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Accelerating technology development to monitor and minimize effects from land-based wind energy on birds and bats

Isabel Gottlieb[1] | **Cris Hein**[2] | **Patrick Field**[3] | **Taber Allison**[1]

[1]Renewable Energy Wildlife Institute, 700 12th Street, Suite 700, Washington, DC 20005, USA

[2]National Renewable Energy Laboratory, 15013 Denver W Parkway, Golden, CO 80401, USA

[3]Consensus Building Institute, 2067 Massachusetts Avenue, Suite 570, Cambridge, MA 02140, USA

Correspondence
Isabel Gottlieb, Renewable Energy Wildlife Institute, 700 12th Street, Suite 700, Washington, DC 20005, USA.
Email: igottlieb@rewi.org

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Abstract

While wind energy is a key sector of domestic energy production for the United States, operation of wind turbines directly and indirectly adversely affects certain species of birds and bats. The cumulative effect of wind turbine strikes can have both biological and regulatory consequences, and, in some cases, delay permitting and construction or affect ongoing operations. Technology can help quantify and minimize these effects, but the pace of development, acceptance, and adoption of technological solutions is slow. Although adopting cost-effective technologies may reduce negative effects on wildlife and help achieve both energy production and conservation goals, consensus is lacking among developers, regulators, and the conservation community regarding how to define technology effectiveness and acceptance and how to develop a standardized process for doing so. Removing barriers to technology advancement requires deviating from the status quo. Changes include 1) creating incentives to mitigate impacts, 2) establishing options for research as mitigation, 3) rethinking how research is funded, 4) increasing stakeholder coordination, and 5) increasing the efficiency of research and development. We recommend the creation of a national framework to establish clear criteria and protocols for technology evaluation and adoption.

KEYWORDS

bats, collision mortality, eagles, risk minimization, technology, wildlife conservation, wind energy

INTRODUCTION

Land-based wind energy is projected to expand rapidly within the next 30 years (Ardani et al. 2021, Larson et al. 2021), but the deployment of wind turbines negatively affects some species of birds and bats (Allison et al. 2019). Use of technology is essential to quantify and minimize effects of wind energy on wildlife without significant constraints on renewable energy production (Gottlieb et al. 2023). Emerging technologies are in development that detect species of interest, deter individuals from approaching wind turbines, shut down wind turbines when target species are at risk of collision, monitor wildlife behavior or activity near wind turbines, and detect collision events (collectively referred to as technologies). The development, evaluation, acceptance, and adoption of these technologies is a challenging, time consuming, and expensive process that requires interdisciplinary and cross-sector collaboration to succeed. In April 2022, the authors (the Renewable Energy Wildlife Institute, the National Renewable Energy Laboratory, and the Consensus Building Institute) convened a virtual workshop to discuss a path forward to accelerate research and development, validation, and adoption of technologies for monitoring or minimizing adverse effects on wildlife from wind energy, which is summarized in Gottlieb et al. (2023). We build on the lessons learned from that workshop and identify recommendations to facilitate acceptance and adoption of technologies to monitor and minimize the environmental effects of wind energy deployment.

Rapid acceleration of land-based wind deployment

To limit the increase in average temperature to 2.0°C, emissions of greenhouse gases must be reduced by 80–100% by 2050 (Larson et al. 2021). From 2000 to 2023, wind energy development in the United States increased from 2.53 GW to 150.5 GW (U.S. Department of Energy 2017, U.S. Energy Information Administration 2023, American Clean Power 2024). By the end of 2023, there were more than 71,000 land-based wind turbines in the United States, generating 10.3% of all electric power (U.S. Energy Information Administration 2023, American Clean Power 2024). To achieve net zero by 2050, wind energy build-out will need to quadruple by 2030 compared to 2020 levels and increase 600%–3,000% by 2050 (U.S. Department of Energy 2017, Ardani et al. 2021, International Energy Agency 2021, Larson et al. 2021). As the demand for electricity accelerates and the rate and scale of wind energy increase to meet domestic energy goals of the United States, so does the importance of understanding and minimizing its repercussions for wildlife (U.S. Energy Information Administration 2025).

Effects of land-based wind energy on birds and bats

Land-based wind energy deployment poses risks to some species of birds and bats from collisions or from habitat loss and alteration (Arnett et al. 2008, Loss et al. 2013, Allison et al. 2019, American Wind Wildlife Institute 2021). In the United States, the annual mean avian fatality rate is 1.83 birds/MW/year (American Wind Wildlife Institute 2020*a*). Although 307 species have been reported as fatalities, the fatality rate for any one species is relatively small (American Wind Wildlife Institute 2020*a*). Thus, the effect of wind facilities does not present a population-level concern for most bird species, though there is concern for certain species with low reproductive rates, such as the golden eagle *Aquila chrysaetos* (Carrete et al. 2009, Bellebaum et al. 2013; U.S. Fish and Wildlife Service 2016, Hunt et al. 2017).

Estimates of bat fatality rates at wind energy facilities are greater and more variable compared to birds, with an annual mean fatality rate of 6.35 bats/MW (American Wind Wildlife Institute 2020*b*). Migratory tree-roosting species, including hoary bats *Lasiurus cinereus*, eastern red bats *L. borealis*, and silver-haired bats *Lasionycteris noctivagans* make up >70% of reported fatalities at wind energy facilities (American Wind Wildlife Institute 2020*b*). While little is known about the population status of these species, their low reproductive rate, and high collision mortality may result in population-level declines (Kunz et al. 2007, Arnett et al. 2008, Arnett and Baerwald 2013, Frick et al. 2017). The fungal infection white-nose syndrome, caused by *Pseudogymnoascus destructans*, is the primary driver of declines for several species of cave-hibernating bats that are (or may soon be) listed under the Endangered Species Act (ESA 1973, as amended; Frick et al. 2010, Turner et al. 2011, Hayes 2012). Although fatality rates from wind energy are low for these species, the remaining populations may be vulnerable to additional sources of fatalities.

Regulatory framework

While much of the regulatory authority rests with state and local jurisdictions, at the federal level, effects from wind energy on wildlife populations are primarily regulated by the United States Fish and Wildlife Service (USFWS) through three federal statutes:

1. Endangered Species Act (ESA 1973, as amended). The ESA protects species listed as threatened or endangered from take, including that which occurs incidentally during an otherwise lawful activity. In the context of wind energy, this occurs when a listed species such as the Indiana bat *Myotis sodalis* or northern long-eared bat *M. septentrionalis* collides with a turbine blade during its normal operation. If there is risk of incidental take of a listed species, a developer may apply for an incidental take permit; this requires the developer to submit a habitat conservation plan (U.S. Department of Interior and U.S. Department of Commerce 2016) to monitor take and identify mitigation measures to avoid, minimize, and offset the predicted take of the listed species.
2. Migratory Bird Treaty Act (MBTA 1918, as amended). The MBTA protects more than 1,000 bird species from take, but the interpretation and application of the laws have changed over time. In the 1970s, the scope of the MBTA was broadened to prohibit incidental take (take that results from but is not the purpose of an activity; e.g., collisions with wind turbines; Ogden 2013). Since 2017, The federal government has reversed its policy on whether incidental take is prohibited under the MBTA three times (2017, 2021, 2025). As of 2025, the interpretation of the MBTA does not protect migratory birds from incidental take (U.S. Department of Interior 2025).
3. Bald and Golden Eagle Protection Act (BGEPA 1940, as amended). Eagles are given additional protection under BGEPA. The definition of take includes disturbance and provides protection to eagles from any activity that might agitate a bald eagle *Haliaeetus leucocephalus* or golden eagle and lead to injury, a decrease in productivity, or nest abandonment. The USFWS can issue incidental take permits under BGEPA. Specific permits (for sites that do not meet general permit eligibility criteria) require an eagle conservation plan that describes measures to minimize and offset predicted eagle take.

Many stakeholders are increasingly concerned about the regulatory implications of recent and potential future listings under the ESA of cave-roosting bat species, including the northern long-eared bat (U.S. Fish and Wildlife Service 2022*a*), tricolored bat *Perimyotis subflavus* (U.S. Fish and Wildlife Service 2022*b*), and little brown bat *M. lucifugus* (Solari 2021), whose populations have been devastated by white-nose syndrome (Cheng et al. 2021). The USFWS has initiated a status review of the hoary bat, which may be in decline because of collisions with wind turbines (Frick et al. 2017), a first step to its possible listing as a threatened or endangered species under the ESA. Given hoary bat fatalities (30.8% of all incidents recorded) at wind energy facilities are so much greater than for hibernating cave-roosting species such as the big brown bat *Eptesicus fuscus*, the cave bat most commonly killed at wind energy facilities (6.9% of incidents recorded; American Wind Wildlife Institute 2020*b*), listing the hoary bat under the ESA could result in prohibitively expensive or infeasible mitigation measures for industry (Arnett and Baerwald 2013, Frick et al. 2017, American Wind Wildlife Institute 2020*b*). Voluntary, industry-wide efforts to minimize bat fatalities and prevent the need to list the hoary bat under the ESA would avoid these costly regulatory requirements. However, the current regulatory landscape lacks clear guidelines to incentivize conservation of bat species not listed under the ESA, or for the wind energy industry to invest in research and development to advance more cost-effective monitoring and mitigation solutions that meet both conservation and energy production goals. Technologies can provide cost-effective solutions to quantify and minimize effects of wind energy on wildlife to meet regulatory requirements or voluntary conservation goals.

OVERVIEW OF TECHNOLOGY SOLUTIONS

Curtailment

This term encompasses strategies to reduce collision fatalities by slowing the rotational speed of wind turbines during times when target species are determined to be at risk. Curtailment requires sophisticated control capabilities of wind turbines, and decisions to curtail are nuanced, influenced by company guidelines, project finances, state and federal policy, bat and bird species present in the area, site-specific landscape, weather conditions, and others. Curtailment to reduce bat fatalities based on the time of day, time of year, and wind speed is commonly referred to as blanket curtailment (Barré et al. 2023, Gottlieb et al. 2023, Hayes et al. 2023). For example, a facility might implement blanket curtailment at night between mid-July and early October when wind speeds are below 5.0 m/s. Although effective at reducing overall bat fatalities, blanket curtailment limits power generation even when bats may not be present (Adams et al. 2021, Whitby et al. 2024).

To reduce excess electricity production losses, curtailing only when target species are present, or predicted to be present, can be implemented. Using sensors to detect or predict wildlife activity to inform more efficient curtailment strategies is referred to as smart or informed curtailment. Smart curtailment may use real-time activity data collected by cameras paired with identification algorithms (Cullinan et al. 2015, McClure et al. 2021), acoustic detectors (SWILD 2015, Hayes et al. 2019), radar (May et al. 2017, Washburn et al. 2022), or global positioning system (GPS) data from tagged individuals (Sheppard et al. 2015) to reduce bird and bat fatalities. Curtailment may also be informed by models that use environmental variables (e.g., temperature, wind direction) and wildlife activity data to predict periods of elevated collision risk (Martin et al. 2017, Peterson et al. 2021, Barré et al. 2023).

Research suggests that smart curtailment using bat activity (Hayes et al. 2019, Newman et al. 2024), temperature (Martin et al. 2017), wind direction (Gottlieb et al. 2024), or other variables may effectively reduce bat fatalities while reducing loss of electricity production by using narrowed parameters for curtailment in comparison to blanket curtailment. Continued research is needed to further quantify fatality reductions and improvements to electricity production, relative to blanket curtailment, before smart curtailment technologies are broadly accepted (Whitby et al. 2021, Hayes et al. 2023). Camera-based systems have been used with some effectiveness to identify and track eagles to inform curtailment decisions when eagles are nearby (McClure et al. 2021). Geofences have also been used to detect GPS-tagged California condors *Gymnogyps californianus* near wind facilities to inform curtailment strategies in southern California (Sheppard et al. 2015).

Deterrents

Another minimization approach is to deter target species from approaching wind turbines. If effective, deterrents allow wind turbines to operate normally without loss in power generation. Visual deterrents are intended to reduce interactions by making wind turbines more noticeable or reduce the number of individuals who might perceive wind turbines as a potential resource (Cryan et al. 2022). These deterrents may be kinesthetic (Albertani et al. 2021) or static, such as using paint (May et al. 2020), ultraviolet light (Dwyer et al. 2019; Cryan et al. 2022), or a texturized coating (Bennett and Hale 2018). Acoustic deterrents emit audible or ultrasonic noise to startle individuals and reorient their flight trajectory away from wind turbines (H.T. Harvey and Associates 2018) or create a disorienting airspace that interferes with navigation and foraging (Arnett and Baerwald 2013, Romano et al. 2019, Cooper et al. 2020, Weaver et al. 2020). Deterrent systems may function constantly over a designated period (e.g., all night for ultrasonic deterrents for bats) or when a target species is detected (e.g., camera-based system detecting a large raptor). To date, no deterrent technology for birds or bats has consistently performed well enough to be accepted as a proven minimization strategy by the conservation community or wind energy industry. Further, long-term operation and effectiveness of deterrents, and whether wildlife might habituate to deterrent signals, are unknown. More published research is needed to justify the acceptance of any specific deterrent technology.

Fatality or activity detection

Technology solutions are being developed to detect the activity of individual animals at risk of collision with wind turbines or to record wind turbine strikes (Happ et al. 2021, Clocker et al. 2022). While technologies that measure collision risk or rates do not minimize risk on their own, these technologies may be used to quantify interactions or strike events in locations where it is not possible to conduct standard fatality searches (e.g., offshore wind energy facilities), reduce costs associated with traditional fatality monitoring, and provide information that could inform smart curtailment strategies. Potential approaches to monitoring include use of blade-mounted strike detectors (Clocker et al. 2022) or camera systems to detect collision events, either with cameras oriented toward the rotor-swept areas or cameras pointed away from the wind turbine to observe the trajectory of animals falling after a collision event has occurred (Przybycin et al. 2019, Happ et al. 2021). Surveys for wildlife fatalities using drones, LIDAR, and artificial intelligence have also been considered as alternatives to humans or detection dog teams as searchers (Miller 2020). In addition, some of these sensor-based systems can provide the location of strikes along the blade length or where in the rotor-swept zone collisions are occurring (i.e., above or below the nacelle) and real-time information on fatality events, both of which are not possible with traditional fatality monitoring. Knowing the location of strike events would be useful for determining where to focus some deterrent technologies. Real-time fatality data, paired with weather and operational conditions, may be useful for designing curtailment strategies.

CHALLENGES TO DEVELOPING AND DEPLOYING TECHNOLOGIES

Functionality

Some technologies employ advanced engineering or artificial intelligence capabilities that must function at a high level for the technology to be viable. For example, technologies that deter or curtail to reduce eagle fatalities based on real-time eagle activity must be capable of rapidly and accurately processing images and identifying species (H. T. Harvey and Associates 2018, Albertani et al. 2021, McClure et al. 2021). In addition, because wind turbines are often subject to harsh environmental conditions, technologies must reliably function in extreme heat and cold, ice, dust, and precipitation over many seasons and years. Technology maintenance could be logistically challenging and require turbines to be shut down periodically, particularly if the technology is integrated with the turbine (Gottlieb et al. 2023).

Integration

Incorporating a novel technology into an operating wind energy facility requires careful planning, execution, and collaboration among wind turbine manufacturers, wind energy operators, and technology developers. Installing a device on a wind turbine may cause warranty issues if structural modifications (e.g., holes, bolts) are necessary or cybersecurity concerns if the wind turbine's communication system is used to transfer data. If a device is installed on turbine blades or curtails turbine operation, it may affect performance or increase wear and tear of the turbine. Integrating a device with the Supervisory Control and Data Acquisition system (commonly referred to as SCADA system) or the network of the facility may introduce challenges with cybersecurity or bandwidth for data (Gottlieb et al. 2023, Vallejo et al. 2023).

Validation

Full-scale validation of technologies at wind energy facilities is complex and may require one or more multi-million-dollar projects over several field seasons (Hayes et al. 2019, Gottlieb et al. 2024, Newman et al. 2024). Validation studies often include rigorous protocols, requiring expensive daily fatality searches of large search areas beneath study turbines. Search plots must be maintained for several months, and landowners must be compensated if the experiment prevents landowner use. Analysis may include extensive data management and vetting if camera or acoustic methods are used to monitor species activity (Peterson et al. 2021, Felton et al. 2024). Fatality events of target species may be rare, so ensuring the proper sample size is achieved to assess the effectiveness of the technology is a significant challenge. Seasonal variability in the activity and collision risk of target species (e.g., bat migration; Sinclair and DeGeorge 2016, American Wind Wildlife Institute 2021) can limit the time frame available for fieldwork. Even if a technology is shown to be highly effective, equivalent performance at other locations may differ because of meteorological conditions, biological communities, landscape features, or other characteristics.

BARRIERS TO THE ACCEPTANCE OF EFFECTIVE TECHNOLOGIES

No consensus on criteria for an effective technology

To be accepted, technologies must consistently function or perform as intended, be easily and safely integrated into wind energy facilities and wind turbines, meet expectations of effectiveness for monitoring or minimize impacts, and perform reliably over an extended period (Gottlieb et al. 2023). Several research and development steps are required to achieve acceptance, and each of these involves financial investment, presents challenges, and requires decision makers to determine if moving the technology's research and development forward is warranted (Figure 1). Despite substantial investment by industry, federal agencies, and science and conservation organizations in the development and evaluation of technologies, there is no consensus around criteria to define a technology as effective. Clear standards to define effective technologies would help technology developers, the wind industry, and regulators determine whether and under what conditions a technology is appropriate to deploy. Important components of a definition for an effective technology include:

1. Performance targets for fatality reduction. Guidelines regarding whether and how a minimization technology can be deployed depend on whether it achieves performance targets related to fatality and risk reduction, detection rates, or other metrics as appropriate. For example, this could be framed as a minimum threshold for a reduction in fatalities to be accepted (e.g., 25%, 50%, or 75%) or a standard by which a reduction of fatalities of any size may be acknowledged and accepted for implementation.
2. Reliability of the hardware and software. Effective technologies should meet standards of reliability related to their continued successful operation and connectivity when deployed in the field and subjected to harsh environmental conditions.
3. Number, duration, and spatial extent of studies. One should consider how much research is needed to understand a technology's performance and consistency, and to accept remaining uncertainties.

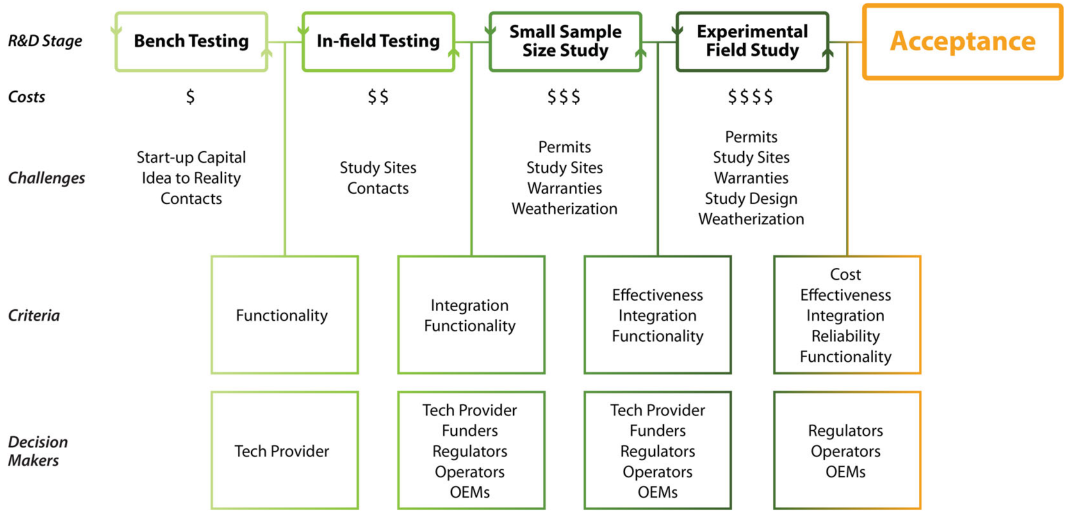

FIGURE 1 A relative framework developed in conjunction with a Technology Acceptance Workshop hosted by the authors in 2022 for the stages of research and development (R&D) necessary to achieve commercial and regulatory acceptance of technologies designed to monitor and minimize effects of land-based wind energy on birds and bats. Each stage includes the relative cost, challenges, and criteria to move forward, and the decision makers involved (tech providers, funders, regulators, operators, and original equipment manufacturers [OEMs]). Functionality relates to the capability of a technology to operate as designed. Effectiveness is whether a technology performs its monitoring or minimization application as intended. Reliability is the long-term dependability of a technology. Graphic by the National Renewable Energy Laboratory.

Develop pathways for technology advancement

Currently, there is no clear pathway to integrate the use of technologies in the permitting process, in adaptive management plans, or to meet regulatory requirements at state and federal levels across regulatory schema and jurisdictions (i.e., MTBA, ESA, BGEPA). Clear protocols to update take predictions based on technology use in incidental take permits for species protected under the ESA or BGEPA would help to achieve conservation goals, facilitate adoption of technologies, and lower compensatory mitigation costs. A robust pathway would include guidance for implementing adaptive management measures in the event of permit exceedance and incentives for early adopters. The USFWS uses adaptive management to guide management decisions at wind energy facilities and has adopted a definition developed by the National Research Council in 2004: "Adaptive management promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood" (U.S. Fish and Wildlife Service 2012).

Permitting agencies can further encourage effect minimization by defining credits with limits for the application of best-available technologies and approaches; for example, with deterrents or curtailment strategies. Such an approach mirrors that used by the Environmental Protection Agency in the Best Available Control Technology procedure in facilitating compliance with emissions levels under the Clean Air Act. Adaptive management responses would be triggered when limits are exceeded. This approach is consistent with application of Tier 5 as outlined in the USFWS Wind Energy Guidelines (U.S. Fish and Wildlife Service 2012).

Adaptive management can be interpreted by the wind industry as an unending process with open-ended financial commitments and risk. Under the premise that not every project exceeds predicted wildlife effects, potentially requiring adaptive management, the financial risk of adaptive management could be pooled by the creation of an adaptive management insurance program. Under this program, developers would contribute to a financial pool that a developer would access when a project exceeds predicted levels of wildlife effects (e.g., collision mortality, habitat loss, displacement). Establishing and implementing an insurance program would require development of tools analogous to actuarial tables for life insurance or risk tables for auto and homeowners' insurance to set adaptive management premiums.

Create incentives to conserve common species

There are currently no legal or regulatory incentives for the deployment of technologies to conserve species that are common presently but may be at significant risk from current and future expansion of wind energy development. While the existing regulatory framework has robust policies for protecting species covered under the ESA, MBTA, and BGEPA, hoary bats and other migratory tree-roosting bat fatalities are a significant conservation concern for wind energy facilities (Frick et al. 2017). Should any migratory tree bat species decline to the extent that they are listed under the ESA, it could result in dramatic constraints on wind energy production. Technologies could play a major role in the proactive conservation of these species; however, there are currently no regulatory incentives to promote the use of technology to reduce fatalities of bat species that are not listed under the ESA.

Establish options for research as mitigation

Although the USFWS has indicated there is potential for the use of research as mitigation (U.S. Department of Interior 2023), there is little guidance on how to implement the policy. Expanding incentives to develop and evaluate minimization technologies is arguably the greatest and most readily addressable need. It is generally assumed that research is not included in the mitigation hierarchy of avoid, minimize, and compensate, as these actions are intended to address the mitigation of the specific adverse effects of an activity, such as development and operation of a wind energy facility. However, there are instances where research has been accepted as compensation. For example, wind energy companies seeking eagle take permits have negotiated with USFWS to address past unpermitted eagle take. In some cases, the companies were able to compensate for this past take by contributing funding toward research evaluating technologies designed to minimize eagle take (e.g., Smith et al. 2025). More recently, the 2023 USFWS Mitigation Policy (501 FW 2, Appendix 1) states that in "rare circumstances, research or education that is directly linked to reducing threats, or that provides a quantifiable benefit to the species, may be included as part of the mitigation package" (Part 6.6.3.2, pg. 14). Following release of the 2023 USFWS Mitigation Policy, the USFWS released a memorandum establishing "that funding research is an acceptable mitigation option for wind power habitat conservation plans that cover bat species affected by white-nose syndrome" (U.S. Department of Interior 2023). In addition to funding research on the cause, effects, and remediation of white-nose syndrome, the memorandum also states that research on "technology that can reduce the effects of wind power projects on white-nose syndrome impacted bats" is acceptable (U.S. Department of Interior 2023). Expanding research as mitigation could provide incentives to invest in developing technological solutions and in evaluating those technologies at operating wind energy facilities.

Rethink funding opportunities for research

Streamlined funding mechanisms that support strategic research questions are needed to expedite technology research and development and meet the national renewable energy goals for the United States. The time required for contract negotiations can persist for many months, and quarterly meetings and status reports can divert limited resources from project objectives. While it is necessary for a funder to track and evaluate the progress of projects, reducing the administrative burden associated with awards would allow for more of the investment to go towards research. For those awarded funding, it is imperative to complete deliverables accurately and in a timely manner to reduce the number of iterations required for those deliverables.

Revisiting how we fund research can also improve our ability to advance technologies. Too often, studies are designed to fit the funding level, which can lead to limited replication, sample size, and duration. An alternative approach is for the funding level to match the experimental design. For a single funding entity, this may result in fewer funded projects, but the quality of the funded research will increase. In addition, coordination among funding entities can increase the number of awarded projects or allow for larger and more complex projects at operating wind energy facilities with robust study designs. Before-after-control-impact study designs are robust but expensive and require that a study is funded, designed, and agreed upon prior to the construction of a wind energy facility. Opportunities to pool funding across sectors are essential to scaling up research. Coordination is necessary within the wind energy sector but can also be useful across energy sectors. For example, some monitoring and minimization technologies may be applicable for solar and land-based wind energy development or offshore wind energy and waterpower projects and can be supported through government agencies that oversee deployment, companies from either sector, or companies that have diverse energy portfolios.

Increase coordination among stakeholders

If the technology does not operate as intended during a validation study, it can confound the results of the study, making it difficult to assess whether the technology is effective. For example, the ultrasonic deterrents evaluated by Arnett et al. (2013) experienced frequent technical issues, including water leakage, making some deterrents inoperable during portions of the study. These issues required unplanned and time-consuming maintenance from on-site staff and undoubtedly influenced study results. To help ensure a technology performs as intended, the technology provider needs to communicate with researchers, wind energy developers, and wind turbine manufacturers to discuss the placement, power, safety, and communication constraints and opportunities associated with installing equipment at a wind energy facility or wind turbine. Coordination during preliminary stages of research and development will likely reduce costs and complications during field validation studies, help ensure a plan is in place in the event the technology malfunctions, and provide more confidence that the technology can be integrated successfully.

To achieve successful integration, wind energy developers and wind turbine manufacturers should connect with researchers and technology providers to convey constraints and opportunities for equipment installation. Consultants and research institutions can act as intermediaries to help make these connections. The research community has made efforts to identify available technologies for monitoring and minimizing wildlife interactions at wind energy facilities, including the International Energy Agency Wind Task 34 (Tethys 2024), Renewable Energy Wildlife Institute (2024), and National Offshore Wind Research and Development Consortium (2024). Encouraging stakeholders to attend conferences, webinars, and workshops outside of their expertise (e.g., wind turbine manufacturers attending the Wind Wildlife Research Meeting, or ecologists attending the North American Wind Energy Academy) can also bring awareness to their products and foster partnerships.

High costs of deploying technologies

Increasing efficiencies in research funding and coordination should lead to reduced costs for technology validation. In addition, conducting performance and weatherization evaluations prior to field deployment will safeguard against unnecessary maintenance and replacement expenses during a study. This will also increase the likelihood of a successful study focused on effectiveness of the applied technology and provide confidence to all that the investment was worthwhile.

Costs of developing and validating a technology, particularly for a niche market, can be prohibitive. Thus, technology developers focused on wind energy should consider other potential markets, such as solar energy, wave and tidal energy, transmission, or transportation. Researchers who work across sectors can assist in making connections to different companies. Some energy companies have different portfolios for wind, solar, or other sources and can transfer information about technologies internally. Technology providers can also invest their time networking with researchers and companies on how to develop and validate their technologies across a range of applications. Cost savings in other areas may help offset the expenses of technology deployment. If fatality monitoring requirements are reduced, cost savings could be applied to the implementation of technologies or other conservation efforts.

ESTABLISH A NATIONAL FRAMEWORK FOR TECHNOLOGY DEVELOPMENT AND IMPLEMENTATION

There is a lack of consensus among stakeholder groups regarding who the decision makers are related to the acceptance of technologies and when there is sufficient buy-in to implement new practices. Buy-in from major stakeholder groups is key but can be difficult to achieve when interests and values do not align. Enacting policy change, particularly at the federal level, is a complicated, lengthy process and should be approached deliberately. As noted above, there are no established criteria for effectiveness. Greater clarity, commonality, and direction are needed regarding criteria to determine whether a technology is considered effective and can be implemented by wind energy developers across projects. The distributed and project-by-project approach increases uncertainty for technology developers and wind energy developers and hampers investment and innovation in wildlife mitigation.

Convening a multi-stakeholder workshop that includes federal and state agencies, wind energy industry representatives, nongovernmental organizations, wind turbine manufacturers, researchers, and technology developers could help establish a robust, clear national framework for technology evaluation and acceptance. The final product of this collaboration would be a guidance document outlining a pathway acceptable to all key stakeholder groups for evaluating and adopting technologies and identifying or creating viable regulatory and financial pathways to incentivize the use of technology solutions to minimize effects of wind energy on wildlife. There is a precedent of other federal agencies playing a leading role in the review and approval of technologies to meet environmental goals under existing regulations. The United States Environmental Protection Agency established the Best Available Control Technology in statute under the Clean Air Act and the Clean Water Act, under which the agency created regulations and guidelines for qualifying technologies. The United States National Oceanic and Atmospheric Administration (NOAA) has helped advance and approve technologies such as vessel tracking (Vessel Monitoring System), electronic monitoring for fisheries (in progress), and vessel strike avoidance to protect the North Atlantic right whale *Eubalaena glacialis* and other marine mammals. The Bureau of Ocean Energy Management (BOEM) and NOAA have published recommendations for use of passive acoustic monitoring in offshore wind monitoring and mitigation programs (Van Parijs et al. 2021). Pacific Northwest National Laboratory undertook an effort with NOAA, BOEM, and others to develop a framework for evaluating tools and technologies for monitoring baleen whales (Szesciorka et al. 2025). We identify several options to create and implement a national framework for technology development and implementation.

1. Develop voluntary guidelines through a Federal Advisory Committee (FAC) process under the Federal Advisory Committee Act that establish a national framework for the development and implementation of technologies without enacting new regulations, such as they did in creating the USFWS Land-Based Wind Energy Guidelines (U.S. Fish and Wildlife Service 2012). Use of the FAC process is a formal, powerful tool to enact change in federal policy. It would signal the federal government's serious intent to address the problem and invest resources in its solution. It allows diverse stakeholders to participate in a collaborative process and arrive at joint

recommendations and requires the convening federal agency to formally respond to the recommendations. Its substantive goal can be to create regulations (along with an associated administrative law, the Negotiated Rulemaking Act) or guidelines. However, the FAC process may be costly, lengthy, and cumbersome to convene. To implement a FAC process, the Office of Management and Budget must approve its creation, allocate substantial federal resources, and obtain White House approval of committee membership.

2. Convene an intergovernmental task force of key state and federal agencies (USFWS, U.S. Department of Energy, state natural resource agencies) that does not trigger FAC as a core group of entities committed to developing the framework. This intergovernmental task force can convene a series of workshops with key stakeholders to explore, advance, and hone a framework that is ultimately written by government entities but widely developed and refined with stakeholder input. This approach does not have the advantages of a FAC in creating a binding, formal process, but it is likely to be implemented more quickly, allows for broad and diverse participation, and permits the agency to retain more control over the final product.
3. Convene a working group recognized by the federal government but led by a nonfederal actor to develop the framework outside the formal confines of the federal government but with participation from the USFWS. For instance, some trade associations have standards-setting bodies under frameworks like the American National Standards Institute that create standards, processes, and procedures across an industry that federal agencies may reference in regulations or guidelines. For instance, the American Petroleum Institute's standards division has created numerous safety, engineering, and engagement standards and recommended practices that have been used by federal agencies such as the Department of Transportation Pipeline and Hazardous Materials Safety Administration. Another example in the offshore wind space was the creation of two regional science entities: Responsible Offshore Science Alliance and Regional Wildlife Science Collaborative. Each entity convenes stakeholders to develop guidance around matters like passive acoustic monitoring deployment and fisheries monitoring by developers. Federal agencies with authority, including NOAA, USFWS, and the BOEM, participate in both governance of the process and substantive work around guidance development for both entities. These approaches have the potential speed and flexibility of a nonfederal process (although American National Standards Institute process requirements are formal and rigorous and sometimes even exceed governmental administrative procedural requirements), and creation of a stand-alone framework. At the same time, this approach risks that the USFWS may not accept and implement the final product, and, if so, it could be of limited use.

We recommend the framework to address the outlined challenges include requirements for each phase of research and development, including benchmarks, sample sizes for experimental studies, and reporting criteria. For example, a new minimization technology could be required to meet or exceed functionality requirements for durability (e.g., ingress protection rating; International Electrotechnical Commission; www.iec.ch/ip-ratings) during the bench testing phase. We recommend that the framework should establish criteria to define effectiveness for a risk minimization technology, including thresholds for reductions in fatality rates of target species, and consistent performance across multiple sites and years.

CONCLUSIONS

As wind energy development expands, the rapid advancement of technological solutions is needed to support cost-effective means of monitoring and minimizing effects on wildlife. However, lack of clarity surrounding acceptance of effective technologies poses major challenges to meeting conservation and renewable energy goals. We believe that a collaborative, national framework for developing and validating technologies with support from regulatory agencies, industry, and researchers is necessary to define a pathway and metrics (e.g., criteria for reduction in fatalities) for technology acceptance, and that increasing incentives for the wind energy industry to support research and streamlining opportunities to fund research would facilitate the adoption of successful technologies.

With prompt action and deliberate collaboration, stakeholders in the wind–wildlife field could create new opportunities and well-defined pathways for technology solutions that improve substantially upon the status quo.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

The Authors declare that this manuscript adheres to high ethical standards. All information shared was sourced from reliable sources. All opinions expressed are drawn from professional experience and research, and solely reflect the views of the authors, and do not necessarily reflect the views of any affiliated institutions. This manuscript was based solely on previously published information, and did not involve collection of data on any vertebrate or human subjects, and this no ethics approvals were required.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no data sets were generated or analyzed during the current study.

ORCID

Isabel Gottlieb https://orcid.org/0000-0003-2003-6222

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SUPPORTING INFORMATION

Additional supporting material may be found in the online version of this article at the publisher's website.

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