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Ecological Solutions and Evidence

PRACTICAL TOOLS

A global decision framework for reducing bat fatalities at wind energy facilities

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Abstract

1. Ensuring wind energy development does not cause biodiversity loss is a global priority. Wind turbines kill large numbers of bats, raising concern that global expansion of wind energy increases the threat of extinction of vulnerable bat species. Uncertainty about bat population size and status has hindered efforts to implement regulatory policies based on solutions known to reduce bat fatalities at wind energy facilities, in large part because the amount of fatality reduction necessary to protect bats has been difficult to define. Adoption of the full mitigation hierarchy for bats is urgently needed, including informed siting to avoid impacts to bats, minimization of bat fatalities using fatality thresholds to set operational conditions (e.g. curtailment) and compensation through offsets.
2. We introduce a method to adapt the use of potential biological removal (PBR) to establish bat fatality thresholds at a project scale even with high uncertainty about bat populations. We propose a decision framework using fatality thresholds to inform turbine operating constraints that will lower the risk of unsustainable mortality and provide better financial forecasting for developers during project planning.
3. Our fatality threshold calculation tool incorporates modified principles of PBR, general bat reproductive biology, IUCN status, local bat ecology, and facility area to define fatality thresholds for individual wind facilities. We use IUCN status and foraging guild to set initial exposure reduction targets and operational constraints meant to lower fatalities to meet thresholds. Adaptive management based on post-construction fatality monitoring can then determine whether curtailment is sufficient to meet a fatality threshold or needs adjusting.
4. Our proposed approach allows for high uncertainty about local bat populations but can incorporate new information that becomes available. Data defining local

bat population density, seasonal variation in bat activity, or changes in IUCN status can be used to update fatality thresholds and operating regimes.

5. *Practical implication.* Defining fatality thresholds to inform mitigation implementation should reduce bat fatalities, ideally to sustainable levels, while providing a measure of success for wind companies to ensure equitable regulatory conditions and help drive innovation for technology to reduce bat fatalities while maintaining or improving energy production capabilities.

KEYWORDS
adaptive management, bats, biodiversity loss, fatality thresholds, mitigation hierarchy, potential biological removal, wind energy

1 | INTRODUCTION

The climate crisis requires effective response strategies, such as reforestation, energy conservation, and shifting to renewable energy, including expansion of wind energy. Meeting the COP28 goals of tripling renewable energy by 2030 requires installing 320 GW of wind energy annually by 2030 (GWEC, 2024). Solutions are needed to provide biodiversity protection as renewable energy expands globally. Thus, renewable energy companies must mitigate impacts on biodiversity, and financial lenders and governments must provide guidance and require monitoring to ensure compliance that safeguards the environment.

Globally, millions of bats die from wind turbine collisions each year (Voigt et al., 2024; Whitby et al., 2024). Bat fatalities are sufficient to threaten population viability of some species (Friedenberg & Frick, 2021). Reducing the likelihood of unsustainable population loss requires an immediate and globally applicable mitigation approach. Yet, ecological traits that are informative for mitigation, such as population size or migratory routes, are largely unknown for most bat species (Frick et al., 2020). Bat species richness and data deficiency increase in tropical latitudes further limiting conservation decisions as wind energy development expands into the Global South (Voigt et al., 2024). Acting on what we do know is required to reduce and prevent unsustainable mortality in the next decade.

Twenty years of research demonstrates that curtailing turbines reduces bat fatalities with minimal power loss (Adams et al., 2021; Whitby et al., 2024). Curtailment has some financial cost, and therefore implementation is unlikely without guidance, incentives, or regulatory requirements. Currently, whether curtailment is used depends on developers' corporate environmental commitments, agencies' regulatory requirements and financial lending standards.

Bat fatality targets are rarely specified for curtailment, resulting in uncertainty for developers during project feasibility assessments. This uncertainty can lead to inequity if companies vary in corporate environmental policies or financing requirements, putting companies that curtail to reduce bat fatalities at a competitive disadvantage. A globally consistent method that determines curtailment requirements during feasibility assessments would provide equity to companies and reduce bat fatalities. Following the mitigation hierarchy should achieve this: avoid bat fatalities through appropriate siting, minimize fatalities through curtailing during high-risk periods, and compensate for bat population losses through actions such as targeted habitat protection. Here, we present the full mitigation hierarchy but focus on minimization. We propose setting bat fatality thresholds during project feasibility assessments to design initial curtailment schedules. Post-construction fatality monitoring (PCFM) can then be used to determine whether curtailment is sufficient to meet thresholds.

2 | MITIGATION HIERARCHY STEPS

2.1 | Avoid: Siting of wind facilities

Constructing wind facilities in certain areas poses higher collision risk and can displace bats (Ellerbrok et al., 2024; MacEwan, Morgan, et al., 2020; Scholz et al., 2025). Project feasibility assessments should include surveys to identify roosting sites, foraging areas, and migration routes. Defining buffers around sensitive areas can help protect local bat populations. There is no current unified guidance on appropriate buffer sizes for bat habitat features, but regional guidance exists (Table S1).

Siting decisions must balance ecological, social, and economic concerns and are often made with uncertainty about bats. Bat occurrences and range maps are available in global databases, but surveys should be conducted during feasibility stages (Table S1). Even with evidence-based siting, collision risk for bats is rarely entirely avoided. Almost all wind energy facilities with PCFM have reported bat fatalities, at rates of 3 bats/MW/year in South Africa, 6 to 7 bats/MW/year in North America and Europe, and from 2 to 57 bats/MW/year in Latin America (Voigt et al., 2024). Therefore, a clear and prescriptive approach to minimize bat fatalities is needed.

2.2 | Minimize: Set bat fatality thresholds

Curtailment is currently the most effective option for reducing bat fatalities (Berthinussen et al., 2021). Determining the amount and

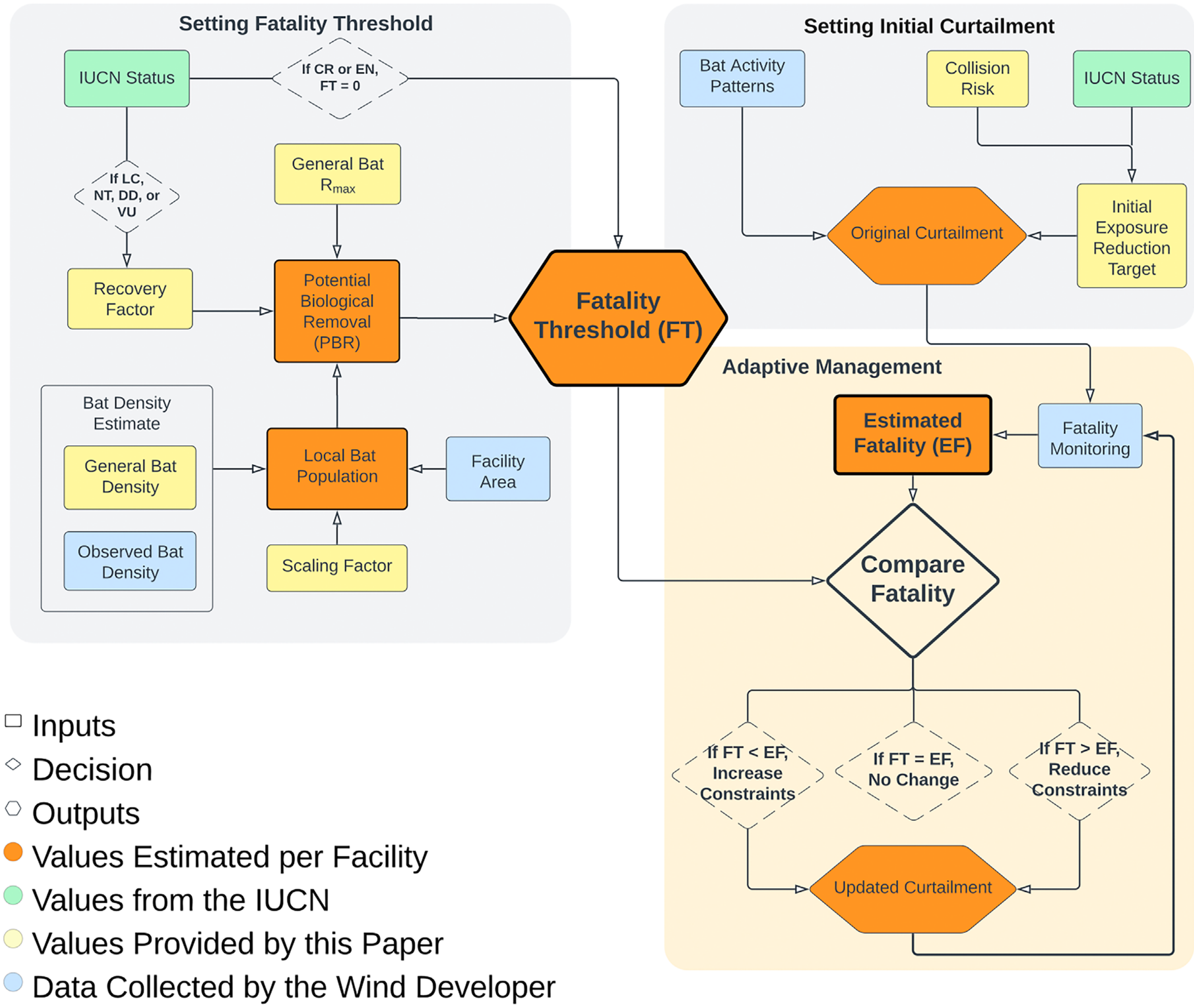

FIGURE 1 The process to minimize bat fatalities at wind energy facilities by setting fatality thresholds, determining initial curtailment and using fatality monitoring to adjust operations to sustain local bat populations.

timing of curtailment that minimizes bat fatalities while maximizing power production is important. The approach must be logical, consistent and easily applied to developing or amending a project's energy yield assessment and financial model forecasts. Four components that can help developers estimate acceptable energy production include methods to (i) define acceptable fatality levels, (ii) set initial curtailment to keep fatalities under the pre-defined threshold, (iii) conduct robust PCFM (see Katzner et al., 2025) and (iv) use adaptive management to adjust curtailment based on evidence. Simple components that apply to any project globally will ensure equitable responsibility for conserving bats among all developers. In our model (Figure 1), fatality thresholds and curtailment can be estimated based on available data and curtailment can be updated using PCFM.

2.2.1 | Setting a fatality threshold

Setting bat fatality thresholds at wind facilities is not widely adopted (Arnett et al., 2013; IFC, 2023; MacEwan, Aronson, et al., 2020). Ideally, fatality thresholds are estimated using population dynamics of target species to determine how many individuals can be removed without causing declines that disrupt ecological function or threaten extinction (Manlik et al., 2022; Niel & Lebreton, 2005). Potential biological removal (PBR) to set fatality limits was introduced by Wade (1998) to manage populations of marine mammals unintentionally killed during commercial fishing. Use of PBR for wildlife killed at wind farms has been criticized because PBR was designed to apply at a population management scale and be regularly adjusted (Chambert et al., 2024). However, PBR has identified birds at risk from wind energy development (BirdLife, 2025; Diffendorfer et al., 2021), and is robust to uncertainties (Dillingham & Fletcher, 2008; Dillingham & Fletcher, 2011; Niel & Lebreton, 2005; Punt et al., 2020; Wade, 1998).

We propose an adaptation of PBR to set bat fatality thresholds at wind farms. Bat population size and density estimates remain an urgent research priority, but we need an approach that is implementable now and ostensibly better than a status quo of no limit. While standard PBR should be applied at the scale of an entire population, there are no regulatory mechanisms to report or respond at that scale. Therefore, fatality thresholds need to be set on a per-project basis.

The PBR equation (Wade, 1998) incorporates the maximum recruitment rate (R_{max}), a recovery factor (F_r) and a defined minimum population size (N_{min}):

$$\text{PBR} = 1/2 R_{max} \times F_r \times N_{min}$$

R_{max} is the maximum recruitment rate, which equates to $\lambda_{max} - 1$, with λ_{max} being the maximum potential annual growth rate. Thus:

$$\text{PBR} = 1/2\left(\lambda_{max} - 1\right) \times F_r \times N_{min}$$

Ideally, λ_{max} is estimated using demographic information under optimal conditions (Caswell, 2001), but demographic data are unavailable for most bats. Niel and Lebreton (2005) developed a demographic invariant approach using estimates of adult survival (s) and age at first breeding (α) for bird populations. Dillingham and Fletcher (2008) incorporated this demographic invariant method with PBR for assessing bird populations.

We adapted Niel and Lebreton's (2005) approach to approximate λ_{max} for bats using their equation that combines constant adult survival (s) and age at first breeding (α):

$$\lambda_{max} \approx \frac{(s\alpha - s + \alpha + 1) + \sqrt{(s - s\alpha - \alpha - 1)^2 - 4s\alpha^2}}{2\alpha}$$

Life histories of bats are constrained by physiological limits imposed on volant mammals, resulting in low variation in fecundity and age to first breeding (Racey & Entwistle, 2000). For most bats, age at first breeding is 1 year, although breeding probability is lower in first-year bats (Jones et al., 2009; Lentini et al., 2015). As a benchmark estimate for age to first breeding for all bat species, we assume an α of 1.5. However, Pteropodidae and other bat families may be better estimated with an α of 2 (Racey & Entwistle, 2000).

Adult survival estimates exist mostly from temperate Vespertilionids (Lentini et al., 2015). We suggest a constant adult survival estimate of 0.9 as a reasonable estimate to use for calculating λ_{max} for bats, which represents the higher end of empirical adult survival estimates (Lentini et al., 2015). The Niel and Lebreton (2005) method creates a counterintuitive relationship between adult survival and λ_{max} wherein higher survival estimates create lower λ_{max} because of life history trade-offs between fecundity and survival (Dillingham & Fletcher, 2008; Lentini et al., 2015; Niel & Lebreton, 2005). Survival rates from mark–recapture studies underestimate true survival given the inability to separate permanent emigration from survival (Gilroy et al., 2012; Lebreton et al., 1992). Furthermore, survival rates are rarely estimated in populations experiencing optimal growth, an underlying assumption for λ_{max}. Under-estimating adult survival leads to over-estimating λ_{max} and thus over-estimating PBR, creating a potential conservation problem. Therefore, we use the higher bounds of adult survival estimates for bats.

Using an $\alpha = 1.5$ and $s = 0.9$, we approximate a global estimate of λ_{max} for bats at 1.24. If α is set to 2 for Pteropididae or other families with later age to first breeding, then $\lambda_{max} = 1.2$. The λ_{max} values here of 1.24 or 1.2 approximate a generalized scenario for maximum growth under optimal conditions for bats for informing PBR calculations in absence of other information.

The recovery factor (F_r) in the PBR equation is set by management goals and species status (Dillingham & Fletcher, 2008; Punt et al., 2020; Wade, 1998), and ranges from 0 to 1 with $F_r = 0.1$ advised for any threatened species experiencing other stressors or sources of fatality (Dillingham & Fletcher, 2008; Punt et al., 2020; Wade, 1998). We use IUCN status to set F_r (Table 1). No additional fatalities are acceptable for IUCN Critically Endangered or Endangered species (Bennun et al., 2024) and thus their fatality thresholds are set to 0, which can be measured as <1 bat per year over a 3-year monitoring period. Data deficient species often share characteristics of threatened species (Welch & Beaulieu, 2018), and therefore we assign F_r at 0.2 (Table 1). We suggest 0.5 for Least Concern species, following Dillingham & Fletcher (2008), unless available data indicate an increasing or stable population trend, justifying a higher F_r. We recommend using F_r at 0.2 (Data Deficient) if an IUCN assessment has not yet been conducted for a species, or if a Least Concern assessment is >10 years old and recent evidence suggests increased risk of decline.

Calculating PBR requires a conservative estimate of population size (N_{min}) suggested by Wade (1998) as the lower bound of a 60% confidence interval for a credible population estimate (N). Bat population data are limited or absent and a credible estimate to derive N_{min} is challenging. We combine an upper and lower estimate for N

TABLE 1 Recovery factor (F_r) based on IUCN Red List status, in rank order (iucnredlist.org).

IUCN status	Recovery factor (F_r)
Least concern	0.5
Near threatened	0.3
Vulnerable	0.1
Endangered	0
Critically endangered	0
Data deficient	0.2

Note: Data deficient species often share characteristics of threatened species (Bland et al., 2014; Welch & Beaulieu, 2018), hence the assignment of F_r at 0.2. Note that $F_r = 0$ for endangered and critically endangered equates to a fatality threshold of 0.

(N_U and N_L) and a coefficient of variation to create this formulation of PBR by Dillingham and Fletcher (2008):

$$\text{PBR} = \frac{1}{2} R_{max} f \hat{N}_{exp} \left(Z_{0.2} \text{CV}_{\hat{N}} \right)$$

where

$$\hat{N} = \sqrt{N_L N_U}$$

and

$$\text{CV}_{\hat{N}} = \sqrt{\exp\left(\left(\frac{\ln(N_U/N_L)}{2Z_{1-\alpha/2}}\right)^2\right) - 1}$$

We estimate N_U and N_L for local populations using proxy bat density estimates applied at a spatial scale relevant to a wind energy facility. We compiled bat density estimates from the literature (Table S2), but more research is needed to provide a comprehensive range of bat densities across ecological contexts and taxonomic groups. See Table S2 for a summary of published density estimates. As a general proxy, we propose using density estimates for *Pipistrellus pipistrellus* (5.5 and 18 bats/km^2) (Speakman et al., 1991; Milchram et al., 2020; Table S2) as follows:

$$N_{local-U} = \text{Project area} \left(\text{km}^2\right) \times 2 \times \text{Upper bat density estimate} \left(\text{bats / km}^2\right)$$

$$N_{local-L} = \text{Project area} \left(\text{km}^2\right) \times 2 \times \text{Lower bat density estimate} \left(\text{bats / km}^2\right)$$

In situations with high uncertainty, using a wide upper and lower bounds for N results in lowering PBR as the CV value increases >1. Obviously, bat population densities vary by species and habitat, and we recommend current literature searches to check for the latest available data. Acting quickly when populations are in rapid decline is a critical component of successful conservation (Martin et al., 2012), so when data are unavailable we suggest values for *P. pipistrellus* may provide a reasonable approximation of bat density for a moderately abundant bat species. The N_{min} value has the most influence on PBR for Least Concern species. Pre-construction survey efforts to estimate bat densities should become part of environmental assessments to provide realistic upper and lower values. We use a scaling factor of 2 (see equations for $N_{local-U}$ and $N_{local-L}$) to adjust for additional uncertainty about local population size relative to the spatial area of a wind farm. We provide a tool (Appendix S1) that calculates bat fatality thresholds per facility (e.g. number of allowable bat fatalities per year) using this approach, which can then be compared to a facility's bat fatalities estimated using GenEst (Dalthorp et al., 2020; Simonis et al., 2018) to inform whether operations should be adjusted to reduce fatalities.

2.2.2 | Operating under fatality thresholds

Research continues to improve curtailment to maximize power generation while minimizing fatalities using algorithms to predict risk (e.g. wind speed, direction, bat activity) or implementing acoustically-triggered curtailment (Hayes et al., 2019; Whitby et al., 2024). Curtailment's impact on power generation can be minimized by defining local bat activity periods of risk and confining curtailment to this period. Government oversight or financial lenders may require pre-construction acoustic monitoring during siting to determine species presence and estimate local activity patterns. Past efforts using pre-construction acoustic monitoring to predict fatality rates have been inconsistent (Baerwald & Barclay, 2011; Solick et al., 2020). Peterson et al. (2021) showed bat activity correlated more closely to fatality risk when studies restricted analysis to when turbines are operational. For non-echolocating bats, estimating local activity patterns may require radar data (Taylor et al., 2018) or visual count surveys for tree-roosting Pteropodids. Bat activity patterns can be combined with other risk predictors, such as wind speed (Barré et al., 2023; Whitby et al., 2024) to determine curtailment requirements before a facility becomes operational.

Curtailment required at wind facilities will vary according to the risk of local bat species. Species can be assigned a general risk category (low, moderate or high) based on foraging guild, which incorporates traits that broadly correspond to collision susceptibility (Arnett

TABLE 2 Exposure reduction target values represent the percent of bat activity that should be avoided during turbine operations.

	Activity exposure reduction target		
IUCN status	Low collision risk (clutter)	Moderate collision risk (edge)	High collision risk (open)
Least concern	0%	25%	50%
Near threatened	25%	50%	75%
Vulnerable	50%	75%	90%
Endangered	75%	90%	90%
Critically endangered	75%	90%	90%
Data deficient	35%	60%	85%

Note: These targets can guide setting initial operational curtailment (e.g. increasing cut-in wind speeds) during relevant seasonal periods to meet fatality thresholds and can be adjusted based on post-construction monitoring data.

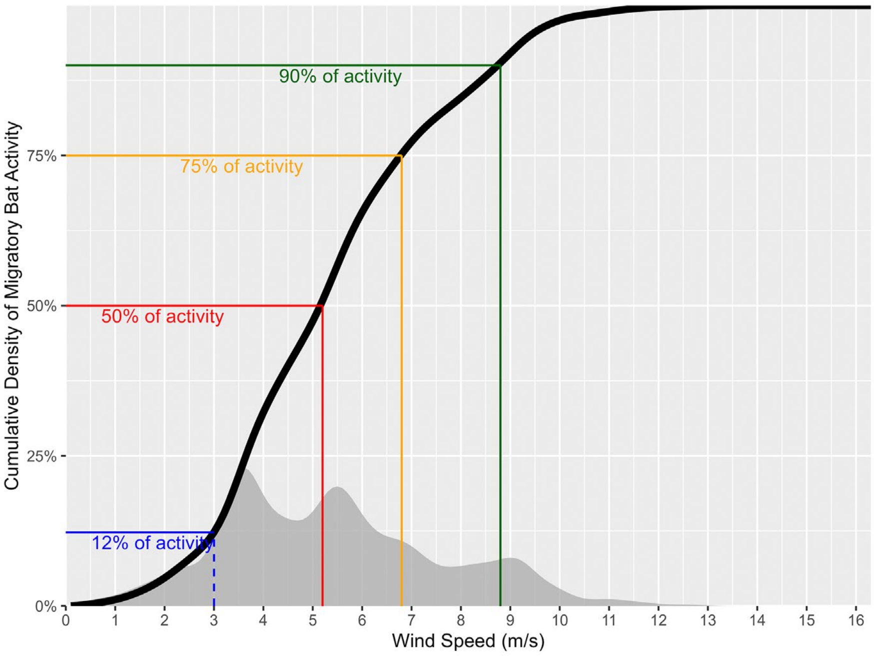

FIGURE 2 Cumulative acoustic activity of migratory bats across wind speeds collected from a wind farm in Iowa, United States. Acoustic activity distributions can be used to designate cut-in speeds to avoid a given percentage of overall activity.

et al., 2008; Arnett & Baerwald, 2013; Kunz et al., 2007). We used three guilds (clutter-space, edge-space, and open-space foragers) adapted from Denzinger and Schnitzler (2013). We combined guild with IUCN status to determine initial curtailment required, given as the percentage of activity to avoid to minimize collision risk and meet fatality thresholds (Table 2; Figure 2).

2.2.3 | Adaptive management

Wind farms must implement robust PCFM to compare observed bat fatalities with fatality thresholds, and recognized monitoring protocols (e.g. IFC, 2023) that rely on adaptive management (Westgate et al., 2013) as outlined in Figure 1. Reliable fatality estimators, such as GenEst, adjust for searcher efficiency, carcass persistence times, and proportion of area searched (Dalthorp et al., 2020; Simonis et al., 2018). As bat fatalities may vary significantly among years, management decisions can opt to use a three-year rolling average of PCFM-estimated fatality. This allows for rare 'take' events without triggering increased curtailment. If fatalities estimated using PCFM exceed fatality thresholds, curtailment should increase. If fatalities are under the threshold, curtailment could be relaxed. Every 3 years, developers or a qualified third party should review information used to set fatality thresholds, such as changes to IUCN status. Continued PCFM beyond 3 years may be voluntary and intended for facilities seeking to further refine curtailment strategies. While conducting PCFM is costly, it is the only way to know whether a fatality threshold has been met. Accounting for these costs during project planning should decrease the burden, and ongoing PCFM innovations can lower costs while improving accuracy (e.g. Smallwood et al., 2020), so it is important to review the literature for updated best practices (IFC, 2023). For example, improvements in acoustic monitoring may help inform adaptive management by defining activity periods more precisely (Peterson et al., 2025).

Special cases may occur in which fatality thresholds cannot be calculated, or previously calculated thresholds may no longer apply. For example, a local population crash due to extreme weather or mass culling would demand a temporary fatality threshold of zero until populations are re-assessed. Furthermore, we recognize that our approach does not fully address cumulative impacts at range-wide scales and that future efforts to devise monitoring and regulatory mechanisms beyond project-level mitigation are warranted.

2.3 | Compensate

Offsets compensating for fatalities should be considered a last resort once all feasible avoidance and mitigation actions have been implemented, and be designed to achieve measurable conservation outcomes for the species impacted such that the net impact is below the relevant species' threshold (Table S1). This is often challenging, but metrics to compare against the scale of impact are necessary to demonstrate project safeguarding and compliance with regulatory and lender requirements. Possible offsets include investing in protecting or enhancing roosting and foraging resources at appropriate temporal and spatial scales, which should measurably benefit population resiliency over time. Appropriate compensation actions will depend on what species and habitats are most relevant to a particular wind energy facility. However, direct mortality from wind turbines is unlikely to be completely offset by habitat protection alone, given bat demographic constraints of low fecundity. See Katzner et al., 2025 for a review of this topic.

3 | CONCLUSIONS

Multiple anthropogenic threats, including wind turbine fatalities, are creating an urgent need to reduce bat fatalities at wind facilities (Frick et al., 2020; Voigt et al., 2024). Uncertainty about population and life history data for bat species should no longer be a reason for inaction towards solutions. Our framework for managing operations to meet fatality thresholds establishes a process that should help achieve both renewable energy and biodiversity goals. Although the use of fatality thresholds based on limited data is not perfect, it is evidence-based and can be improved through adaptive management. Importantly, our approach can be implemented immediately, preventing some bat fatalities that will otherwise occur without limit. By adopting the use of bat fatality thresholds to guide operational conditions at wind facilities, regulatory bodies and the wind energy industry in consultation with conservation practitioners should be able to expedite financial planning and compliance while improving bat conservation. Moving towards global implementation of guidelines that provide a definition of successful compliance will also incentivize the development of novel models and technology that reduce energy loss while protecting bats.

AUTHOR CONTRIBUTIONS

Winifred F. Frick, David Wilson, Michael Whitby, Kate L. MacEwan, Simon Hulka and M. Teague O'Mara conceived the ideas and methods. Winifred F. Frick and Karin L. Akre led writing and revisions. All authors contributed to drafts and gave final approval. Our study intentionally applies to a global audience including all wind energy stakeholders to ensure equitable responsibility for and benefit from outcomes.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

No original data were used in this paper.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1: Bat PBR calculator. By determining species IUCN status, species density (minimum and maximum) or density proxy (minimum and maximum), species-appropriate R_{max} and facility size, you can use this calculator to determine the site-specific PBR, or fatality threshold. Examples are included.

Table S1: Actions and recommendations for mitigating bat population impacts from bat mortality at wind energy facilities. We provide example actions at each step of the mitigation hierarchy with corresponding existing tools and guidance and identify future research priorities. This list is not exhaustive.

Table S2: Bat population densities from the literature. We used two searches to gather bat species density estimates from the literature on 5 February 2025. We searched Clarivate Web of Science using the term: 'bat NEAR/10 "population density" NOT algorithm' to find publications estimating bat population densities, but excluding a popular optimization algorithm called 'bat'. We also searched Elicit AI (elicit.com) by first asking the question 'What are the population densities for every bat species available?' then filtering the returned studies to include density or densities in the abstract.

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