain aquatic animals are observed in the immediate vicinity to avoid exposing them to potentially injury-inducing noise. Stoppage of construction activities does not address the potential for other types of impacts, such as behavioral modifications and masking of communication, over a much larger geographic area than can be monitored by observers. New mitigation approaches, such as bubble curtains that minimize sound propagation, have the potential to shrink this impact zone.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This *Issues in Ecology* describes what is currently known about the risk wind energy poses to wildlife, how to avoid and minimize that risk, and where uncertainties remain. Wind energy is also considered to have important environmental benefits, and the rapid expansion of wind energy is considered an essential part of the strategy to reduce carbon emissions and air pollution and mitigate the worst effects of climate change on wildlife and human society. Various scenarios for meeting U.S. emission reduction goals indicate that a four- to five-fold expansion of land-based wind energy from the current 97 gigawatts (GW) by the year 2050 is needed.

Given the environmental benefits of wind energy, a focus on rapid improvement and implementation of effective strategies will help reduce the negative impacts of this rapidly growing technology on wildlife. The wind energy industry, state and federal agencies, conservation groups, academia, and scientific organizations have collaborated to promote research needed to reduce these uncertainties in risk to wildlife and to avoid and minimize that risk. However, the pace and scale of wind energy installations and the amount of new wind energy facilities needed to reduce carbon emissions indicate that we must further focus our research priorities, improve coordination and sharing of research results, and increase the rate at which we incorporate research results into the development and validation of best practices.

We provide a brief list of priority recommendations for future research below. Many of these recommendations were first made when concerns about wind energy's impacts on wildlife emerged in the 1990s. This does not mean we have made little progress on these concerns. To the contrary, progress has been substantial. What this replication indicates is that we have been asking the right questions, but that they are challenging questions, and that obtaining more answers remains a priority.

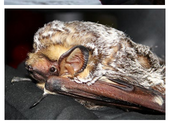
Our general research recommendations include (1) focusing on species of regulatory concern or those where known or suspected population-level concern exists but corroborating data are needed *(Figure 6)*, (2) conducting research that improves risk evaluation and siting to avoid impacts, (3) evaluation of promising collision-reducing technologies and operational strategies with high potential for widespread implementation, and (4) coordinating research and pooling data to enable statistically robust analysis of infrequent, but potentially ecologically significant impacts.

Specific recommendations include:

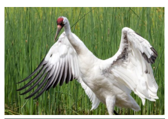
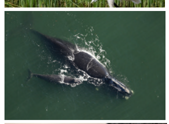
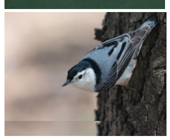
Continue research to improve risk assessment and siting of wind energy facilities. Numerous authors suggest siting of wind energy facilities and individual turbines may be the best approach for reducing impacts to some species. For example, avoiding placement of turbines near bat hibernacula, or near migratory routes of raptors, may reduce collisions. There is, however, much more to learn about the factors that contribute to collision fatality risk: how birds and bats are distributed across space, flight activity, and migratory behavior. For example, understanding how raptors use topography during flight may facilitate micro-siting individual turbines to reduce collision risk. Likewise, knowing the location of areas of concentrated migration of birds and bats

Figure 6. *Species groups that have been a focus of concern regarding the potential for adverse impacts from wind energy development. Each grouping describes: 1) key species, 2) their conservation status, 3) potential impacts, and 4) potential mitigation approaches. The included species are a representative, but not comprehensive list of the major groups for which there is concern. The species are organized into two groups: 1) species with a science-based concern for significant adverse impacts from wind energy (see text), and 2) species where environmental regulations require actions to mitigate effects of wind energy development, although impacts from wind development are still being explored. (photo credits: Prairie grouse - Patty McGann; eagle – Jason Mrachina; bat – Cris Hein – BCI; whooping crane – Jason Mrachina; right whale and calf- Florida Fish and Wildlife Conservation Commission, CC BY NC-ND 2.0; white-breasted nuthatch- Russ, CC BY 2.0)*

Species of management concern with evidence of impacts

	**Prairie Grouse**	• Lesser and Greater Prairie-Chicken, Greater Sage-Grouse • Species under ESA review: lesser prairie chicken • Concerns: Possible habitat loss and fragmentation, displacement and demographic impacts • Mitigation: lek buffers, avoidance of core habitat
	**Raptors**	• Bald and Golden Eagle, Ferruginous Hawk, Swainson's Hawk • Legal protection: Bald and Golden Eagle Protection Act and/or Migratory Bird Treaty Act • Concerns: Collisions, possible nesting disturbance • Mitigation: detection and informed curtailment; deterrence; under study
	**Bats**	• Hoary Bat, Eastern Red Bat, Silver-haired Bat, Mexican Free-tailed Bat • Legal protection: none for these four species • Collision mortality: the four species constitute ~80% of fatalities nationwide • Mitigation: Curtailment at low wind speeds, ultrasonic acoustic deterrence under study

Species of management concern with regulatory concerns

	**Endangered Species**	• California Condor, Whooping Crane • Legal protection: Federal Endangered Species Act • Concerns: Collision mortality, no collisions of either species reported to date • Mitigation: detection and deterrence or curtailment under study
	**Marine Mammals and Reptiles**	• North Atlantic Right Whale, Kemp's Ridley, Leatherback • Legal protection: Federal Endangered Species Act • Concerns: Injury or disturbance from underwater noise, vessel collisions • Mitigation: construction curtailment or sound reduction and reduced vessel speed need study
	**Songbirds**	• Cerulean Warbler, Grasshopper Sparrow, Le Conte's Sparrow • Legal Protection: Migratory Bird Treaty; mostly abundant, some species of conservation concern due to habitat loss • Concerns: Collisions for some declining forest species, displacement for grassland species • Mitigation: FAA-approved lighting to reduce attraction of night migrants

may facilitate the siting of entire facilities. Additional research is also needed to further evaluate the sensitivity of some species, such as grassland songbirds, sage grouse, and prairie chickens to the presence of wind turbines.

Continue and expand investment in the development and evaluation of technologies and operational strategies that minimize collision fatalities of bats, raptors, and other protected species and are feasible to use at a wide range of facilities.

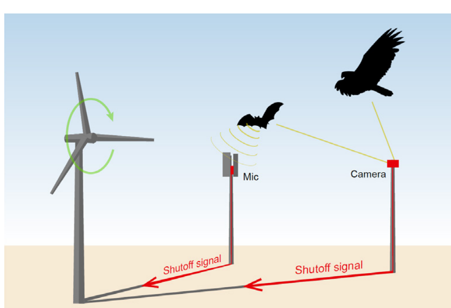


Figure 7. *Automated detection and shutdown technology uses microphones and/or cameras to identify species and can shutdown turbines when necessary.*

We support increased investment in the promising efforts to utilize technology and artificial intelligence to decrease impacts of wind energy to wildlife. For bats, research on 'smart curtailment' involves testing additional environmental variables, such as temperature and barometric pressure that affect bat activity, in addition to wind speed, or studying behavior of bats around turbines to decrease bat fatalities while reducing power loss. The use of camera-based systems that employ machine-learning to 'inform' turbine shutdowns and reduce collision risk to eagles and condors is expanding at wind energy facilities in the western U.S.

Acoustic deterrents for bats and detection-deterrent systems for raptors have been developed and new approaches to improve these technologies are in development (Figure 7). Coordinated and independent research-based evaluation of these technologies supported by government agencies and the wind industry is now underway at multiple wind energy facilities, but more is needed for these technologies to gain widespread adoption by the industry and wildlife agencies.

Conduct replicated studies focused on terrestrial and marine species assumed to be at greatest risk of direct and indirect habitat impacts. Some of the greatest wind resources coincide with some of the most imperiled natural landscapes in the U.S., such as the temperate grasslands of the Northern Great Plains. Well-designed studies are needed on species considered likely to be affected by this development. Habitat-based impacts, including displacement, may not be apparent for several years after construction and operation of a wind energy facility, indicating the need for long-term research. Existing research should be evaluated to determine whether it is appropriate to extrapolate results from related species, for example, from greater prairie-chicken to lesser prairie-chicken, or from oil and gas development to wind. This evaluation could guide future research.

Promote coordinated research at multiple wind energy facilities to enable statistically robust analysis of fatalities and strategies to minimize them. Information critical to informed decision making about wind energy and wildlife interactions is laborious and expensive to collect. For example, detecting rare events—such as the collision fatality of an Indiana bat—is extremely difficult. As noted earlier, current estimates of fatalities are highly uncertain, in part because the facilities sampled do not represent the distribution of turbines across the U.S. Improving our ability to estimate the number of fatalities, or to determine displacement of rare species by wind development, requires coordinated research across multiple facilities. Coordination will facilitate adequate sampling and the pooling of data from multiple studies—using a common database such as the American Wind Wildlife Institute's (AWWI) American Wind Wildlife Information Center (AWWIC)—to facilitate meta-analysis of results. In addition, coordination across facilities will allow more rapid and efficient testing of curtailment strategies, deterrent technologies, or automated shutdown methods.

Develop accurate demographic data for key species of concern to evaluate the population-level significance of collision fatalities and other impacts (e.g., displacement), and establish appropriate mitigation targets. We cannot easily take information about estimated fatalities, changes in behavior, and habitat loss from wind energy, and consider how these affect populations. In some cases, doing so requires basic information that is currently not available. We note that the challenge of understanding impacts to populations is not unique to wind energy development. The potential for cumulative impacts is assumed for threatened and endangered species, but for other taxa, evaluating the necessary level of minimization to maintain populations requires a better understanding of their demographic attributes. For example, the demographic consequences of reducing migratory tree bat fatalities through curtailment at low wind speeds is unknown because of the lack of knowledge regarding population numbers for these species. Quantitative methods, such as demographic models, are well-developed in applied ecology and will likely continue to play a large role in estimating population impacts from wind energy. Many of the suggested research topics above will help generate the types of data required to parameterize these models and improve the quality of their predictions. Understanding when fatalities caused by wind turbines are compensatory (i.e., the turbine-caused deaths would have taken place naturally) or add to the background rate of death is a key issue when considering population-level impacts from wind energy, or from any anthropogenic activity.

The above topics focus attention on those species for which there is greatest concern based on current knowledge. The growth of wind energy and advances in turbine technology will likely increase the exposure of wildlife to potential adverse impacts. Advances in turbine technology may allow wind energy development in regions where it currently is rare, and thus expose new species to potential impacts. We should be prepared to address new concerns as they emerge and also continue to look for solutions that would allow increased wind energy supply and reduced effects on wildlife.

Making significant progress on these research priorities will provide critical knowledge necessary for informed management practices. A great deal of our understanding of the adverse impacts of wind energy and how to mitigate these impacts comes from research at operating wind energy facilities that is funded by government agencies, academia, conservation organizations, and the wind energy industry, either voluntarily or as required by the regulatory process. There are diverse stakeholder groups working on these myriad issues, and collectively they have played a critical role in closing gaps in our understanding and evaluating methods to reduce collisions. Such groups include the National Wind Coordinating Collaborative (NWCC) Wildlife Workgroup founded in 1994, the Bats and Wind Energy Cooperative (BWEC) founded in 2003, and the AWWI founded in 2008. Most recently, the wind industry created the Wind Wildlife Research Fund in 2018. These initiatives demonstrate a commitment to finding science-based solutions to achieve the environmental benefits of wind energy while minimizing its environmental consequences.

FOR FURTHER READING

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