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Mitigating wildlife collisions with wind turbines: A review of techniques, evidence, knowledge gaps and avenues for future research

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ABSTRACT

As global wind energy production rapidly expands, so too have concerns about collision impacts for bird and bat species conservation, driving development of a diversity of anticollision technology. This review compares seven metrics across bat and bird anticollision strategies: (1) detection range, (2) detection probability, (3) species specificity, (4) changes to avoidance behaviour, (5) collision fatalities, (6) setup and maintenance costs, and (7) energy production losses. Of 52 operational and deterrent strategies or tools reviewed, less than half have independent testing data available and many knowledge gaps persist, especially for newer or under-development methods. For large birds, radar systems have greatest detection range (6.13 ± 3.99 km), but limited species specificity, and have no available data for anticollision success. Cameras have shorter range (0.69 ± 0.44 km) but good identification accuracy for large birds (83 ± 20%), with 66 ± 23% collision reduction. Blade painting has had mixed results (two successful and two unsuccessful studies to date; average 7 ± 61% reduction in bird mortalities). For bats, acoustic detection reveals the most proximal collision risk, and acoustic-activated curtailment shows the greatest success in reducing fatalitites (66 ± 34% anticollision success), while ultrasonic bat deterrents have had limited success (23 ± 40% reduction in fatalities). Technology investment ranges from relatively low (e.g., blade feathering below cut-in, blanket curtailment, deterrents such as vegetation removal through mowing, or blade painting prior to construction), through to very high (e.g., radar, camera, and acoustic detection systems for smart curtailment), with varying degrees of maintenance also required. There is a general lack of data on the lost revenue due to energy production losses. Additional data on energy production losses are required to balance the economic costs of curtailment with conservation benefits (i.e. fatalities per MWh) to help inform decisions in selecting mitigation approaches for the wind industry. This review provides researchers, project proponents, and policy makers with a scientific and comprehensive reference for the effectivness of anticollision technology, improving biodiversity outcomes for this important renewable energy resource.

1. Introduction

Renewable energy industries can have large environmental footprints, destroying habitat and impacting many native species both directly, through collision with turbine blades and towers [5–7], and indirectly through displacement and habitat loss [8]. As the number of wind projects increases globally [9], so has the scrutiny of their impact on wildlife [5–7]. The highest number of fatal incidents for wildlife at wind turbines (WT) has been observed for bats, especially migratory species [10]. Turbine collision is also significant for birds [11,12] and is a major risk for large soaring birds (e.g. vultures, other birds of prey, storks) and nocturnally-active migratory species, while offshore WTs pose particular risk for some gulls and terns [12]. The cumulative consequences of WT collision threatens conservation-significant species, especially those that are long-lived with low reproductive rates and slow maturation [13–18]. With the global wind industry on the cusp of unparalleled expansion in pursuit of reduced carbon emissions, it is imperative that we also keep sight of biodiversity targets [6,19,20]. Tools for mitigating turbine strike are therefore essential for meeting environmental regulations, and ensuring financing endorsement and

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Abbreviations and terminology

Active deterrent	Deterrent that is activated by the presence of the target animal.
BACI	Before-after control-impact experimental design.
Blade feathering	Pitching wind turbine blades on the wind turbine to reduce the blade angle to the wind, reducing rotor speed (consequently the turbine reduces the amount of power produced). If this occurs at wind speeds above cut-in, then this would result in energy production loss. At wind speeds below cut-in, this reduces freewheeling speed.
Blanket curtailment	Consistent application of shutting down wind turbines when the wind speeds are below a pre-defined speed in order to reduce bird or bat fatalities, without consideration of other site-specific information [1,2]. Sometimes referred to as 'operational curtailment' [3].
Cut-in speed	The wind speed at which the turbine begins to generate electricity.
Curtailment	Where the power output of a wind turbine is below the expected power output at the occurring wind conditions. A direct consequence of curtailment is the loss of power production.
Freewheeling	The state where a WT's rotor is rotating without being connected to the generator or load, allowing it to spin freely in the wind. This occurs when wind speeds are below turbine cut-in speed.
Informed curtailment	In addition to wind speed, informed or 'multi-factor' curtailment approaches also include real-time data for environmental variables (time of night, temperature, precipitation, insect abundance, or storm fronts) to support curtailment decisions. Sometimes referred to as algorithmic [3] or multi-factor curtailment.
Passive deterrent	Deterrent that is always present, with or without presence of the target animal.
RSA	Rotor-swept area (also sometimes referred to as 'rotor swept zone').
SCADA	Supervisory Control and Data Acquisition – the system of hardware and software that controls WT operation.
Seasonal curtailment	Curtailment during periods of high collision risk
Shutdown	To bring a turbine rotor to a complete stop or significantly reduce its speed to a point where the turbine has zero electricity generation output.
Smart curtailment	Shutdown-on-demand informed by the presence of bats or birds in the air space around WTs – an advanced strategy using real-time animal activity data to make curtailment decisions and communicating with WT operation control (SCADA) to initiate shutdown ('sensor-based curtailment', sensu [4]).
WF	Wind farm.
WT	Wind turbine.

social licence for wind energy projects [6,7].

There are a growing number of publications reviewing WT collision mitigation approaches. For example, Marques et al. [21] and May et al. [22] reviewed species- and habitat-specific factors influencing bird collisions with wind turbines, including avian sensory, aerodynamic and cognitive perspectives. Arnett & May [23] reviewed options for mitigating collision for bird and bat species, emphaising the importance of planning and avoiding predicted high-risk areas, a conclusion also supported by Guo et al. [24]. More recent reviews have emphasised the steadily growing range of technological approaches to mitigating turbine collisions (e.g., Refs. [25–27]). A general conclusion of these reviews is that there is often too few data to support suggestions for viable alternatives to mitigating turbine strike (e.g., Refs. [22,28,29]). For example, Gulka et al. [25] reported that the vast majority (86%) of 211 mitigation approaches relevant to both onshore and offshore wind lacked any evidence of effectiveness, an observation similarly reported elsewhere (e.g., Ref. [30]). Importantly, the success of many mitigation methods also appears to be species- and location-specific [26]. Comprehensive review of the limitations and outcomes of different anticollision strategies is therefore needed to identify whether there are common and generalisable results that can inform operational and policy decisions.

This systematic review describes turbine anticollision methods: WT shutdown below cut-in, curtailment approaches, as well as passive and active deterrents. We specifically collated information on commercial anticollision technologies currently available. We describe operational requirements, technical limitations, and field application, collating available data on detection distance and probability, identification accuracy, deterrence, and effectiveness in terms of reducing collision fatalities. Where available, setup and maintenance costs, as well as energy production losses are described.

2. Research methodology

This systematic review consisted of four components (Fig. 1). (1) We undertook a literature review of 10 databases for relevant sources (keywords and eligibility criteria listed in Fig. 1), which yielded a total of 9373 articles. After filtering out duplicates and removing obviously irrelevant articles, the remaining 734 articles were screened by abstract. (2) Online searches of original equipment manufacturers (OEM) were carried out to identify technical specifications and all forms of available reporting. (3) We identified 16 OEM based on (1) and (2) who were approached in order to address knowledge gaps where identified (seven responses to our survey- Appendix A - received). (4) Invitations were sent out to 14 wind farm operators or consultants, to obtain their first-hand experience with different anticollision technology (two responses).

We report on 136 information sources, including journal articles (26%). The majority of information sources we report represent non peer-reviewed content: theses 1%, technical and environmental impact reports 24%, developer's websites* 31%, conference or webinar presentations* 10%, online newsletters and articles* 1%. The last three categories involve self-reporting, and references are marked by asterisks (*) to assist the reader with critical assessment of the results. Personal communications (7% of information sources) are indicated by two asterisks (**).

For field studies, we extracted data for (1) detection range (distances in km), (2) detection probability (% of flights detected), (3) species specificity (% of flights correctly identified), (4) deterrence – shown as changes to avoidance behaviour (e.g., % of flights where birds changed direction, or % difference in time spent in the focal area for bats), (5) effect on collision fatalities (% saved by application of the anticollision technology; often re-calculated from raw data provided in the original reference), (6) setup and maintenance costs (US$), and (7) energy production losses (Annual Energy Production (AEP) loss (time or MWh as a % of annual production), or % comparison with blanket curtailment). Where provided, we extracted data ('records') for each species, set of conditions trialled, or variables measured. We used *plotdigitiser* [32] to extract information from graphical presentation where required. For all metrics, we have calculated the 'percent saving' due to the experimental treatment over a control scenario (Appendix B); values may therefore vary from those reported in the original studies.

Values are given as averages ±1 SD [95% confidence intervals].

3. Results and discussion

In this review, we examined 52 operational and deterrent strategies or tools applied to bat and bird collision mitigation (Table 1). Of the 52, we found independent testing data for less than half (n = 21; Table 1).

Broadly, these 52 strategies or tools fit into a hierarchy of mitigation methods, including (1) blade feathering and braking below turbine cut-in speeds, (2) curtailment approaches (reducing turbine operation at wind speeds where electricity would otherwise be generated), and (3) deterrents (Fig. 2). Because curtailment terms are not used consistently in the literature and across the wind energy industry [4], we include definitions of these terms in the Glossary. Each approach has advantages and disadvantages in terms of the degree of technology investment required, technical issues, and energy production losses (and predictability of those losses) (Table 2).

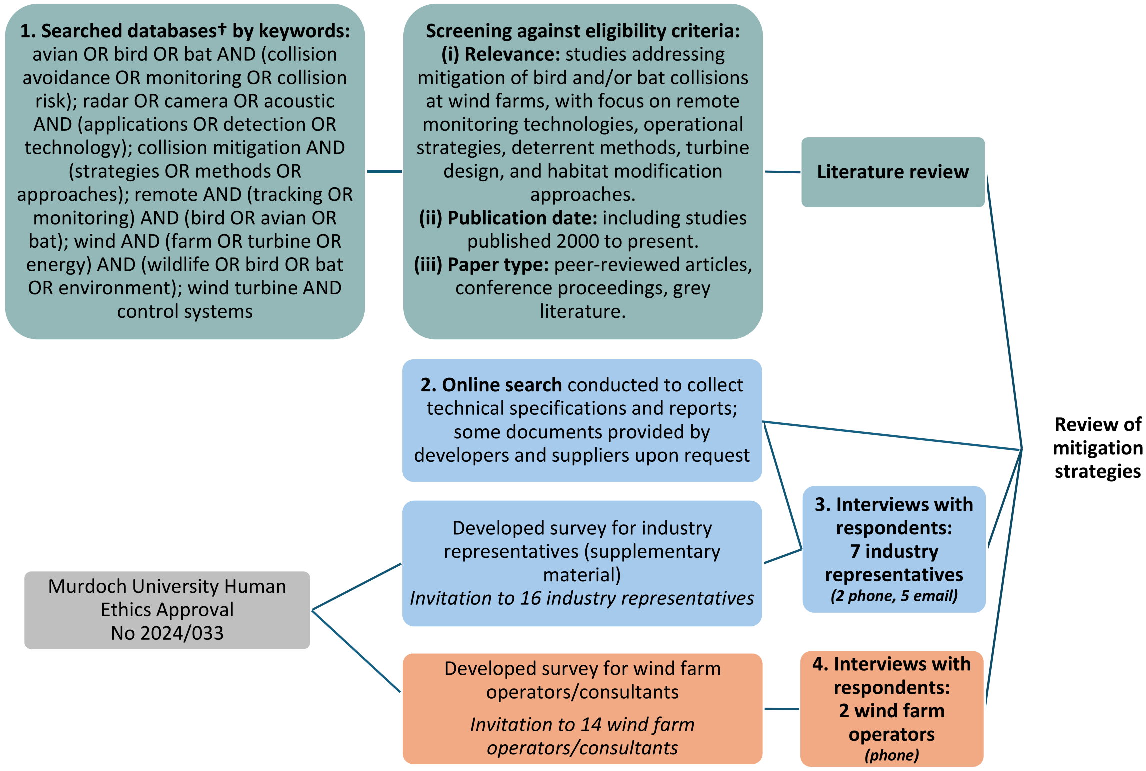

Fig. 1. The methodology used in this study consists of four main parts: (1) a literature review, (2) detailed online searches for relevant anticollision methods and technologies (including technologies listed by REWI [31] that had a technology readiness level score of 9), (3) a survey conducted through interviews (Appendix A) with original equipment manufacturers [OEM1-7], and (4) a survey of wind farm operators/consultants [WF1,2]. † Databases: EBSCOhost, IEEE Xplore, ScienceDirect, Web of Science, Scopus, Google Scholar, JSTOR, Wiley Online Library, Taylor & Francis Online and ProQuest.

3.1. Overview of field validation studies

A range of experimental designs have been applied in field validation studies (Fig. 3, Appendix C,D), which means that data and derived interpretations vary markedly in their robustness. For many technologies reviewed—especially newer or under-development approaches—there has been no independent testing to date, and we could only include the manufacturer's specifications for these (marked herein as self-reporting*). Experimental studies include control-impact (CI) experimental designs, allowing for randomisation of treatment conditions amongst turbines. Testing WT operation (e.g., curtailment) or application of acoustic deterrents to specific WT can allow before-after control-impact (BACI) experimental design, but have often only been analysed as BA or CI. Experiments testing curtailment, quantifying fatalities for the same WT on days under different operational schedules (i.e. using randomised block design) has provided the most robust experimental BACI design, independent of site-specific factors that influence collisions. Validation studies (VS) include comparing detections against visual observations of birds for radar and camera detection systems, and quantifying proportion of detections of eagle-like Uncrewed Aerial Vehicle (UAV) flights for cameras. A few studies have used laboratory or modelling simulations, or meta-analyses.

We identified seven metrics that have been applied as part of field studies (summarised in Figs. 4 and 5):

(1) **Detection range (**Fig. 4a**).** Detection distance is directly related to the amount of time available to initiate and carry out WT shutdown, bringing WT blade speed to a safe range. The shorter the detection distance, the less time available for turbine shutdown. For example, a detection distance of 1.5 km would be required for an 85% success of bringing a WT (asynchronous WT with blade length of 89 m operating at 15 m/s hub-height wind speed) to a safe speed after detecting a Golden eagle (*Aquila chrysaetos*) (average flight speed around 13 m/s) [131]. This highlights the significance of early detection for wildlife protection near WT infrastructure, and the importance of this metric in reviewing available approaches.

(2) **Detection probability (**Fig. 4b**).** For conservation significant species, every individual is protected [132–134], requiring mitigation action. High detection probability is therefore required to ensure that appropriate action can be taken. To be effective in mitigating turbine collision risk, while minimising false positive signals (Fig. 6), monitoring systems have to be accurate both in regard to the detection and identification of targets (to species, species group, or size classes). False positives arise where the system detects an object as a target when there is none present, or a non-target species is mis-identified as a target. False negatives result where the monitoring system fails to detect a target completely (targets go unnoticed by the system despite being in its field of view), or where the target was detected but mis-identified as a non-target. How accurately the system detects and categorises targets therefore determines its overall efficacy.

(3) **Species specificity (**Fig. 4c**).** While reducing all bat and bird fatalities is key for overall biodiversity conservation, there can be legislative and social licence implications of causing deaths in protected species [132–134]. Consequently, there is considerable focus on correct identification of conservation-significant species where their presence triggers mitigation measures, as false positives will result in unjustified WT shutdowns, and therefore economic losses (i.e., energy production loss as well as WT fatigue).

(4) **Changes to avoidance behaviour (**Fig. 4d**).** Animal responses to some deterrents have been measured either ex situ or on WFs. Such data are vital for informing development of deterrent tools,

Table 1
52 operational and deterrent strategies or tools for the mitigation of bat and bird collisions with wind turbines <reviewed>. This table does not include methods with a technology readiness level (TRL) < 9 [31], indicating that they were unlikely to have a commercial product yet.

Type	Method/technology	Installation[a]	Examples of independent testing	Other sources
Bats				
1. Curtailment				
1a. Feathering			[33,34]	
1b. Blanket curtailment	Curtailment		[29,33–46]	
1c. Seasonal curtailment	Informed by site specific seasonal data		[43]	
1d. Informed curtailment	Bat Protection System, Vestas Wind Systems, Denmark			
	EchoPITCH, Stantec, USA		[43]	
	Optimized Smart Curtailment™ (OSC™)			[47,48,49]
	Wildlife Activity Detection System, Wildlife Imaging Systems, USA			[50]
2. Smart curtailment				
2c. Camera detection	DTBat®, Liquen Consultoría Ambiental, S.L., Madrid, Spain	WT, N; Off	[51]	[52]
	SafeWind, BioDiv-Wind SAS, Boujan-sur-Libron, France			
2d. Acoustic detection	AudioBat®, BioDiv-Wind, Boujan-Sur-Libron, France	WT, N		[53]
	BATmode, Germany			
	BPS (Bat Protection System), Topwind, UK			
	EchoPITCH, Stantec			
	EchoSense®, EchoSense, NY USA		[39]	
	FlexiMaus, Fleximaus GmbH, Germany			
	SafeWind, BioDiv-Wind SAS, Boujan-sur-Libron, France	WT		
	SMART, Wildlife Acoustics, Maynard MA, USA	WT, N; Off		[54,OEM7**]
	TIMR^{SM}, Turbine Integrated Mortality Reduction, Normandeau Associates, USA		[55]	
3. Deterrent				
3a. Acoustic signal	AT800 (Binary Acoustic Technologies, Tucson, AZ)		[56]	
	Ultrasonic acoustic deterrent (Deaton Engineering, Georgetown, Texas)		[40,57]	
	Bat Deterrent System		[37,58]	
	GE Bat Deterrent System (BDS)		[59,60]	
	NRG bat deterrent (NRG Systems, Hinesburg, VT)		[36,40]	
	Binary Acoustic Technology		[61]	
	Ultrasonic acoustic deterrents (for bats)			[52,54]
4. Combined				
4a. Curtailment and deterrent	Bat Deterrent System		[37,40]	
	NRG bat deterrent (NRG Systems, Hinesburg, VT)		[36]	
Birds				
1. Curtailment				
1b. Informed curtailment	FlexiBird, Fleximaus GmbH, Germany			[62]
2. Smart curtailment				
2a. Visual observation	Direct visual observations		[63]	
2b. Radar detection	3DFlighTTrack Diadès Marine, France	F; Off		[64]
	BirdScan MS1 Swiss Birdradar Solution AG, Switzerland	F; Off		[65,66]
	BirdScan MV Swiss, Birdradar Solution AG, Switzerland	F; Off		[67]
	BirdTrack STRIX, Portugal	V; Off		[68]
	MAX, Robin Radar Systems B.V., Netherlands	F	[69,70]	[71]
	Merlin, DeTect Inc, Florida, USA	V; Off	[72]	[73]
	Nvbird, Nvisionist, Athens, Greece	F; Off		[74]
2c. Camera detection	AVES Wind® Anti-Collision System, ProTecBird GmbH, Germany	WT	[75–77]	
	Bioseco Bird Protection System, Bioseco, Gdańsk, Poland	WT; N	[78–80]	[66,81]
	BirdRecorder, Zentrum für Sonnenenergie- und Wasserstoff-Forschung, Stuttgart, Germany	V		[82,83]
	BirdVision, GmbH & Co. KG, Niedernhall, Germany	WT; N		[84,85,OEM4**]
	Digisec, Digisec A.E., Athens, Greece	WT		[86]
	DTbird, Liquen Consultoría Ambiental, S.L., Madrid, Spain	V; Off	[78,87–92]	[87,91,93,94, OEM3**]
	Identiflight, Boulder Imaging, Louisville, CO, USA		[95–100]	[101,102]
	Nvbird, Nvisionist, Athens, Greece	WT; Off		[74]
	SafeWind, BioDiv-Wind SAS, Boujan-sur-Libron, France	WT		[103,104]
3. Deterrent				
3a. Acoustic signal	DTbird	V, Off		
	Xbird Radar BioDiv-Wind SAS, France			[105]
	Nvbird Nvisionist, Athens, Greece			[74]
	SafeWind BioDiv-Wind SAS, Boujan-sur-Libron, France			[103,104]
	Digisec Digisec A.E., Athens, Greece			[86]
	Nvbird WTG Nvisionist, Athens, Greece			[74]
	SafeWind, BioDiv-Wind SAS, Boujan-sur-Libron, France	WT		[103,104,WF2**]
	Bioseco Bird Protection System, Bioseco, Gdańsk, Poland	WT		[81,84]
3b. Blade painting	1 black blade		[106,107]	
	1 red blade		[108]	
	UV paint		[109]	
3c. Lighting & marking	UV illumination		[110]	
	Bioseco Bird Protection System Bioseco, Gdańsk, Poland			[66,78,79,80,81]
3d. Habitat modification	Mowing		[111]	
	Planting			

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Table 1 (*continued*)

Type	Method/technology	Installation[a]	Examples of independent testing	Other sources
	Tillage		[112]	
4. Combined	MUSE, DHI, Denmark			
5. Other	Aerial Digital Surveys (ADS)			
	Bioseco Bird Protection System, Bioseco, Gdańsk, Poland			
	Waterfowl Alert Network			
	Autonomous Avian Geofence Alert System			
	Bird Sentinel®			
Birds & bats				
1. Curtailment				
2. Smart curtailment				
2b. Radar detection	Accipiter® Avian Radar System			[113]
	BirdTrack STRIX, Portugal			[68]
	MAX, Robin Radar Systems B.V., Netherlands			[71]
	Merlin, DeTect Inc, Florida, USA			[73]
2c. Camera detection	Identiflight, Boulder Imaging, Louisville, CO, USA	F		[114]
	SafeWind, BioDiv-Wind SAS, Boujan-sur-Libron, France			[115]
4. Other monitoring approaches				
Bird & bat collisions	B–finder, B-finder Team, Poznań, Poland	WT		[116]
	WT-Bird TNO Ventures, Netherlands	WT		[117]
Monitoring activity	ArtificialVision, Barcelona, Spain			[118]
	ATOM (Acoustic and Thermographic Offshore Monitoring), Normandeau Associates, USA			[119]
	Thermal tracker 3D Pacific Northwest National Laboratory PNNL, USA		[120]	[121]
Modelling	ProBat 7 and ProBat Inspector, Erfurt, Germany			[122,123]

[a] Installation options (F) freestanding, (WT) on the WT tower, (N) nacelle, or (V) various options, depending on the site (Off) Offshore installation options available.

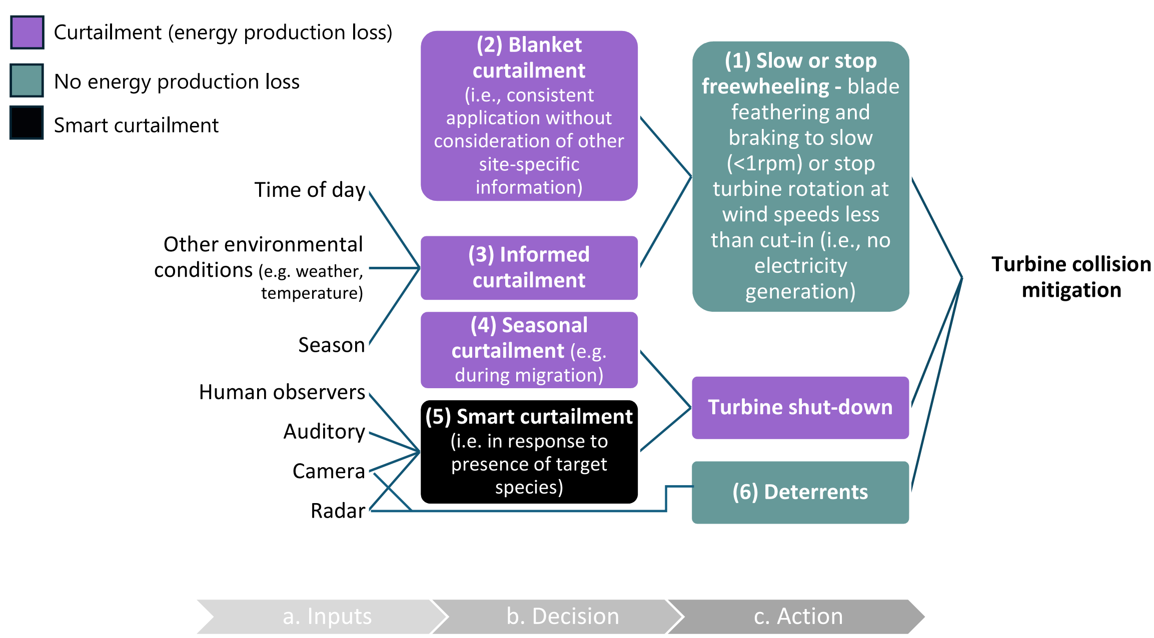

Fig. 2. Hierarchy of mitigation methods to reduce wind turbine collisions with bats and birds, including slowing or stopping freewheeling (1; section 4.2.1), different forms of curtailment (2-5; section 4.2.2) and deterrents (6; section 4.2.3). Only (1) feathering below cut-in and (6) deterrents have no energy production loss (green), while curtailment options involve slowing or stopping the turbine at wind speeds above cut-in and therefore incur energy production loss. Technology for monitoring activity and collisions (section 4.3) is not shown in this figure.

as it allows separation of the animal's behaviour from collision, and reduces reliance on fatalities for validation (which have limited statistical power).

(5) **Collision fatalities (Fig. 5).** Quantifying numbers of bat and bird collisions under different experimental treatments is fundamental in determining the effectiveness of collision mitigation tools or strategies. However, because turbine strike fatalities are relatively uncommon, many studies have failed to collect sufficient data to make a case for effectiveness. Properly accounting for carcass longevity and searcher efficiency [6] adds further complications to fatality monitoring, although we have not attempted to assess the robustness of fatality monitoring against these requirements.

(6) **Setup and maintenance costs.** Setup and maintenance costs vary widely between the different anticollision methods and are an important consideration for WF operators. Incorporating financial and social costs therefore forms part of this review.

(7) **Energy production losses.** There is an important balance between energy production losses and biodiversity conservation driving the development of anticollision tools. In the literature, energy production loss is presented in a variety of ways, including losses in operating hours, losses in energy, and losses in revenue.

Table 2
Summary of technology investment required, potential technical issues and energy production losses associated with (a-e) different forms of curtailment, and (f) deterrent options for mitigating wind turbine collisions.

	Technology investment	Technical issues	Energy production losses (and predictability)	Targeted wildlife
a. Slow or stop freewheeling – blade feathering and braking to slow or stop turbine rotation at wind speeds less than cut-in	• Low – technology for shutdown of the rotor (reducing power, often by pitching the blades to a feathered position to slow the rotor) is part of WT design and operation.	• Due to their inertia, large turbines require faster pitching to meet rapid wind speed changes; this contributes to greater fatigue [124].	• Control system connects WT generator to grid once certain wind speed reached. Below this wind speed, feathering blades and braking can be automated to reduce rotor speed or halt rotor. • No energy production losses, as below WT cut-in speeds.	• Bats • No available data for birds
b. Blanket curtailment – raised cut-in speed	• Low – once rotor speeds are low enough, rotor can be halted, if necessary, by applying mechanical disk brake on shaft of turbine. • Monitoring of wind speeds only.	• Higher cut-in wind speed leads to greater transient loads when the turbine transitions from an idling state to the required operational speed; this can result in greater fatigue [125]. • Fatigue damage concentrated into fewer operating hours but operating at higher wind speeds [125]. • Less wear on machinery compared with more reactive curtailment approaches.	• Energy production losses somewhat predictable - varying with site, time of day.	• Bats • Minimal data for birds
c. Seasonal curtailment – avoiding times of year with increased wildlife activity (e.g., migration)	• Requires site-specific and species-specific research on bird and bat behaviour. • Requires additional equipment for ongoing monitoring of e.g. bat and bird activity.	• Least wear on machinery compared with more reactive (i.e., informed or smart) curtailment approaches.	• Somewhat predictable energy losses concentrated around specific times of year can be accommodated through alternative energy production strategies.	• Bats *Target avoidance of migratory species* • Birds *Target avoidance of migratory species*
d. Informed or 'multi-factor' curtailment – include environmental variables to support curtailment decisions	• Requires additional equipment for ongoing monitoring of e.g. weather conditions that are proxies of insect activity, adjacent farming activities.	• Start-up, shut-down, and intentional speed changes for control purposes create dynamic loading on the blades associated with fatigue [126]. • Additional wear on WT machinery due to repeated braking during operation [127]. • Dynamic loading and fatigue due to repeated start-up, shut-down, and intentional speed changes associated with curtailment [126].	• Energy production losses unpredictable – vary with site, time of day, and time of year. • Reduced energy production losses compared to blanket curtailment; effectiveness can be further enhanced by targeted operational strategies (e.g., Refs. [48,49,123,128,129]).	• Bats • Birds
e. Smart curtailment – shutdown-on-demand	• Requires methods for the detection, identification and tracking of targets that are likely to enter the RSA, with sufficient early warning (detection distance) to provide adequate time for turbine response (e.g., Fig. 4a). • Technology advances in radar, camera and acoustic technology (see Table 3) are accelerating the range of options available. • 2-dimensional (2D) or 3-dimensional (3D) flight data can be used to inform collision risk. • Equipment for monitoring is a substantial additional cost to purchase and maintain.	• Start-up, shut-down, and intentional speed changes for control purposes create dynamic loading on the blades associated with fatigue [126]. • Additional wear on WT machinery due to repeated braking during operation [127].	• Minimised non-operational time and therefore reduced energy production losses compared to blanket or seasonal curtailment. • Unpredictable energy production losses, that vary with site, time of day, and time of year.	• Bats *Potentially specific target species, depending on distinctiveness of their echolocation calls* • Birds *Potentially specific target species, depending on the detection technology used*
f. Deterrents – reducing wildlife activity around wind turbines	• Different forms of technology investment required as site selection is based on physical site properties (e.g. wind resources, topography) as well as a suite of biological factors (including species-specific research on bird and bat behaviour). • Some methods have low technology requirements (e.g., mowing, use of decals, WT tower design), but active deterrents (e.g., acoustic or lighting deterrents) involve considerable technology investment that can be costly to install and maintain.	• Painted blades can overheat, causing mechanical damage [130]. • Technical limitations on acoustic deterrents due to sound attenuation. • Acoustic deterrents can vary markedly in their range of operation temperatures. For instance, DTbat state a range of 0 to 40 °C [52] whereas SMART state a range of −20 °C to either 70 or 85 °C, depending on model [54].	• No energy production losses. • Pre-construction research to inform microsite planning can provide predictable energy production outcomes. • Expense of undertaking deterrence is predictable and can be minimised by incorporating into wind farm planning (e.g., site selection), and WT design at manufacture (e.g., blade painting). • Auditory and lighting deterrents incur energy costs.	• Bats *Acoustic deterrents can have species-specific responses.* • Birds *Visual deterrents (e.g., blade-painting, decals). Can also target removal of food for species foraging around WT (e.g., mowing, tillage).*

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Table 2 (*continued*)

	Technology investment	Technical issues	Energy production losses (and predictability)	Targeted wildlife
	• Blade painting post-construction expensive. • Continued maintenance required for some post-construction habitat modification methods (e.g., mowing). • Ongoing monitoring required to determine whether bats and birds habituate to acoustic or visual deterrents, potentially requiring changes in deterrent modalities over time. • Ongoing monitoring required for non-target impacts (e.g. audible sound deterrents).			

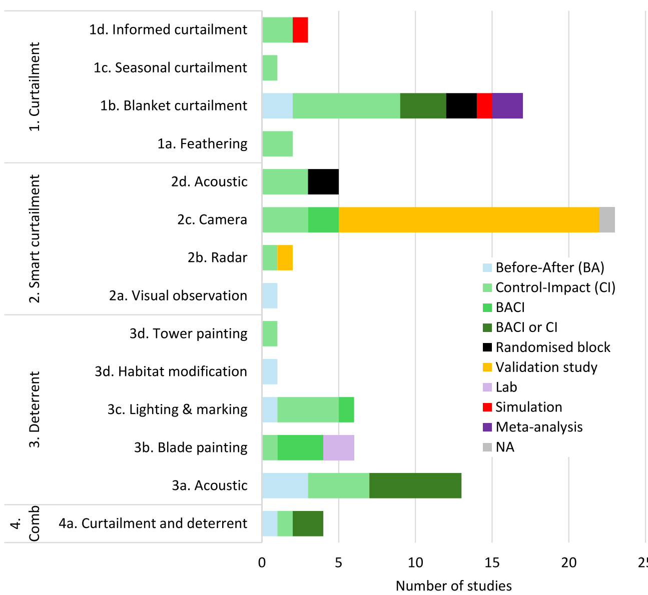

Fig. 3. Experimental designs used for field validation trials of anticollision methods reviewed. NA for experimental design: insufficient information provided (conference abstract). Validation studies include comparing detections against visual observations of birds for radar and camera detection systems.

Analysis of the data requires comparison of like-for-like values. In this paper, we have focused on energy losses in terms of Annual Energy Production (AEP) loss since this was the most common metric reported. This is the reduction in AEP in e.g. MWh or GWh as a percentage of the AEP without curtailment.

Further interpretation of Figs. 4 and 5 is provided throughout section 3.2.

3.2. Description of mitigation approaches

3.2.1. Blade feathering and braking at wind speeds below cut-in

Blade feathering at wind speeds below the WT's cut-in reduces the speed of the freewheeling rotor. There is the option to stop the rotor if the freewheeling speeds are low enough to apply the mechanical disc brake.

(1) **Detection range** & (2) **Detection probability.** NA for this method.

(3) **Species specificity.** In North America, ~80% of bat WT fatalities are *Lasiurus* (especially Hoary bat *Lasiurus cinereus* and Eastern red bat *Lasiurus borealis*) and *Lasionycteris* (i.e., Silver-haired bat) species (e.g., Ref. [44]), which are most active during low wind speeds. A synthesis of 21 post-construction studies across 19 WFs in the USA and Canada [135] revealed that up to 85% of bat fatalities (mostly representing these species) occur when turbines operate below 6 m/s (21.5 kmph), with especially high mortality on nights with very calm winds (<4 m/s or 14.5 kmph). Even at these low wind speeds, spinning blades still caused significant fatalities.

(4) **Deterrence.** NA for this method.

(5) **Effect on collision fatalities.** We estimate that feathering can reduce bat collision mortalities by 52 ± 15 %, but we do not have access to raw data that have been analysed by other authors. A meta-analysis comparing 10 years of data at operational WF in North America showed that reducing turbine rotation (to <1RPM) during these high-risk periods (e.g., Refs. [136,137]) can significantly reduce bat deaths by 20–75% [29], although the strategy likely varies by turbine model, and is unlikely to reduce fatalities for turbines that are already designed to be feathered up to the cut-in speed. For instance, the Casselman Wind Power Project in Pennsylvania uses GE SLE 1.5 MW turbines. The turbines have feathered blades at speeds <3.5 m/s and only spin at very low rotation rates if at all. Additionally, Mitsubishi Heavy Industries (MHI) use blade pitch control in several of their wind turbines (e.g. MWT-450, MWT-95, MWT-1000A) to feather blades when wind speeds are below cut-in to prevent unnecessary rotation and excessive loading [41,138]. We have found no reports addressing whether feathering below cut-in can reduce bird turbine strike (Fig. 5), but it is likely that the slow-moving blades would be visible in daylight and therefore represent minimal risk for birds.

(6) **Setup and maintenance costs.** Feathering and braking do not require additional expenses, but there could be additional wear for large turbines that require faster pitching to meet rapid wind speed changes; this contributes to greater fatigue [124].

(7) **Energy production losses.** Because this action is below cut-in wind speeds (i.e., there is insufficient movement of the blades to generate electricity), there is no energy production loss [33] (Fig. 7).

3.2.2. Curtailment – reducing wind turbine operation, even if there is wind

3.2.2.1. Blanket curtailment. Blanket curtailment refers to raising the cut-in speed above manufacturer settings (Fig. 7) – shutting down all WTs at a wind facility when wind speeds are below a pre-defined speed in order to reduce wildlife fatalities, without consideration of other site-specific information [1,2].

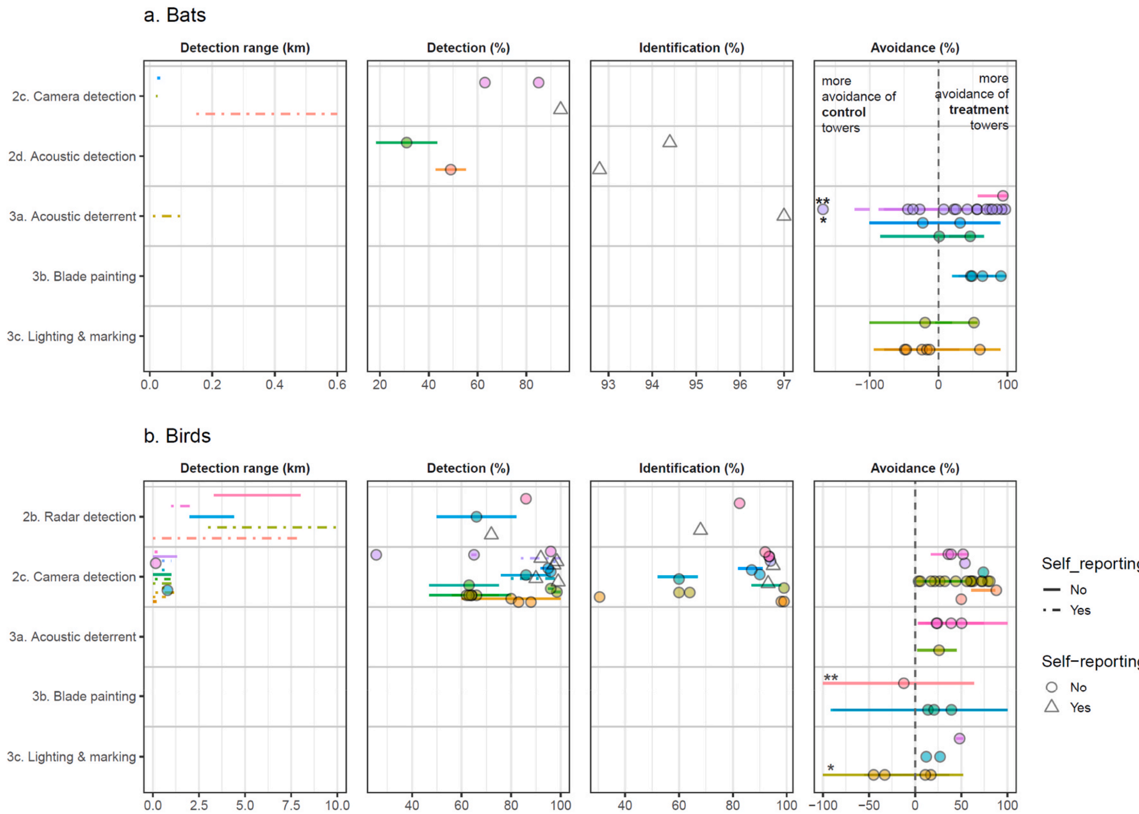

Fig. 4. Results of field studies for (a) detection range (km), (b) detection rate (%), (c) identification accuracy (%), and (d) change in behaviour (avoidance) for bats and birds for (2b-d) radar, camera, and acoustic detection methods for smart curtailment, (3a-c) acoustic and visual (blade painting, lighting/marking) methods. Colours represent different publications, with multiple data points representing different species or specific conditions tested by the author(s). We distinguish between independent testing (solid symbols) and self-reporting (hollow symbols) shown as separate dots on the same line. Some authors present means and a measure of error (95% confidence intervals shown by lines), while others simply present a mean value without any measure of error (circles only) or a range (lines without circles). Axes for avoidance are truncated at −100 and 100 for graphical purposes (*truncated CI, ** outlier not plotted).

(1) **Detection range** & (2) **Detection probability.** Blanket curtailment relies on accurate monitoring of wind speed only (at the nacelle, or a local meteorological mast), and therefore detection of target species is not relevant.

(3) **Species specificity.** Avoiding low-wind periods when some bats are most active can effectively reduce risk for *Lasiurus* and *Lasionycteris* bats [28,29,140], and therefore increasing cut-in wind speed has been strongly recommended as an option for mitigating bat collisions [6,7,29,132,141]. However, other bat species continue to fly during strong winds. There is little evidence that the marginal operational cut-in speed increases that are successful in mitigating losses of *Lasiurus* and *Lasionycteris* bats similarly reduce mortalities for stronger and faster fliers such as *Tadarida* and other molossid bats [142]. Further studies across different ecosystems are therefore warranted.

(4) **Deterrence.** NA for this method.

(5) **Effect on collision fatalities.** Field studies raising cut-in speeds from ~3.5 to 6.5 m/s, show that blanket curtailment can reduce bat mortalities by 49 ± 23% (n = 14 studies; Fig. 5). When they include covariates (e.g., difference between revised and manufacturer's cut-in speeds), meta-analyses across North American WF average 62% [54–69%] reduction in bat fatalities, or 33% reduction in total bat fatalities for every 1.0 m/s increase (29 operational curtailment treatments across six WF [29]; 36 control-treatment studies across 17 WF [28]). We have found no published reports addressing whether raising cut-in speed can reduce bird turbine strike (but see unpublished data for Common kestrel, Red kite and Griffon vulture linking collisions with blade tip speed [143]).

(6) **Setup and maintenance costs.** Expenses would include the cost of a technician to modify the power curve on the turbines to allow for cut-in at a higher wind speed. The technician should also test the updated power curve to ensure that it does not cause damage since curtailment options can increase fatigue and wear generated through greater transient loads associated with commencing operation during higher wind speed [124,125].

(7) **Energy production losses.** AEP loss due to blanket curtailment averages 1.27 ± 1.02% across 5 studies [4,35,39,41,42] or 0.496 ± 0.516% per 1 m/s increase in cut-in. This value will vary between sites and varies from year-to-year according to wind conditions. AEP loss should logically increase with the change in cut-in speed from the manufacturer, but there are too few published data to date to report this relationship.

3.2.2.2. Seasonal curtailment. Seasonal curtailment describes curtailment during periods of high collision risk, for example during bat and bird migration periods. Correlations between bat and bird activity with particular times of day, wind and temperature conditions, or season are therefore informative [4,144,145].

(1) **Detection range** & (2) **Detection probability.** NA for the same reasons as **3.2.2.1.**

(3) **Species specificity.** Identifying times of year when most mortalities occur can help reduce collisions. For example, in North America, calm weather conditions during bat migration periods (late summer and fall) are recognised as particularly hazardous, as bats are more active in calm wind conditions when insects are active, and approaching storms can trigger increased movement

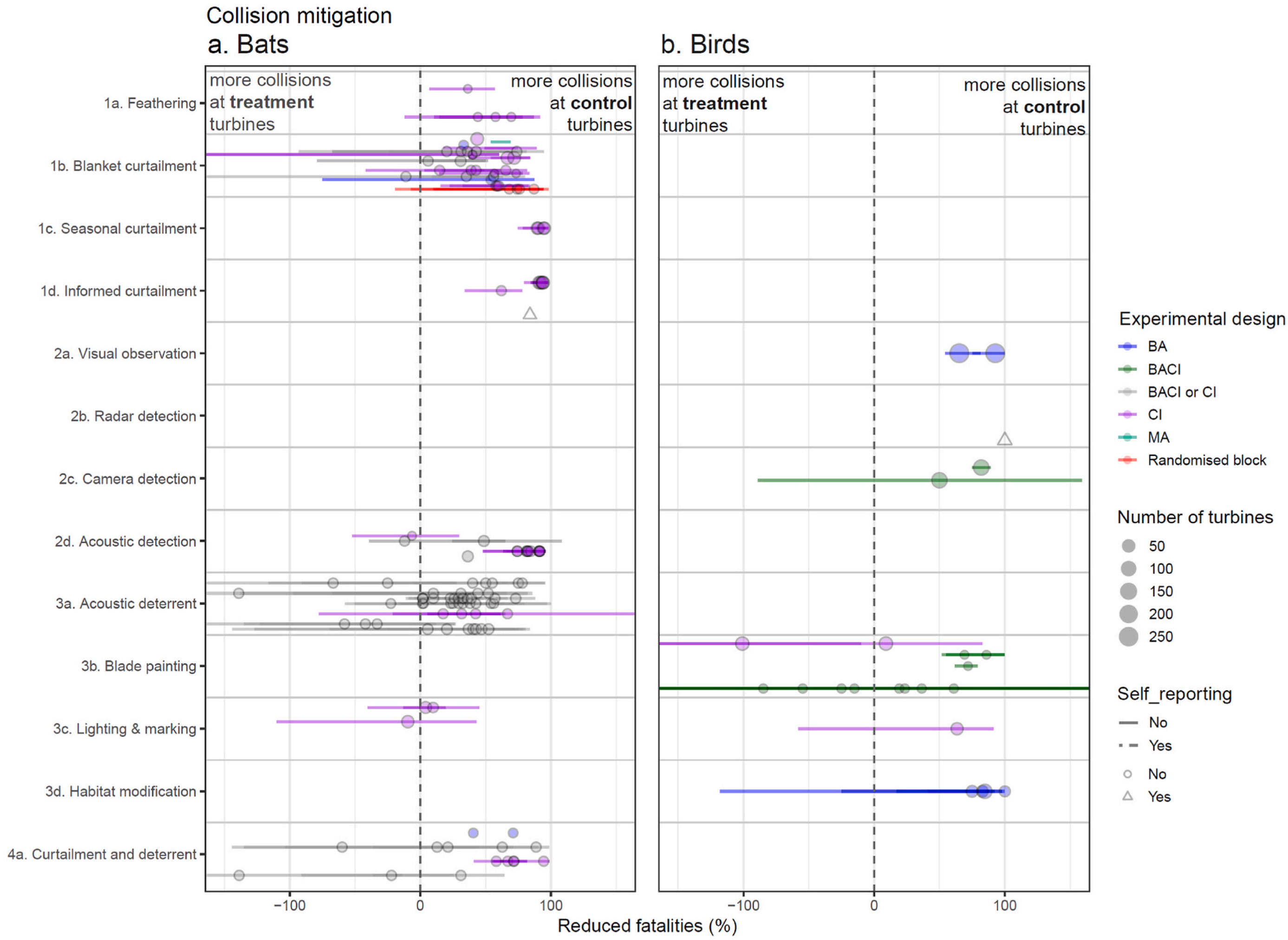

Fig. 5. Results of field studies testing collision mitigation for (1a-d) curtailment, (2a-d) smart curtailment, (3a-d) deterrent methods, and (4) combined (curtailment and deterrents). The relative size of each point reflects the number of wind turbines included in the study. Colours represent different experimental methods, with multiple data points representing different species or specific conditions tested by the author(s) (multiple data points on a line represent a single study). Axes are truncated at −150 and 150 for graphical purposes.

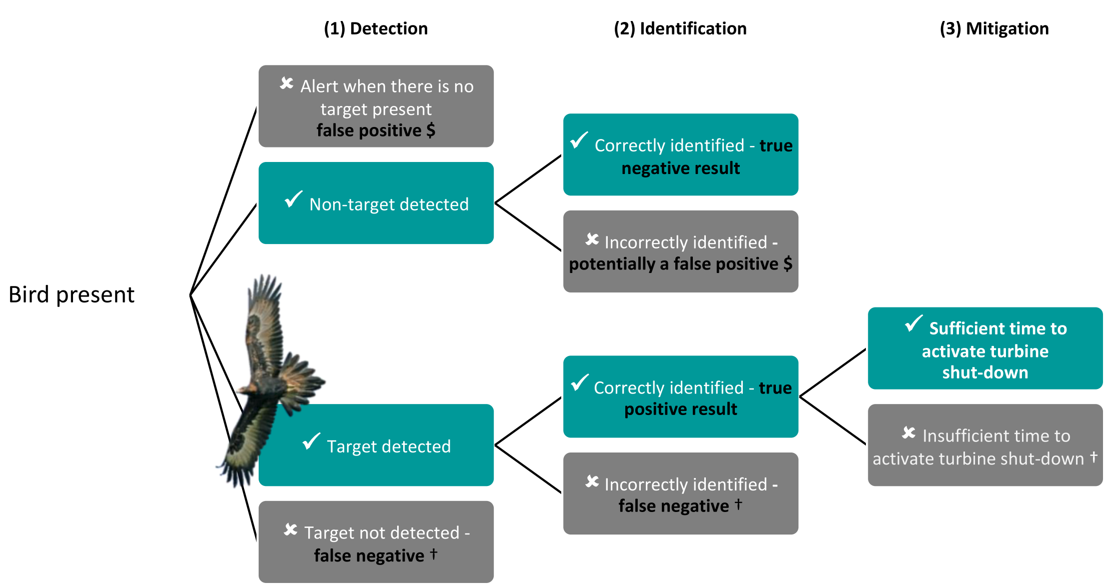

Fig. 6. The hierarchy of detection and identification leading to a correct (green) or false/inadequate mitigation response (grey). False positives would incur a financial cost due to energy production loss ($), while false negatives would incur a conservation cost due to increased risk of collision (†).

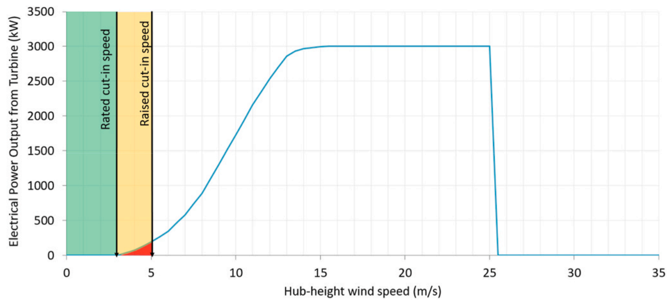

Fig. 7. A power curve showing power production as a function of wind speed, with the manufacturer's cut-in speed (3 m/s) and a potential raised cut-in speed (5.0 m/s) recommended as part of mitigating bat collision risk. The green area on this graph represents wind speeds at which feathering (to reduce free-wheeling speed of the turbine) can be implemented with no cost in terms of lost power production as these represent wind speeds below the turbine cut-in speed. Raising the cut-in speed above the manufacturer's value (orange area) will cause some loss of power production (red area). The turbine chosen is a Vestas V112/3000 since Vestas represent 19% of operational turbines around the world (the largest share) [139] and the sample power curve could be downloaded from www.thewindpower.net/.

[146].

Seasonal information and weather patterns have also been used to predict bird movements and therefore minimise blanket curtailment periods. Resident grassland and soaring birds, which occupy WF areas year-round, show relatively consistent collision risk throughout the year, without clear seasonal peaks, but most fatalities of long-distance migratory woodland species occur when birds travel through open landscapes between breeding and wintering areas during spring and autumn [146]. Buler et al. [147] showed that weather radars provide accurate measures of relative wintering waterfowl density over large spatial extents in the USA, which can therefore inform WF activities. Radar have similarly been used to record and therefore predict largescale bird migration patterns in the North Sea, to predict WT downtime [145].

(4) **Deterrence.** NA for this method.
(5) **Effect on collision fatalities.** Targeting shutdown to high-activity periods could reduce collisions. In southeastern Australia, 91% of bat mortalities occur between January and May, and 78% between February and April—targeting curtailment to these times of the year (e.g., increasing cut-in speed between dusk and dawn) can therefore substantially reduce mortalities [148]. We note, however, that fatality monitoring at the Altamont Pass Wind Resource Area, California USA, suggested that seasonal shutdown was ineffective in reducing fatalities of many bird species, including migratory Golden eagles [149].
(6) **Setup and maintenance costs.** Extensive monitoring and data analysis is required to inform seasonal shutdowns.
(7) **Energy production losses.** We found no empirical data on AEP loss due to seasonal curtailment. However Maclaurin et al. [4] modelled three seasonal curtailment windows, including 3, 4 and 7 months, showing increasing AEP loss with the greater periods of curtailment.

3.2.2.3. Informed curtailment. While increasing the cut-in speed of WTs is a proven method for reducing bat fatalities (section 3.2.2.1), refining curtailment times to only target periods of high bat and bird activity can markedly reduce AEP losses associated with blanket curtailment. Time of night, precipitation, storm fronts, or insect activity can be used to predict bat activity [149], which in turn is strongly correlated with WT collisions (number of bat passes explaining ~80% of the variation in carcass estimates [43]). An example of informed curtailment for bats is for turbines to be curtailed at night, when wind speeds are below 5 m/s, and when temperatures are above 4 °C (40 °F) (when insects and bats are more active), during the fall bat migration season [3].

(1) **Detection range** & (2) **Detection probability.** Informed curtailment includes monitoring of environmental conditions.
(3) **Species specificity.** Model-based informed curtailment systems use environmental predictors of bat activity to generate predictive or reactive responses/alerts. Operators can select from different curtailment scenarios based on target fatality thresholds, allowing flexibility to reduce bat fatalities, while also minimising energy production loss (e.g., ProBat, Optimized Smart Curtailment (OSC) system, Wildlife Activity Detection System, EchoPITCH).

Predictions of bird activity can also be incorporated into curtailment operations. For example, migrating birds tend to fly at night, and use lower altitudes during storms, low clouds and rain, increasing their collision potential with WTs [145,150]. Some birds are also attracted to disturbance, and their activity can be predicted by surrounding land use. For example, fire can attract raptors feeding on insects and small vertebrates escaping the flames [151], and therefore environmental approvals can require curtailment of WT operation after recent burning (e.g., Ref. [152]). Agricultural cultivation can similarly attract some birds, which may necessitate WT curtailment for regulatory compliance (e.g., FlexiBird can detect agricultural activity in adjacent fields to minimise unnecessary downtime, and optimises WT operation time [62]).
(4) **Deterrence.** NA for this method.
(5) **Effect on collision fatalities.** Analysis of an estimated 67,007 bat fatalities across 19 WF in Iowa, USA, indicated that collisions decreased with wind speed, but also increased with temperature [153]. Application of these findings has therefore been applied to inform WT operation times.
(6) **Setup and maintenance costs.** Setup expenses include, e.g., temperature monitoring equipment, algorithm and computing requirements.
(7) **Energy production losses.** Including temperature in curtailment operations reduced energy production losses by 18% over blanket curtailment [38], while Optimized Smart Curtailment™ purports to improve on AEP losses by 46% [47]. Maclaurin et al. [4] evaluated 18 scenarios across combinations of three cut-in speeds (5.0, 6.0, and 6.9 m/s) and three timeframes (3, 4, and 7 months) for both blanket and informed (by our definition) curtailment, assuming that bats were more active at air temperatures >10 °C, and >1 mm rainfall would inhibit bat activity. In their modelling, the relative benefit of informed curtailment increased for the highest cut-in and greater length of seasonal curtailment, with least AEP loss for informed curtailment (<1%) compared with blanket curtailment (~16.6%).

3.2.2.4. Smart curtailment (shutdown-on-demand). We define smart curtailment as shutdown-on-demand informed by the presence of specific birds or bats of conservation significance in the air space around WTs. We reviewed the application of different detection systems to access the WT's control system through the Supervisory Control and Data Acquisition (SCADA) system—a computer-based system used to monitor and control the WF from a centralised location. An alert is based on predetermined criteria, indicating when the WT should first initiate deterrents, or be shutdown to avoid collisions as the target approaches the turbine (Fig. 8).

We consider the advantages and disadvantages of visual observations, radar, camera, and acoustic detection systems (Table 3), in particular how they can meet the minimum detection distances required for effective shutdown-on-demand [154]. The ability to detect and track targets within the RSA is also a consideration. Collecting data on the animal's behaviour can inform further analyses, even in cases where triggering WT curtailment is not feasible. Garcia-Rosa and Tande [26] propose a control system ('SKARV') that uses projected flight trajectory of birds close to the turbine blades and adjusts turbine speed to ensure that the animal passes through the spaces between the blades, with minimal cost to energy production. Exploration of novel technologies such as this require reliable detection and monitoring methods.

3.2.2.4.1. Visual observations. Visual observation can be used as triggers for WT shutdown. Multiple trained observers are stationed at vantage points around the site, who can initiate turbine shutdown when a target species is observed (e.g., Refs. [63,100,156]).

(1) **Detection range.** Detections are limited to the visual range of observers, and will likely require maintenance of multiple observation viewpoints [100].
(2) **Detection probability.** A limitation of this approach is that observations are limited to daylight hours, with reduced effectiveness during early morning and late afternoons [157].
(3) **Species specificity.** False positives commonly arise due to confusion between protected species and more common bird species [157]. The skills and experience of the observers can make a significant difference in efficacy and efficiency of this approach, as mis-identifying non-target species for conservation-significant species can become costly.
(4) **Deterrence.** NA for this method.
(5) **Effect on collision fatalities.** There can be a delay of minutes between observers spotting a bird and manual initiation of WT shutdown. For example, a long-term selective curtailment protocol in Cádiz, Spain, became mandatory in 2008 to reduce collisions of Griffon vultures (*Gyps fulvus*) [63]. Between 2008 and 2020, a total of 269 WTs across 20 WFs were temporarily shut down whenever vultures or other large soaring birds were observed approaching on hazardous flight paths, typically within 3 min of observation. This targeted approach resulted in a 92.8% reduction in Griffon vulture mortality and a 65.2% reduction in fatalities across all soaring birds.
(6) **Setup and maintenance costs.** High personnel demands are noted where this approach has been implemented; this can be viewed in a positive light as valued employment [156].
(7) **Energy production losses.** Ferrer et al. [63] report minimal impact on energy production—just 0.51% average AEP loss, despite more than 2000 shutdowns each year. Robbelein et al. [158] highlight that the impact of stop and start cycles under various curtailment regimes on the fatigue life of WT support structures cannot be neglected. Assuming a moderate average downtime of 10 min, the average time between start-up and shutdown for 2000 shutdowns a year would be 4.2 h. Luan and Moan [159] derive a factor of 205/n for the relative increase of long-term fatigue damage on tower bases due to transient loads, where n is the average time between startup and shutdown. This suggests that 2000 shutdowns per year may result in around a 50% increase in long-term fatigue damage. Wind turbine manufacturers would account for this in the safety margins used in the design of turbines, but minimising the number of false positives in regard to shutdown-on-demand is nonetheless a high priority.

3.2.2.4.2. Radar tracking. Seven market-ready radar systems specifically designed for bat and bird monitoring at WFs were reviewed (Table 1). Radars work by emitting radio waves, typically in the form of short pulses, from a radar transmitter. These waves travel through the air until they encounter an object in their path and are scattered by the object, with the portion of back-scattered radio waves ('echoes') being subsequently received by the radar detection unit. Measuring the difference in time it takes for them to return is indicative of distance to the object, and the radar cross-sectional area is indicative of approximate body size. Field validation data for radar are scarce, with many aspects of their anticollision performance not yet quantified.

(1) **Detection range.** Radar systems operate day and night under various environmental conditions, including fog and rain, since they do not rely on visibility or ambient light [145]. Radar detectability is influenced by several factors: target size, orientation to the radar, distance, and environmental clutter (e.g., vegetation, turbines, waves in offshore sites, rain). Large birds can be detected up to 12 km away, but small bird and bat detection is limited to shorter ranges with a reported maximum of ≤3.3 km based on available data for Robin MAX [71]. Landscape topography strongly influences detectability, with 'blanking areas' as a consequence of clutter preventing radio waves penetrating further, and radar traces are lost when the animal flies below the radar horizon. Installation typically requires a minimum distance of 50–150 m from turbines to reduce interference from WT.
(2) **Detection probability.** Depending on the configuration, radar systems provide either 2-dimensional (2D) or 3-dimensional (3D) flight data. Horizontal scanning radars (HSR) track the position, speed, and flight direction of the target (e.g., Robin 3D Fixed/Flex -S-band only), while vertical scanning radars (VSR; e.g. Robin 3D Fixed/Flex -X-band only) offer altitude data. Some systems (e.g., 3DFlighTTrack, BirdScan MS1, BirdTrack, Robin 3D Fixed/Flex

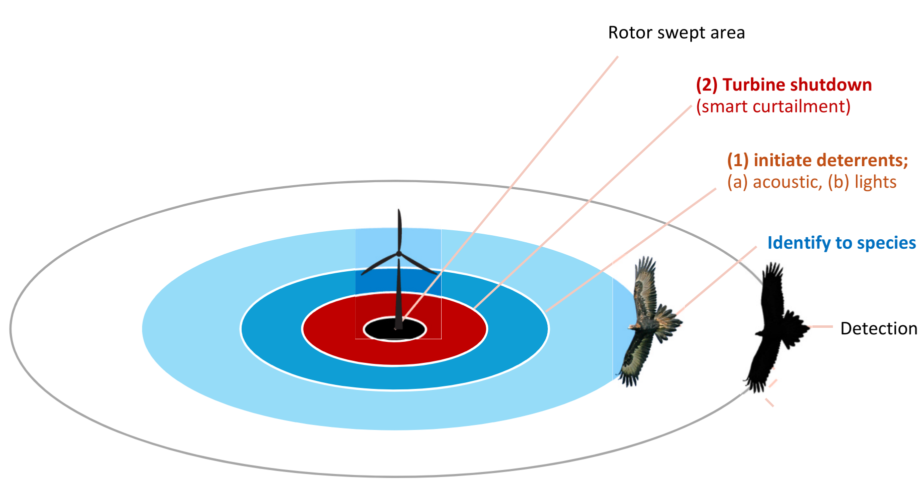

Fig. 8. Processes of detection, identification of target species, and the initiation of deterrents or turbine shutdown when the target continues to approach towards the wind turbine.

Table 3
Advantages and limitations of (a) radar (b) camera, and (c) acoustic technology for detection of bird (and bat) activity for the purposes of activating shutdown-on-demand as part of smart curtailment systems.

Advantages	Limitations
a. Radar	
Technological • Wide field of view – 360° horizontal coverage with vertical field-of-view adjustments (−20° to +90° across models). • Long range detections. • Small targets are able to be tracked. • Can capture 2D- and 3D-flight path data.	• Interference (e.g., topography, WT generators, vegetation, rain) can limit coverage. • Limited capability to track targets within the RSA.
Operational • Environmental resilience – systems can operate in extreme conditions (extreme temperature, fog). • Can detect day and night. • Real-time data collection – facilitates targeted, smart responses (shut-down on demand). • Automated mitigation protocols that activate deterrent signals (audio/visual) and turbine shutdown.	• Low quality data does not allow species (or species group) identification for targeted collision prevention. • Species recognition requires sufficient AI training to identify target species. • Interference limits functionality, e.g., WT generators, vegetation, rain. • Limited capability to track targets within the RSA. • Cost.
b. Camera	
Technological • Wide field of view – 360° horizontal coverage with vertical field-of-view adjustments (−20° to +90° across models) – therefore camera placement allows monitoring of the RSA. • High quality data can allow species (or species group) identification for targeted collision prevention. • Some systems: - have adaptive monitoring that adjusts sensitivity based on weather conditions and the parameters of targeted species. - have video/image stabilisation with predictive tracking, compensating for camera movement and vibration. - can capture 2D and 3D flight path data. • Thermal imaging cameras provide night vision to detect nocturnal species.	• Interference from non-target species and WT generators (for thermal cameras). • Automatic detection systems detect more large species than medium species and more individuals foraging than individuals transiting [155]. • 3D systems detected more birds than 2D systems [155].
Operational • Environmental resilience – systems can operate in extreme conditions (temperature, rain, hail). • Real-time data collection – facilitates targeted, smart responses (shut-down on demand). • Automated mitigation protocols that activate deterrent signals (audio/visual) and turbine shutdown.	• Limited functionality under some weather conditions (e.g., fog). Automatic detection systems detect more flying birds when humidity, nebulosity and temperature were moderate (~40%–50%, 3-6 oktas and 10–25 °C, respectively), visibility and wind speed were low (<20 km and <5 m/s, respectively) [155]. • Small targets are difficult to detect, identify and track. • Species recognition requires sufficient AI training to identify target species. • Thermal images are less accurate for target species recognition. • Cost.
c. Acoustic	
Technological • High quality data can allow species (or species group) identification for targeted collision prevention. • Ability to identify bat species based on unique echolocation calls and therefore target shutdown-on-demand to conservation significant species. • Enables detection of nocturnal bat species.	• Limited detection range due to acoustic attenuation, varying with: - environmental conditions (e.g. temperature, humidity, wind, and barometric pressure) - masking due to background anthropogenic noise - bat species (call frequency and vocalisation amplitude) - adverse weather conditions - directional nature of bat echolocation Consequently, 50–70% of bat passes can be missed. • Larger turbines may require multiple microphones to ensure full coverage.
Operational • Real-time data collection – facilitates targeted, smart responses (shut-down on demand).	• Acoustic shadowing (resulting in ‘acoustic blind spots’). • Microphones and enclosures need to be protected against dust and precipitation. • Require custom detection criteria to distinguish relevant bat calls from background noise. • Cost.

S- and X-band combined, Robin MAX, Merlin) combine HSR and VSR, providing 3D flight path data including position, speed, direction, and altitude, offering more complete information on space utilisation and the ability to navigate around obstacles.

(3) **Species specificity.** Radar can categorise targets by size and flight behaviour, which is only sufficient for differentiating between general groups (e.g., bats, small passerines, large raptors) and cannot distinguish targets to species level. Some radar (e.g., BirdScan MS1) incorporate micro-Doppler analysis and echo signature interpretation to improve object classification based on wingbeat patterns and flight behaviour. Integration with complementary technologies such as cameras or acoustic devices (e.g., Merlin) can further improve species-level identification. Most systems include filtering algorithms to distinguish bats and birds from insects, rain, and non-biological objects, reducing false positives (e.g., Merlin, BirdTrack, Robin MAX).

Performance data from radar detection field validation studies are scarce. However, in one study, Robin MAX demonstrated 82.5% accuracy in classifying Wedge-tailed eagles within 4 km [70,100]. Most systems require site-specific algorithm calibration and fine-tuning during deployment to optimise detection accuracy and minimise false triggers [68,71,73,OEM1&2**].

(4) **Deterrence.** NVbird systems cascade from radar detection through to an alert signal for air traffic controllers; the same system could be applied for deterrence of activity around WT, although we found no record of such.

(5) **Effect on collision fatalities.** The reviewed radar systems are capable of monitoring avian and bat activity and integrating with

the SCADA system to automatically trigger WT curtailment if predefined criteria are met. These criteria can include flight characteristics such as altitude, speed, direction, and proximity to turbines, as well as species classification. For example, Merlin uses these flight parameters along with additional sensors (e.g., cameras and microphones) to support species-level identification and customisable curtailment rules. BirdTrack can account for the number of individuals, presence of flocks or threatened species group, and migratory flux intensity—particularly for soaring birds. BirdScan MV applies spatiotemporal distribution and mean traffic rate, combined with environmental conditions such as visibility, humidity, and wind speed to assess when curtailment should be initiated.

(6) **Setup and maintenance costs.** As ballpark figure for radar units, the CEO of Robin Radar said in September 2025 that the IRIS drone detection radar, based on their bird-detection radars, cost "less than US$1M per unit" [160].

(7) **Energy production losses.** Over a four-year adaptive management period, BirdTrack reduced curtailment time by 91% and eliminated mortality for target species [161].

3.2.2.4.3. Camera monitoring technology. Ten market-ready camera systems were identified and reviewed (Table 1). Cameras capture real-time footage and images of animals across a wide field of view, allowing the tracking of movement and behaviour. The systems, designed specifically for WF monitoring and collision prevention, can operate in severe environmental conditions such as extreme temperatures, rain or hail. Installation flexibility of camera technology allows deployment of cameras on WT towers, meteorological masts, or as portable free-standing units depending on monitoring needs. The flexibility of set-up allows cameras to be deployed in opportunistic positioning, and therefore camera technology has frequently been deployed around offshore WTs (depending on site conditions and system configuration, they can be installed in locations where deployment is most practical).

(1) **Detection range.** Environmental factors such as high humidity, bright sunshine, clouds, fog, dust and precipitation can affect camera performance, reducing visibility to zero in some cases [75]. For example, Bioseco is optimized for medium-to-large bird species with wingspans between 0.5 and 1.1 m (small) and over 1.1 m (large) [OEM5**]. The developer indicated that birds with wingspan less than 0.5m are filtered out to reduce false alarms and "focus on larger avian species" [OEM5**]. Similarly, BirdVision focuses primarily on large species through size-based classification before initiating turbine shutdown when collision risks exceed preset thresholds for these birds. Detection range derived through independent testing averages 578 ± 534m across four cameras (AVES Wind®, Bioseco, DTbird, Identiflight). Thermal cameras for detection of bats at night have a range of ~100m (DTbird [OEM**]), although infrared radiation emitted by WT towers and nacelles can interfere with detections, potentially reducing detectability of animals flying close to the structures.

(2) **Detection probability.** Some cameras are equipped with motion sensors or acoustic triggers and are activated only when motion or certain sounds are detected; this feature helps save energy and data storage while increasing monitoring efficiency, especially in areas with irregular bird and bat activity. Some camera systems operate exclusively during daylight hours (e.g., Identiflight, BirdVision, BirdRecorder). For example, BirdVision has been designed specifically for onshore wind farms, with the fully automated system activating at dawn and deactivating at dusk [OEM4**]. Other systems can also operate at night, using a combination of optical with infrared (thermal) (e.g., DTbird, SafeWind, Digisec), or night vision optics (e.g., ThermalTracker-3D) to capture nocturnal bats and birds. Detection probability derived through independent testing averages 76 ± 19% across four cameras (AVES Wind [75–77], Bioseco [78,79], DTbird [87,88,91,92,162], Identiflight [96,98]).

(3) **Species specificity.** Multiple cameras allow for stereo view of birds combining 2D (e.g., SafeWind) and 3D (e.g., Merlin, DTbird, Identiflight, Bioseco, BirdRecorder, BirdVision, Digisec) flight path data. For example, SafeWind consists of a multi-camera array installed on WT towers, with two cameras per direction—one oriented horizontally and one angled upwards.

Species identification capabilities in camera systems are enhanced by continuous improvements in species recognition software. These cameras are designed to automatically process images, identifying and classifying bird and bat species with high accuracy [163]. Turbine shutdown can therefore be selective, based on proximity, trajectory, and flight characteristics of the animal observed (e.g., Identiflight, AVES Wind Onshore). Another challenge is the difficulty in tracking the trajectories of small targets, particularly due to interference from insects. In areas of high insect activity, insect flight paths can intersect with those of bats and birds, making it difficult to accurately distinguish, identify and track animals [163]. Processing time for identification is also an important criterion for successful responses; processing time for Bioseco is around 20 s, resulting in a risk zone of 320m from the WT towers [164].

Independent field testing for identification accuracy averages 82 ± 21% for four camera systems (AVES Wind [75–77], Bioseco [78–80], DTbird [78,87,90–92], Identiflight [96,99,100]). General findings indicate better success for larger bird species, but less confidence in detection or identification of small bird species.

(4) **Deterrence.** Commercially available systems are capable of monitoring the activity of flying species and integrating with the WT control system to trigger mitigation measures: initiating deterrents such as visual strobe warnings (e.g., Bioseco) and audible sound deterrents (e.g., DTbird, SafeWind, Bioseco, Digisec, Nvbird), followed by turbine shutdown if the animal continues to approach the turbine. For example, DTbird classifies targets to size groups, and employs a progressive deterrence protocol that (1) first issues a warning acoustic signal (a mechanical sound), (2) escalates to stronger 'dissuasion' acoustic signal (more raucous and annoying sound composed of combinations of avian distress calls and mechanical sounds), and (3) finally initiates turbine shutdown if collision risk persists [93,OEM3**]. Deterrence has only been quantified for DTbird, resulting in a 49 ± 24% change in bird behaviour in response to the camera-triggered acoustic signal [87,89–92,165].

(5) **Effect on collision fatalities.** The only system that has been tested for an impact on mortalities is IdentiFlight, with a BACI design showing an average of 66 ± 23% reduction in collision fatalities (averaged across [95,97]; Fig. 5).

(6) **Setup and maintenance costs.** Cameras are generally purported to be operable without specialist knowledge, requiring minimal operator involvement, and annual maintenance conducted by manufacturer specialists (e.g., BirdVision [OEM4**]). However, maintenance requirements include annual servicing, with additional cleaning cycles as needed, particularly for camera lenses exposed to environmental contaminants (e.g., DTbird [93]). Felton [87] reported that the standard DTBird V4D8 model (with Falco cameras and Larus software) cost around US$18–22K, installation costs $4–6K/unit, plus yearly service sale cost ($2–3K) and maintenance ($0.6–2K/unit/year), bringing the total investment to purchase and operate a single DTBird unit for the first year to a minimum of $24,600.

(7) **Energy production losses.** It has been estimated that Bioseco can reduce AEP loss to 1% of annual production [166].

3.2.2.4.4. Acoustic monitoring technology—bats. We reviewed nine acoustic systems designed specifically to detect bat activity at WFs (Table 1). Acoustic systems consist of microphones mounted on either

WT structures (e.g., nacelle, tower, or even blades – to maximise detection coverage of the RSA) or at various heights on a wind mast to understand how bat activity changes with altitude [167]. The microphones capture bat's species-specific echolocation calls—the signals bats use for navigation, foraging, and social interactions [168]. There are few data for field validation of acoustic-triggered smart curtailment systems.

(1) **Detection range.** Acoustic systems have inherent limitations due to sound propagation properties, microphone capabilities, and environmental characteristics, with notable advantages and limitations (Table 3) [10]. The acoustic detection range of these systems depends on the bat species (call frequency and vocalisation amplitude), wind direction, temperature, humidity, and barometric pressure. Distances between 10 and 100 m from the detectors are reported (but not verified through independent testing), with detections further reduced under adverse weather conditions, including high winds [169]. Some bat species are also relatively quiet, making them less detectable (e.g., Ref. [170]). The limited range of audio detection can therefore delay responses, potentially identifying approaching bats too late to trigger effective WT shutdowns.

(2) **Detection probability.** Acoustic shadowing can be problematic, where rotating WT blades obstruct and disperse sound waves, reducing the system's effectiveness in monitoring the RSA [10]. This results in acoustic blind spots where bat calls may go undetected, potentially leading to gaps in monitoring. AudioBat can be combined with SafeWind camera technology (from the same developer) to enhance the detectability of bats not emitting ultrasound [53]. As bats emit focused beams of sound, directional echolocation can also reduce detectability [10]. Microphone placement is therefore critical to ensure calls are captured across different flight paths. If a bat approaches from outside the microphone's acoustic field of view, the likelihood of detection is significantly reduced. Validation studies comparing acoustic data with independent methods (e.g., visual surveys, videography) has shown that only about 40 ± 13% of independently documented bat passes are also recorded by audio recorders [171,172], markedly limiting the reliability of audio monitoring for preventing turbine strike.

(3) **Species specificity.** Echolocation calls provide data for species identification and activity assessment but require custom detection criteria to distinguish relevant bat calls from background noise. Identification accuracy for DTBat has been reported as 97% [52*]. However, while echolocation calls of many bat species are distinctive, other species' calls vary only subtly (e.g., Australian long-eared bats *Nyctophilus* spp.) [173]. The degree of interspecific variation in echolocation calls at a specific site is therefore a limiting factor in terms of whether it is possible to discriminate species for targeted curtailment options.

(4) **Deterrence.** Some systems can incorporate AI to analyse calls in real time, either triggering mitigation measures when specific bat species' activity is detected (e.g., DTBat, EchoSense) or raising an alarm to notify the turbine control network of bat presence for further action (SMART [OEM7**]). An optional stop control module can trigger turbine shutdown based on the presence of animals and/or predefined environmental factors such as wind speed, ambient temperature, humidity, atmospheric pressure (i.e., informed curtailment) (DTBat, AudioBat). The time required for turbine shutdown after detecting an animal is reported for one system (SMART: issues a curtailment order within 2–3 s of the appearance of a bat [174]), but deceleration rate depends on the WT design. For DTbat, the total time required ranges between 10 and 52 s, depending on the WT design and wind speed [51,175].

(5) **Effect on collision fatalities.** Three acoustic-triggered smart curtailment systems have been field tested to date, averaging 66 ± 34% reduction in collision mortalities over control WT but with highly variable outcomes (EchoSense®: −6% [39] i.e., an increase in fatalitites recorded, VBPS: 36% [176], TIMR℠: 74 ± 28% [42,55]; Fig. 5).

(6) **Setup and maintenance costs.** Larger WT may require multiple microphones to ensure full coverage; the number of units required per site is dependent on local conditions [OEM7**]. Acoustic systems require considerable maintenance, which needs to be planned for and costed out. Setup requires that microphones are protected from dust and precipitation. For some systems, daily updates are available through remote access for configuration, status checks, and maintenance, also allowing automation of daily maintenance tasks—such as data backups and microphone health checks (SMART [OEM7**]). Maintenance requirements of acoustic monitoring systems include seasonal adjustments (by a bat biologist) to adapt to changes in turbine acoustics (SMART [OEM7**]), periodic checking of microphone mounts for stability, and annual reviews help to optimise performance.

(7) **Energy production losses.** Estimated AEP loss for curtailment following acoustic identification represents a substantial improvement over blanket curtailment (TIMR℠: 48% [55], EchoSense: 49% [177], SMART: 85% [174]).

3.2.3. Deterrents

3.2.3.1. Ultrasonic deterrents. We found data for seven ultrasonic acoustic deterrents (Table 1), although some appear to have been prototypes and therefore not likely to be commercially available.

(1) **Detection range.** Sound attenuation is a major limitation for ultrasonic deterrents [36]. Environmental conditions, such as temperature, humidity, wind speed and atmospheric pressure can limit the distance sound travels [57,178,179], therefore limiting the range over which the deterrent is effective. Attenuation tends to be greatest for high frequencies [58], when the temperature is around 35 °C, and the relative humidity is low – around 10% [180]. Finally, foliage can also block signal transmission [181]. Attenuation therefore limits the range over which deterrents would be functional; for example, Kinzie et al. [181] report rapid diminishment of deterrence over only a short distance from the speaker (mean 94 ± 7(SE)% deterrence at 0–10 m; compared with 39 ± 22(SE)% at 20–30 m).

(2) **Detection probability.** Ultrasonic deterrents are continuously playing acoustic signals that do not rely on the detection of an animal to trigger them. However, active deterrents that respond to the presence of the animal are less likely to encourage habituation compared with constant signals.

(3) **Species specificity.** Ultrasonic deterrents produce a broad range of ultrasonic signals (generally between 20 and 120 kHz) that ensonifies the air around the WT, 'jamming' the ability of bats to successfully use their echolocation calls. The broad signal covers the peak call frequency of most echolocating bats, but higher-frequency signals degrade more rapidly in air than low frequency (<30 kHz) signals [58]. Therefore, high-frequency echolocating species might not encounter the deterrent until already within the dangerous zone, by which time their echolocation is jammed and they are more vulnerable to collision with the turbine blades.

(4) **Deterrence.** Deterrence measurements at roost emergence or around drinking ponds show an average 27 ± 63% reduction in activity in the presence of ultrasonic deterrents [40,56,59,61]. Bats may become habituated to static signals as a jamming avoidance response, diminishing long-term effectiveness [182]; both pulsed and continuous deterrent signals have been tested, again with mixed results. Alternatively, it has been argued that

bats may learn to avoid all turbines over time, based on their experience with those equipped with deterrents [57]. Future deterrent designs are exploring dynamic signal modulation to counteract habituation and enhance species-specific efficacy.

(5) **Effect on collision fatalities.** There are marked technology, species, site, and even interannual differences in effectiveness of ultrasonic deterrents, which could reflect environmental conditions influencing insect and bat species' activity, as well as the effectiveness of the auditory signals (Fig. 9). Collision data yields an average of 23 ± 40% reduction in mortalities (Bat Deterrent System: 40 ± 21% [37] 29 ± 55% [58], GE: 26 ± 24% [59] 30 ± 21% [60], NRG: −44 ± 13% [36] 0 ± 79% [40], Deaton: 35 ± 16% [57]; Fig. 5).

(6) **Setup and maintenance costs.** Because they are an active deterrent, ultrasonic deterrents require constant power and maintenance and a wind farm will incur the associated costs. A blade-mounted passive (i.e., not requiring an electricity supply) whistle, which produces a broad range frequency, has been developed and tested [183,184] which would reduce costs. The whistles—targeting 20 kHz and 10 kHz frequencies—have been designed, prototyped, and tested in wind tunnels, but have not yet been field tested. A challenge will likely be matching the frequency of sound generated to the target species, as the signal varies with speed of airflow. A drone-mounted deterrent device (producing auditory and visual signals while moving through the air) shows promise during field testing, but has not been deployed at scale [185]. These technologies may circumvent some of the sound attenuation issues.

(7) **Energy production losses.** Acoustic deterrents do not require WT shutdown and therefore there is no AEP loss associated with their use.

3.2.3.2. Audible sound deterrents. Audible sound deterrence utilises low-frequency, high-amplitude acoustic signals to discourage animals from approaching the RSA.

(1) **Detection range** & (2) **Detection probability.** Most acoustic deterrents are continuously playing acoustic signals that do not rely on the detection of an animal to trigger them. Audible deterrents may cause unpredictable effects on the bat's flight trajectory, and therefore caution has been advised when the deterrent is applied at a short distance from WTs in case the result is the bat flying into the turbine [21].

(3) **Species specificity.** Acoustic deterrents have used a broad frequency range or predator sounds, aiming to deter multiple species [93,186].

(4) **Deterrence.** The deterrent sounds fall within the audible frequency range of both birds and many bat species. These signals can elicit aversive responses to unfamiliar or potentially threatening sounds. For example, when flying through a flight corridor, Zebra finches (*Taeniopygia guttata*) maintained significantly greater distances (up to 50%) from an obstacle and adjusted their flight paths earlier [187]. While no statistically significant differences were found between the four sound types tested—broadband noise and frequency-modulated tones in the 4–6 kHz and 6–8 kHz ranges—the modulated signals in the 4–6

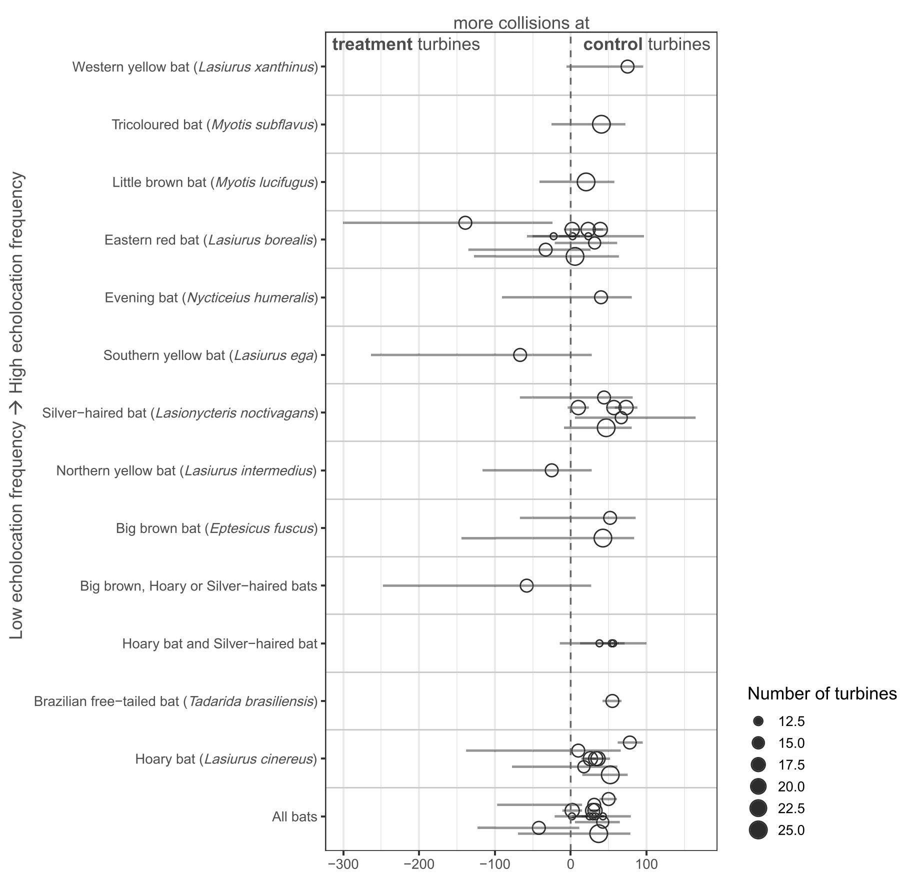

Fig. 9. Reductions in bat mortalities at wind turbines fitted with acoustic deterrents compared with control turbines, shown by bat species. Species are listed in ascending order of echolocation call frequency (or species average where separate species data were not presented). None of the data sources were self-reporting and they all used a BACI or CI experimental design [36,37,40,56–60].

kHz range tended to elicit stronger collision-avoidance responses. Passive deterrents risk animals habituating to them, while active deterrents that respond to the presence of the animal are less likely to encourage habituation compared with constant signals.

(5) **Effect on collision fatalities.** A field study in Nova Scotia, Canada, found only marginal difference in bird abundance or flight behaviour in response to bioacoustic deterrents (predator and alarm calls) played at intervals through speakers mounted near a WT base [186]. Field testing of DTBird—which emits an audible deterrent signal triggered in direct response to close approach of a bird identified on camera—shows 49 ± 24% of birds are successfully turned away from the RSA (section 3.2.2.4.3c).

(6) **Setup and maintenance costs.** In addition to potential habituation, audible sound deterrents may disturb nearby residents and non-targeted wildlife [92], which could incur mitigation costs.

(7) **Energy production losses.** Acoustic deterrents do not require WT shutdown and therefore there is no AEP loss associated with their use.

3.2.3.3. Visual deterrents. Visual deterrence strategies aim to reduce collisions with WTs by enhancing the visibility of turbine structures and triggering avoidance behaviour. For these strategies to be effective, they must align with the perceptual capabilities of the target species, function under varying weather and light conditions, and be feasible for implementation during turbine construction or routine maintenance [16]. Therefore, effective visual deterrents are characterised by high contrast or biologically meaningful patterns, placed at critical impact zones such as the rotor blades or tower base. They should be perceivable from appropriate distances, be non-disruptive to turbine function or structure, and ideally informed by site-specific bird behaviour and ecology. Other key criteria include durability in environmental exposure, minimal maintenance, and cost-effectiveness, especially when applied pre-construction.

3.2.3.3.1. WT lighting. Obstruction lights are a requirement at most wind energy facilities. Obstruction lighting, either flashing red or white lights, is mounted at the nacelle to provide aviators with visual cues during poor visibility conditions. These lights could potentially influence bat and bird behaviour, and lighting has also been argued for use as a deterrent, increasing visibility of WT and therefore reducing wildlife collisions.

(1) **Detection range.** Illuminated offshore WT could act as sensory traps, and bats are lured in to forage for insects or to roost on the structure [188]. Obstruction lighting has also been argued to potentially lure bats to WF over several kilometres [189].

(2) **Detection probability.** NA for this method.

(3) **Species specificity.** Lighting colour is likely to influence visibility for different species, due to different retinal photoreceptors [16,189].

(4) **Deterrence.** Research on offshore installations [145,190] reveals that continuous illumination can increase collision risk for birds, especially under poor visibility conditions (e.g., fog, overcast skies). Birds are often attracted to bright light sources in red or white wavelengths, which can lead to disorientation and circling behaviour. In contrast, green light (~530 nm) causes considerably less disorientation [190].

The use of UV lighting to increase visibility of WT as a deterrent for bats and birds has been considered [110]. An experiment showed a 27% reduction in bird flight activity for ultraviolet (UV) illumination (~365 nm) of WT compared to control nights (no lighting), and 12% decrease for violet light (~400 nm) [191]. Violet light also encouraged birds to fly higher, further reducing the risk of collision [191]. While lighting effects are most pronounced for nocturnal migrants, resident birds may become less responsive to artificial lighting over time as continuous exposure tends to reduce their sensitivity to the light [192]. The effectiveness of UV lighting as a bat deterrent shows conflicting results across studies, likely due to differences in experimental methods and lighting parameters. Experiments using different UV lighting configurations reported a 44% reduction in Hawaiian hoary bat (*Lasiurus semotus*) activity, but 40% longer visits near trees illuminated with continuous, UV light [193]. A 1-year-long field study testing flickering UV arrays mounted directly on the surfaces of two operating WTs found no statistically significant effect on bird, bat or insect activity compared to control (unlit) nights [194]. Overall, there is no indication of a deterrence effect of UV illumination (average −9±36% deterrence [191,193,194]).

(5) **Effect on collision fatalities.** There is little evidence that artificial lighting influences bat activity or collision risk at WFs [135], with no pattern for two studies examining US Federal Aviation Administration (FAA) lighting (red flashing strobes) (average 1 ± 10% mitigation [195,196]; Fig. 5). There is also no significant effect for birds [196].

(6) **Setup and maintenance costs.** Where mandated, obstruction lighting for e.g. aircraft that also benefits wildlife would not incur an additional cost. Any variation in lighting specifically for visual deterrence would require additional installation costs. Where they are shown to increase risk for wildlife, an option is for aircraft detection lighting systems (ADLS) to be used, so that obstruction lighting is only activated when aircraft are detected in the WF area. However, justifying this additional cost requires more field trial data. Lighting also has its own energy requirements.

(7) **Energy production losses.** There would be no AEP loss with this approach.

3.2.3.3.2. Blade painting.

(1) **Detection range.** Blade contrast painting aims to enhance rotor visibility and reduce 'motion smear'—as the bird approaches a WT, the image of the turbine blades accelerates to the point where it becomes a transparent blur that the bird probably interprets as a 'safe' area to fly through [197]. Laboratory simulations on American kestrels (*Falco sparverius*) tested achromatic and chromatic blade patterns, showing that a single black blade (of three blades) was about twice as visible as all-white blades, and red, green, and black colours were significantly more detectable than controls [197]. A separate study of Great tits (*Parus major*) found that high-contrast, aposematic signals (black-red-black-yellow-black stripes) on all three blades [198] were more conspicuous than 1 black blade or 2 red stripes on all three blades (each compared with plain white blades), suggesting potential mitigation value under complex backgrounds [199]; field validation of this patterning is still needed. It has also been argued that painting all three blades may be the most effective choice for enhancing visibility over distance and therefore maximising mitigation outcomes [WF2**].

(2) **Detection probability.** It is likely that the colour vision of bird species will strongly influence their ability to discriminate colour contrasting blades, and effectiveness of blade painting also depends on environmental conditions (i.e., visibility) [15–18]. The photoreceptors thought to be responsible for motion sensing (double cones) are sensitive to a broad spectrum of wavelengths centred around ~570 nm, while the photoreceptors for observing red colours effectively have a narrower sensitivity with a peak around 600 nm (LWS + droplet) [200,201]. A deep red colour pigment (reflecting light with a wavelength >600 nm) is therefore believed to have the best chance of being detected through motion while also utilising the bird's colour vision capabilities.

Background contrast likely also influences visibility of WT, with laboratory testing suggests green was effective against vegetation but poor against sky, while black was consistently visible [197].

(3) **Species specificity.** Laboratory testing of visual acuity has been carried out for a limited range of raptor and passerine species [197,199].

(4) **Deterrence.** The only data on behaviour of birds around painted turbines is for a large-scale testing of UV-reflective paint at Foote Creek Rim WF, USA, which showed substantially greater bird activity around the painted turbines (~2.5x greater raptor activity) [109]. Less is understood about the effect of blade painting on bats, which might be attracted to light reflected off turbine surfaces. Jonasson et al. [202] released bats into a Y-maze with choice between either a white turbine blade under artificial moonlight, or a black blade either lit or unlit, and found that bats were more likely to fly towards white turbine blade sections compared to less reflective black ones (62 ± 20% 'deterrence' due to blade painting).

(5) **Effect on collision fatalities.** Field testing of blade painting has been undertaken across a number of WF globally (Fig. 10). At Smøla WF, Norway, where one blade on each of 4 WT was painted black as part of a BACI experiment, an average 72% reduction in bird fatalities was recorded, with the strongest effect on raptors—no White-tailed eagle (*Haliaeetus albicilla*) carcasses were found after treatment [107]. At Umoya WF, South Africa, two red stripes were applied to one blade of 4 WT, with 20 control WTs in a BACI study [108]. Results show 91% reduction in overall bird fatalities and complete avoidance by raptors, with no evidence of displacement to neighbouring turbines [108].

Expanding on these small-scale trials, a single blade was painted black on 7 WT at Eemshaven WF, Netherlands, but results show no statistically significant reduction in collisions (marked variability in fatalities was recorded), although weak positive trends were observed for large gulls and diurnal species [106]. Researchers suggested that the limited effectiveness may be due to poor contrast between the black blade and the background, and to the reduced relevance of motion smear for modern, slower-rotating turbines. At Foote Creek Rim WF, USA, 77 WT were painted with UV-reflective paint that should have increased visibility of the WT for birds. This trial was a marked failure, with double the number of bird mortalities at the painted compared with control WT [109].

To date there are insufficient replicates of the same treatments for direct comparison. Testing a wide range of paint colours across different landscapes is required. The South African Wind Energy Association guidance note on blade patterning recommends red asymmetric blade stripes as a bird collision mitigation measure, combining aviation safety compliance with improved blade visibility [203]. Other blade painting studies are ongoing in Europe, South Africa and the USA [204,205].

We found no data on bat fatalities at painted turbines.

(6) **Setup and maintenance costs.** Although blade painting is low technology and requires minimal maintenance, initial costs can be high, as it requires sanding, cleaning and painting the blades [204]. At Iberdrola WF, the tasks were undertaken when there was little wind (and no rain) to ensure worker safety, with each 65-m long, up to 14-m wide blade, taking a week to paint [204]. At Umoya WF, South Africa, painting four WT took three months (waiting for low wind periods to access the blades) and cost R2.4m (US$150,000) due to the cost of requiring the access platform for this duration [206]. Implementing blade painting before construction would significantly minimise these costs.

Maintenance costs could also increase for painted over white blades. The Spanish Wind Energy Association relate the experience of blade manufacturers on the use of painted blades, validated by accelerated heat transfer tests on painted samples [130]. The report concludes that the use of black paint on blades for WTs in hot climates was not recommended. Compared to white or grey paint, black paint:

1. Is weaker and less-impact resistant, which accelerates the process of wear and cracking on the blade;
2. Can attain temperatures that are 30-40 °C higher through overheating on sunny days. A blade may exceed the glass transition temperature where the epoxy resin that binds the fibreglass sheets that form the blade changes from "a glassy, solid state to a soft, rubbery state". This increases the probability of structural failure of the blade; and

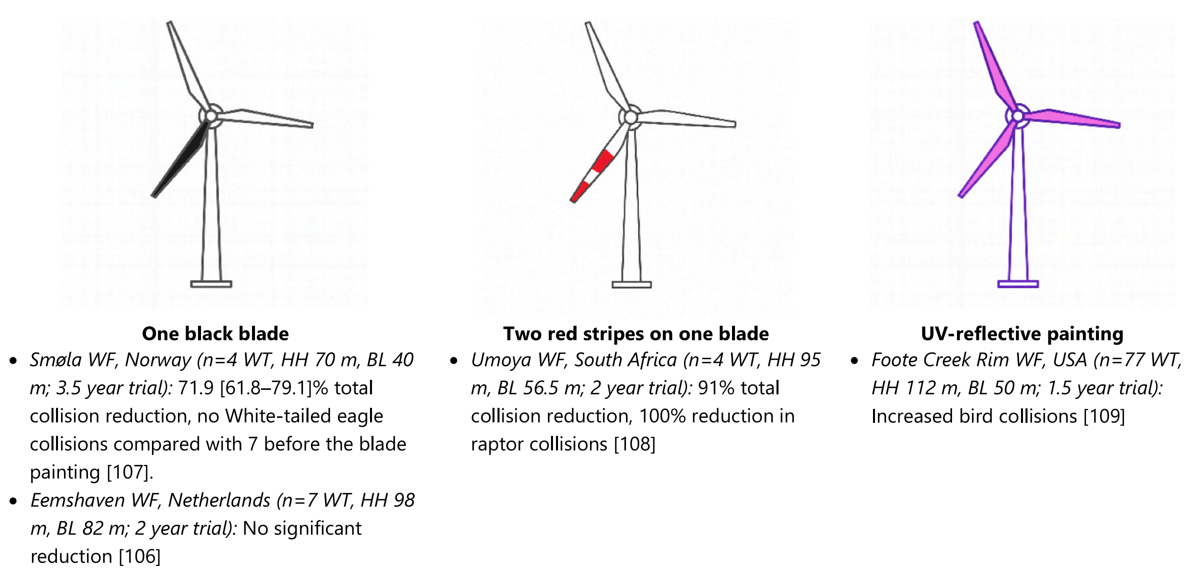

Fig. 10. Results of field testing of blade painting patterns undertaken across four wind farms (number of WT, HH hub height and BL blade length). All four studies used a before-after control-impact (BACI) experimental design, but trial duration reflects time since blade painting. Red text indicates no statistical significance. Values are [95% confidence intervals] where available.

3. Has conductive properties that can negatively affect the lightning protection system of the blade.

(7) **Energy production losses.** There are no AEP losses associated with this approach.

3.2.3.3.3. Tower painting.

(1) **Detection range.** Some bird species have poor visual discrimination, or fly under low light conditions, and risk collision with WT towers [207].

(2) **Detection probability.** NA for this method.

(3) **Species specificity.** Contrast painting of WT tower bases could mitigate collision for low-flying birds. Galliform birds are prone to colliding with WT towers (rather than rotor blades) due to their natural low flight altitudes, limited flight manoeuvrability, poor vision and activity during low light periods around dawn and dusk [107,207].

(4) **Deterrence.** At the Lourdes-Tarbes-Pyrénées airport in south-eastern France, presentation of a pair of 'eye spots' was shown to be effective at deterring raptors and corvids, with birds still showing deterrence after 5 weeks (i.e., they had not habituated to the signal over this time) [208]. Applying this method, Iberdrola WF added two vinyl transfers that look like staring eyes to more than 60 towers on seven WFs to discourage birds of prey [204]. The 1 m-diameter concentric circles have been fixed at between 3.5 and 4 m from the base of the WTs. It is not clear whether the efficacy of these decals has been monitored (no published reports have been found).

(5) **Effect on collision fatalities.** Observations at the Smøla WF in Norway showed that Willow ptarmigan (*Lagopus lagopus*) made up 41% of bird mortalities at WT, with 24% of carcasses found within 10 m of the tower base [207]. Using a BACI design, painting the lower 10 m sections of 10 towers black (noting that this colour provided contrast with the environment at this site) and comparing these with 10 control turbines, Stokke et al. [207] report a 48 [44–52]% reduction in ptarmigan collisions for the painted towers.

(6) **Setup and maintenance costs.** Implementing tower base painting during the construction phase can reduce costs and improve feasibility as there is no need to hire separate personnel and equipment after construction, and the painting can be done alongside other construction works.

(7) **Energy production losses.** There are no AEP losses associated with this approach.

3.2.3.4. Wind turbine design. WT design directly influences collision risks for bats and birds. Structural features (e.g., tower type, turbine dimensions, and auxiliary installations like meteorological masts) affect wildlife interactions with turbines. Appropriate design of WT can deter bats and birds from entering hazardous areas close to WTs. This section discusses the implications of different WT configurations, including lattice versus tubular towers, turbine size, and guyed towers, and outlines mitigation strategies—where possible—to reduce associated fatalities.

3.2.3.4.1. Lattice and tubular towers.

(1) **Detection range** & (2) **Detection probability.** NA for this method.

(3) **Species specificity.** Lattice towers may provide perching opportunities that encourage birds to approach and rest near the RSA, increasing risk of collision, especially for birds of prey. Observations at Altamont Pass WF, USA, indicated that lattice structures were frequently used as perches by raptors, especially Red-tailed hawks (*Buteo jamaicensis*) and Golden eagles [209]. Perching near the nacelle or mid-tower sections often preceded collisions, suggesting that lattice designs could elevate collision risks for certain species. This concern is supported by documented evidence of soaring birds (e.g., Griffon vultures, Common kestrels) frequently using lattice towers as perches, although about 75% of observed birds used tower sections below RSA height.

(4) **Deterrence.** Assuming that perching in the higher sections of the lattice towers increases the risk of collision, it is suggested that modifying the middle and upper sections, such as by installing physical barriers or altering the design to discourage perching, could effectively reduce fatalities by preventing birds from resting in these higher-risk areas [209].

(5) **Effect on collision fatalities.** There are very little data for an effect of WT tower design on fatalities. Although the carcass count was extremely small (total 5 fatalities), comparison between two German WF did not support the premise of greater risk for lattice towers, with 1.4 bird of prey fatalities per turbine/year at Dretzen (lattice towers) compared to 3.3 at Etzin WF (tubular towers) [210].

(6) **Setup and maintenance costs.** Turbine design reflects economics in construction and engineering. There are no separate costs identified in respect to wildlife collisions.

(7) **Energy production losses.** There are no AEP losses associated with this approach.

3.2.3.4.2. Turbine size.

(1) **Detection range & (2) Detection probability.** NA for this method.

(3) **Species specificity.** Because of individual species' behaviour, the overall impacts of WT size parameters (hub height, blade length, and power capacity rating; Fig. 11) are highly species-specific, depending on the species' flight height distributions and behaviour [25,211,212]. Taller towers have increased ground clearance (the distance between the ground and the rotor blade), reducing risk for low-flying species but increasing risk for those flying at height. For example, simulation based on GPS flight height data predicts that increasing ground clearance from 20 to 100 m is likely to reduce collision risk by 56–66% for Montagu's harrier (*Circus pygargus*) and Hen harrier (*Circus cyaneus*), but lead to a 38% increase in collision risk for the Short-toed eagle (*Circaetus gallicus*), which typically flies between 120 and 260 m [211].

(5) **Effect on collision fatalities.** Barclay et al. [213] compared bird and bat fatalities at 33 wind farm sites in North America and found that the number of bat fatalities (Hoary bat, Eastern red bat and Silver-haired bats) increased exponentially with tower height, with the greatest number of fatalities occurring at turbines ≥65 m [213]. The authors hypothesised that as turbine towers are increasing in height, they are occupying the airspace where migrating bats fly (flying at heights between 0.1 and 1

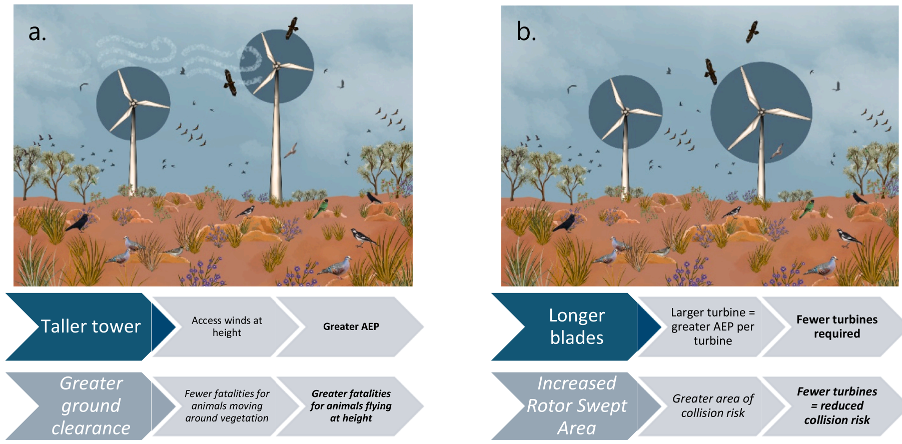

Fig. 11. Schematic showing the different effects of larger towers or longer wind turbine blades on Annual Energy Production (AEP) (blue) and fauna (grey, italics). Images: Natalie Grassi.

km), and that some bats may not echolocate during migration.

Larger capacity WTs have longer blades and therefore greater RSA (which increases as a square function of blade length), increasing collision risk overall, especially for medium- and high-flying species [211,212,214]. For example, expanding rotor diameter from 50 to 160 m increased collision risk for Red-tailed hawks and Horned larks (*Eremophila alpestris*) by 151–558%, although effects were weaker for low-flying species like Montagu's harrier [211]. Linking the increase of rated power of WTs to larger rotor diameters determines whether the collision risk for a given targeted power capacity can be mitigated by using fewer, larger turbines.

(6) **Setup and maintenance costs.** Turbine size has been driven through economies of scale in WT designs. There are no separate costs identified in respect to wildlife collision mitigation.

(7) **Energy production losses.** Larger WT have greater AEP. Increasing tower height increases hub-height wind speeds (due to wind shear in the Earth's atmospheric boundary layer), and therefore has greater commercial value (Fig. 11a). Increasing blade length and therefore RSA also increases energy gain (Fig. 11b).

3.2.3.4.3. Guyed towers. While guyed towers are not used for modern WT structures, they remain prevalent at WFs as they are used for meteorological (met) masts for wind resource assessment. The thin support cables (guys) create substantial collision hazards for birds.

(1) **Detection range & (2) Detection probability.** NA for this method.
(3) **Species specificity.** Migratory songbirds and raptors are particularly vulnerable to striking guy wires during nocturnal migration or low-visibility conditions (e.g., fog, precipitation) when the risk of collision peaks [215]. The type of lighting used on these towers also significantly impacts avian mortality, especially for nocturnal migrants.
(4) **Deterrence.** Wire marking—installing highly visible marker such as spirals, flags, or UV-reflective devices on wires—can enhance their detectability for birds in flight.
(5) **Effect on collision fatalities.** Comparison of guyed and un-guyed communication towers in Michigan, USA, reported significantly more bird mortality for guyed towers: 116–146 m guyed towers averaged 8.2 bird deaths per tower over 20 days of observations, compared with only 0.5 bird deaths for similar-height un-guyed towers (i.e., guyed towers had 16-times more bird deaths) [216]. Taller guyed towers (over 305 m) caused even more fatalities, averaging 34.7 bird deaths per tower over the same period [216]. Lighting effects also increase collision risk. The most hazardous configuration was a combination of steady red lights and flashing strobes, with an average of 12.3 bird fatalities per tower during 20-day migration periods for medium-height towers and 44 fatalities for tall towers. In contrast, towers with only flashing red lights recorded just 3.7 fatalities at medium heights, representing 70% fewer mortalities [216].

A meta-analysis of 35 field studies demonstrated that wire marking reduces bird strikes by an average 50.4% [217]. Another potential mitigation strategy for reducing bird fatalities associated with guyed towers is the use of UV illumination. Applying near-UV light at power lines resulted in 98% reduction in bird collisions and 82% decrease in dangerous flights [110]. During 19 nights with UV lighting activated, only one collision occurred, compared to 48 collisions on nights when the lights were off. This method also had a positive ‘neighbour effect’, where collisions were reduced on nearby structures not directly illuminated.
(6) **Setup and maintenance costs.** Wire marking is a cost-effective and widely used method to prevent bird collisions with power lines, which can also be applied to guyed towers on WF.
(7) **Energy production losses.** These passive strategies potentially reduce collision risk without interfering with WF operations.

3.2.3.4.4. Micro-siting and habitat modification. While WF approvals can consider species’ geographic ranges and avoidance strategies (e.g., Refs. [218,219]), WF location is usually based on engineering or production goals. The challenge in arguing for WF siting for biodiversity conservation is not helped by the fact that there is often little correlation between pre-construction biodiversity surveys and perceived risk compared with post-construction fatalities (e.g., Refs. [220–222]) (although patterns may be more apparent at a larger scale: for example, meta-analysis of 62,147 bat carcasses across 327 WF indicates larger numbers of bat carcasses of listed species at projects with summer/-maternity colonies on site [223]).

Similarly, specific placement of WT within a WF (‘micro-siting’) usually aims to maximise wind energy production and minimise fatigue loads (and associated maintenance costs) on the WT [224]. Less often is micro-siting selection based around biodiversity outcomes [225–227], despite a growing body of data indicating relevance of habitat for bat and bird activity around WTs [223] and the importance of identifying potential high-risk ‘problem’ WT sites pre-construction (e.g., Refs. [224, 228–231]). To mitigate issues with high-risk WTs, an option may be to modify the habitat immediately around the turbine, to shift bats and birds away from the hazardous area by removing foraging, roosting, or nesting resources in the area.

(1) **Detection range** & (2) **Detection probability.** NA for this method.
(3) **Species specificity.** Habitat modification has specifically targeted raptors and other large species that are attracted to regions with abundant prey or favourable hunting conditions [21]. Agricultural plains with extensive grassland areas support insect, reptile and small mammal populations that make them attractive hunting grounds for birds, and the open space (sparse vegetation) makes such areas suitable for foraging by species like kestrels and vultures [112,232]. At the Parque Eólico da Serra dos Candeeiros WF, Portugal, the Bio3 mitigation project [111] planted scrub species to increase vegetation density near turbines and suppressed other vegetation types through mowing to reduce prey availability, with the aim of reducing collision risk for the Common kestrel (*Falco tinnunculus*). Livestock grazing may also reduce vegetation cover and therefore reduce habitat for insect or small vertebrate prey, which could decrease collision risk for predatory birds, although this does not appear to have been tested, as it has for solar facilities [8].
(4) **Deterrence.** There is strong evidence for adjacent habitat influencing bat activity around WT (e.g., Refs. [231,233–235]). However, we found no published evidence for habitat manipulation as a deliberate measure to reduce bat activity around WT.
(5) **Effect on collision fatalities.** Eliminating natural vegetation around WTs, using a plough, tiller, or cultivator, thereby reducing prey availability, has effectively reduced foraging opportunities for raptors, with a 75–100% decline in Lesser kestrel (*Falco naumanni*) WT-related mortality [112].
(6) **Setup and maintenance costs.** Mowing and tilling require constant maintenance. Planting could be particularly beneficial due to its long-lasting impact with minimal ongoing maintenance.
(7) **Energy production losses.** These passive strategies potentially reduce collision risk without interfering with WT operations.

3.3. Combined approaches

Limitations of each detection system have warranted development of integrated systems such as MUSE (Multi-sensor Unstructured Surveillance Environment, DHI, Denmark). MUSE combines horizontal and vertical radar for large-scale tracking (up to 5–6 km), cameras for species-level identification within ~1 km, and acoustic sensors for detecting vocalising species [236]. All inputs are synchronised in a central platform for flight path reconstruction, altitude estimation, and species-specific identification in real time, and the system can also incorporate WT-Bird for post-collision verification.

Combining ultrasonic acoustic deterrents with curtailment may be effective in mitigating risk for bat communities. For example, increased cut-in alone reduced overall bat mortality by 42.5% at Pilot Hill WF and Kelly Creek WF (Illinois, USA), but did not reduce fatalities for Silver-haired bats, which continue to fly in windy conditions [37]. However, when curtailment was combined with ultrasonic deterrents, overall fatalities reduced by 66.9%, with 71.6% saving for Silver-haired bats [37]. For ultrasonic deterrents and curtailment in combination, collision data average 31 ± 63% reduction in mortalities (BDS: 72 ± 13% [37], NRG: −44 ± 88% [36] 25 ± 57% [40], ND: 56 ± 22% [45]).

3.4. Monitoring technology for mitigation

We also reviewed technologies that, while not directly involved in turbine curtailment, may serve complementary roles in wildlife protection at WFs (Table 1). Some of these tools provide valuable data on activity (e.g., ThermalTracker-3D [120,121], ATOM [119], ArtificialVision [118]) that can be used to understand why animals are active around WT.

There are two market-ready collision detection systems specifically designed for bird and bat monitoring at WFs. B-Finder uses thermal and video cameras (operational both day and night) installed at multiple levels on the WT tower to detect falling bats and birds within a 100 m radius, with field testing showing 95% detection efficiency [116]. WT-Bird uses highly sensitive fibre-optic vibration sensors mounted on the WT blades to detect impact events, distinguishing them from operational or environmental vibrations, and then activates thermal and daylight cameras to capture the event [117]. Field testing [237] showed the system can reliably detect impacts from objects as small as 50 g and 6.5 cm in diameter, representing small bird species. WT-Bird has also demonstrated reliable performance in offshore conditions, including extreme weather such as typhoons and salt-laden air [237].

4. Limitations of this study and future research

Before drawing conclusions from this review, it is important to recognise the limitations of this research. Firstly, although we had a good response to the OEM survey (7/16 = 44%), the response to the WF survey was low (only 2/14 = 14%). This is likely to reflect the sensitivity of the subject of bird and bat collisions for wind farm operators.

There is a lack of independent testing data and it is possible that the effectiveness of the technologies has been overestimated in technical reports from OEMs. Many studies have not included measures of error and/or confidence intervals for their results. Care therefore needs to be taken when interpreting these results, especially for fatality data where the number of collisions is very low.

Due to commercial reasons, OEMs have been reluctant to share costs of technologies, and we therefore can only present representative costs for one camera, one radar, and two wind farm operator's experience of blade painting. This remains an important knowledge gap.

There is a need for future rigorous research resulting in independent test data on anticollision technologies. As technologies mature and more products enter the market, more data should emerge, including cost data. This will allow further analysis on the effectiveness of the products and a refinement of statistical methods used in this analysis. A full economic analysis of an anticollision technology would incorporate the capital cost of the product, annual operation costs, and the costs in lost energy production due to curtailment.

5. Conclusion and recommendations

Of 52 operational and deterrent strategies or tools applied to bat and bird collision mitigation, less than half have independent test data available—especially newer or under-development technologies. This is a significant limitation to robust comparison between methods.

(1) **Detection range (Fig. 4a).** Given that this metric is vital for feasibility of shutdown-on-demand approaches, it is surprising how few data are available regarding detection ranges of the different technologies with most measurements relying on self-reporting (*) by the manufacturers. As turbine blade lengths and deceleration times increase, it will be vital to have technologies with large detection ranges. Radar systems have the greatest range, averaging 6.13 ± 3.99 km for raptors and large birds across 7 radars (2,5* records). Cameras have much shorter detection distances, averaging 0.69 ± 0.44 km for large birds over 9 cameras (16 records: 6,10*). While acoustic methods have the shortest detection distance (up to 100 m, but range depends on loudness of the bat's call), these arguably provide indication of the most immediate threat.
(2) **Detection probability (Fig. 4b).** All safety-critical measurements should have a ‘live zero’. For example, if relying on using activity to curtail a WT, then we need to know that the detector is working effectively. Comparable detection probability data are reported for 2 radars (76 ± 18% flights detected, 3 records: 2,1*), 5 cameras (80 ± 18% flights detected, 25 records: 19,6*), and 2 acoustic detectors (40 ± 13% flights detected, 2 records).

(3) **Species specificity (Fig. 4c).** We report on a range of tools that have varying specificity, from passive deterrents that are 'always on', through to targeted shutdown in response to the presence of conservation-significant bird species. Identification using radar relies on body size and aspects of flight behaviour, with correct identification for 2 radars averaging 75 ± 10% (n = 2 records: 1,1*). Cameras have greater success in correctly identifying birds (83 ± 20% accuracy across 6 cameras, 19 records: 17,2*). Species-specific echolocation calls suggests that acoustic detectors should have high potential for species discrimination; the single record we identified was 97%*.

(4) **Changes to avoidance behaviour (Fig. 4d).** The central assumption of deterrents is that they cause animals to avoid the space around the WT, and thus reduce collision risk. We found articles describing independent data for changes to behaviour for 7 ultrasonic deterrents for bats (28 ± 57%, n = 26 records), but only 1 deterrent technology for birds (DTbird; 49 ± 24%, n = 22 records). Laboratory trials testing visibility of painted blades, and field observations of behavioural avoidance, show conflicting data (−5±35%, n = 14 records).

(5) **Collision fatalities (Fig. 5).** Because turbine strike fatalities are relatively uncommon, it can be difficult to obtain sufficient carcass monitoring data to quantify effectiveness of mitigation tools. Field validation studies therefore require sufficient scale (sufficient numbers of WT and duration of monitoring) to capture a range of wildlife species, variety of potential environmental factors, and have sufficient statistical power. The type of curtailment method employed has a significant effect on mitigating collisions. Feathering, blanket, seasonal and informed curtailment result in an average 59 ± 26% (47 records) reduction in bat collisions, while smart curtailment further improves on this value (66 ± 34%, 16 records). Acoustic deterrents for bats have widely variable success (23 ± 40%, 49 records). For birds, smart curtailment triggered through visual observations (79 ± 20% reduction in fatalities, n = 2 records) or camera (66 ± 23% n = 2 records) have been successful (noting there are no data for radar detection systems). Blade painting requires further data (two successful and two unsuccessful studies to date; average 7 ± 61% n = 14 records). There have only been few trials of lighting (81 ± 24% n = 2 records) and habitat modification (86 ± 10% n = 4 records), also requiring further data.

(6) **Setup and maintenance costs.** Technology investment ranges from relatively low (e.g., blade control system adjustment and blade feathering below cut-in, power curve modification in blanket curtailment, some deterrents such as vegetation removal through mowing, or blade painting prior to construction), through to high (e.g., radar, camera, and acoustic detection systems for smart curtailment). Information on the costs of different anticollision methods were not willingly shared as part of our discussions with manufacturers. The size of a WF, terrain and other logistical issues are all considerations in terms of the numbers of devices that are required to provide adequate coverage, and therefore require site-specific assessments. For example, the Musselroe WF in Australia found a single Robin Radar MAX unit unsuccessful in meeting their Wedge-tailed eagle (*Aquila audax*) detection requirements, and the WF operators subsequently examined the potential for deploying a second radar for more complete coverage [69,70], which would have doubled the technology investment cost.

(7) **Energy production losses.** There is a general lack of data on the lost revenue due to energy production losses. Additional data on AEP losses are required to balance the economic costs of curtailment with conservation benefits (i.e. fatalities per MWh [238]) to help inform decisions in selecting mitigation approaches for wind WF.

Key recommendations arising from this study:

- **Choice of technology** varies according to the target species:
  - **Bats:** curtailment is argued to be the only proven solution to mitigate bat mortality at WTs [239], with inconclusive data for acoustic deterrents for bats, likely reflecting the complexities of sound attenuation varying with auditory signal and echolocation frequency used by each species.
  - **Migratory birds:** seasonal curtailment and informed curtailment to predict bird activity around WT can be effective. Surprisingly little validation of such approaches for mitigating collision is available.
  - **Diurnal birds:** radar- and camera-triggered shutdown detection systems have been successful in mitigating turbine strike in larger bird species, while smaller species remain difficult to detect in sufficient time to initiate shutdown-on-demand approaches. There is varying success of visual deterrents for diurnal birds, including blade painting (with conflicting data to date, and largescale field trials still running [204,205]), visual cues on tower bases [34], as well as acoustic deterrents activated in response to bird presence.
- Local environmental conditions influence bird and bat behaviour, as well as the effectiveness of technologies. For both bats and birds, site selection and possibly also targeted removal of likely feed sources around WT may be effective. More trials need to be carried out to allow generalisations.
- Integrative approaches combining multiple anticollision technologies can enhance their effectiveness. This can be a fusion of technologies working as a whole or separately serving different purposes.
- There is need for standards or best practice guidelines that employ a unified approach to assess the performance and cost of anticollision technology. This will allow comparison of technologies with the certainty that all criteria are assessed according to standardised protocols. We report here on seven metrics that could be recorded in future studies to allow for comparison between anticollision approaches: (1) detection range, (2) detection probability, (3) species specificity, (4) changes to avoidance behaviour, (5) collision fatalities, (6) setup and maintenance costs, and (7) energy production losses. Consistent reporting is also required.
- Ongoing research and development is needed to improve the performance of existing technologies and to develop new solutions that can better address wildlife protection challenges. Offset funding for environmental approvals should be set to quantify the impacts of WT on wildlife, and address some of these vital knowledge gaps.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors report financial support and article publishing charges were provided by Murdoch University. The authors report a relationship with Fortescue Ltd that includes: consulting or advisory and funding grants. All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2026.117333.

Appendices.

6.1 Appendix A – Survey

6.2 Appendix B – methods for quantifying of percentage change and 95% confidence intervals

When raw counts were available, 95% confidence intervals (CIs) were estimated using Poisson log-ratio methods; when only summary statistics were available, uncertainty was approximated from reported ranges or quartiles. Intervals were not truncated, allowing negative values where treatment and control overlapped.

Percentage changes (e.g. mortality savings, deterrence, or increases in activity or latency) were calculated as proportional differences between treatment and control conditions using the ratio of central tendency estimates. Specifically, percentage change was defined as:

$$\%\ \text{change} = \left(\frac{\text{T}}{\text{C}} - 1\right) \times 100$$

where T is the treatment value and C is the corresponding control value. Positive values indicate an increase relative to control, while negative values indicate a reduction (i.e. savings or deterrence).

When raw counts were available, treatment–control ratios were estimated assuming Poisson-distributed counts, and 95% confidence intervals (CIs) were derived using the log-ratio method:

$$SE(\text{In}\ R) = \sqrt{\frac{1}{T} + \frac{1}{C}}$$

with CIs obtained by exponentiating $\ln R \pm 1.96 \times SE$ and converting to percentage change.

When only summary statistics (e.g. medians with non-outlier ranges or quartiles) were available, central estimates were based on medians, and uncertainty was approximated using the full non-outlier ranges of treatment and control values. Lower and upper bounds of percentage change were calculated from the minimum plausible treatment–control ratio and maximum plausible ratio, respectively. These range-based intervals are descriptive and reflect variability rather than formal sampling uncertainty.

Negative percentage values were retained and not truncated, allowing overlap between treatment and control conditions to be explicitly represented.

6.3 Appendix C – Summary of field data records (excel spreadsheet)

6.4 Appendix D – Examples of validation studies

Examples of field validation studies of effectiveness of different methods for mitigating wind turbine collision risk. Knowledge gaps include robust peer-reviewed field testing for most technologies – self-reporting articles are indicated by asterisks. Values are means with ±SE, ±SD, or [95% confidence intervals] where available.

Infrastructure; Risk Mitigation strategies	Examples where tested	[a]Exp. design	Examples of effectiveness
a. Lattice towers; Roosting/nesting on the tower infrastructure, increasing collision risk			
Modify middle and upper sections, e.g., installing physical barriers to discourage perching	Altamont Pass WF [209].	CI[b]	Perching behaviour near the nacelle or mid-tower sections often preceded collisions [209].
	Dretzen (lattice towers) and Etzin (tubular towers) WF, Brandenburg, Germany [210].	CI[b]	40% reduction in breeding pairs around lattice towers, cf. 27% decline near tubular towers [210], but lattice-tower site had 69.8% fewer bird observations overall [210].
b. Guyed towers; Collision risk with the cables			
Flashing red lights	Tested at communication towers across Michigan, USA [216].	CI	**70%** fewer mortalities compared to steady red lights and flashing strobes [216].
UV illumination	2 69-kV transmission line spans crossing the Platte River, Rowe Sanctuary, Nebraska, USA. [110].	CI	Application of near-UV light resulted in a **98%** reduction in bird collisions and an **82%** decrease in dangerous flights [110].
Guy wire marking	Meta-analysis of multiple implemented treatments across transmission and distribution lines in North America, Europe, Africa, and Asia [217].	MA	An average reduction of **50.4 [40.4–58.8] %** in bird strikes.
c. Habitat modification: Natural vegetation growth attracts animal foraging activity around WT, increasing collision risk			
Tillage	Cerro del Palo, Cerro Calderón, and La Muela I WFs, Spain [112].	BA	**75–100%** decrease (range across 3 years) in Lesser kestrel (*Falco naumanni*) mortality [112].
Mowing	Parque Eólico da Serra dos Candeeiros WF, Spain.	BA	Reduction in risky bird movements within the RSA observed for Common kestrel (*Falco tinnunculus*) [111].
Planting	Parque Eólico da Serra dos Candeeiros WF, Portugal.	BA	The Bio3 mitigation project planted scrub species to increase vegetation density near turbines [111]. This form of habitat

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(*continued*)

Infrastructure; Risk Mitigation strategies	Examples where tested	[a]Exp. design	Examples of effectiveness
			modification measure could be particularly beneficial due to its long-lasting impact.
d. Turbines (blades); Collision, barotrauma			
Feathering below cut-in and **raised cut-in speed**	USA & Canada: meta-analysis of 29 implemented treatments across six WFs.	MA	Overall reduction in bat fatalities averaged of 62% [54–69%], but was as high as 91% [29]. Can be ineffective in mitigating turbine strike for species that continue to fly during high wind speeds (in which case, combining with audio deterrents can be effective). In the case of endangered bats, the USFWS prescribes avoidance by curtailing up to 6.9 m/s [4].
	Cape Nelson North WF, VIC, Australia.	BA	**54%** reduction in bat species mortality through raising turbine cut-in from 3.0 to 4.5 m/s between dawn to dusk, only had 0.16% generational loss, equivalent to 0.09% reduction in revenue [35].
Seasonal curtailment	Canada		Wind farms with an estimated annual mortality that exceeds 10 bats/turbine/year during this period are required to mitigate via operational curtailment (raised cut-in speed to 5.5 m/s) between July to September throughout the lifetime of the project [144].
Informed curtailment			
'ProBat'	35 different WF (two turbines each), Germany [123]	BA	Effectively reduced bat fatalities while maintaining high energy yields – average annual energy loss associated with ProBat-based curtailment was 1.4% [123]
Smart curtailment			
Turbine Integrated Mortality Reduction ('TIMR')	Blue Sky Green Field Wind Energy Center WF, Wisconsin, USA [128]	BA	Ultrasonic microphones mounted on the nacelle and below the rotor had an effective detection range of ~30 m. Curtailment triggered when bat calls were detected within the preceding 10 min and wind speeds <8.0 m/s **84.5%** reduction in overall bat fatalities; Eastern red bat (*Lasiurus borealis*, −82.5%); Hoary bat (*Lasiurus cinereus*, −81.4%); Silver-haired bat (*Lasionycteris noctivagans*, −90.9%); Big brown bat (*Eptesicus fuscus*, −74.2%); and Little brown bat (*Myotis lucifugus*, −91.4%). Curtailment time reduced by 48% compared to curtailment based solely on increased cut-in speed; reported energy loss 3.2% [128].
Direct visual observations	20 WF in Cádiz, Spain [63];	BA	**92.8%** reduction in Griffon vulture (*Gyps fulvus*) mortality and a **65.2%** reduction in fatalities across all soaring birds; minimal energy production losses [63].
Robin Radar	Musselroe WF (Woolnorth Renewables), Tasmania, Australia [70,100].	VS	**86%** detection (**82.5%** identification accuracy) for Wedge-tailed eagles (*Aquila audax*), but both measures highly dependent on distance [70].
IdentiFlight	Field tests at two WF (Top of the World – treatment site; and Campbell Hill – control site), USA [96].	CI VS	>**96%** detection (**≥90%** identification accuracy) of 149 Bald eagle (*Haliaeetus leucocephalus*) and Golden eagle (*Aquila chrysaetos*) (562% more birds within 1 km than observers) [96], and showed **82%** reduction in fatalities[b] [97]. Greater accuracy for larger bird species (wingspans >60 cm) typically flying individually (rather than in flocks); reduced accuracy for non-eagle species [96]. [b]But see reanalysis of the same dataset, suggesting only 50% [-159–89%] reduction (or possible increase) in the fatality rate [95].
	Wind Energy Research Cluster South, Stötten, Germany.	VS	**88%** detection of 103 Red kite (*Milvus milvus*) and Black kite (*Milvus migrans*) tracks identified by laser range finder (LRF) (**98%** identification accuracy) [98]; **83%** detection of 121 Red kite GPS tracks (**99%** identification accuracy) [98].
	Cattle Hill WF, Tasmania, Australia.	VS	**94%** identification accuracy of Wedge-tailed eagle and White-bellied sea-eagle (*Haliaeetus leucogaster*) targets; significantly lower accuracy for various non-eagle birds [99].
	Musselroe WF, Tasmania, Australia.	VS	**>92%** identification accuracy of Wedge-tailed eagles [100].
BirdVision	2WT at Weißbach WF, Baden-Württemberg, Germany	VS	12% false positive. Birds the size of a red kite or common buzzard are reliably detected by the camera system at a distance of approximately 300 m; birds flying higher than 300 m usually not detected [240].
	.	VS	**97–100%** detectability rate for raptors [OEM4**].
Bird Protection System	Modelling bird movements and speeds.	SIM	Estimated WT shutdown for **92.9%** of Red kite flights [164].
BirdRecorder	Baden-Württemberg and Saarland WFs, Germany.	VS	**99%** detection (**≥93.1%** identification accuracy) for target species [83].
BirdTrack (STRIX) Radar	Barão de São João WF, Portugal.	BA	Shutdown criteria were set for 'flocks of migratory soaring birds', 'intense migratory flux of soaring birds', 'threatened soaring bird species, and 'imminent collision risk.' Bird fatalities decreased from 30/year (when mitigation measures were triggered manually) to zero [241]. Shutdowns reduced by 86%; downtime decreased by 91%, from 1.2% to 0.2% of annual operational time [161].
ProTecBird cameras, AVES Wind Onshore anticollision system	2 WT at Gnutz-Timmaspe WF, Germany.	VS	**95–97%** detection (**87–98%** identification) of Red kites with a response radius of **385 m**, for 12,024 LRF points representing 237 Red kite flights [75,76]. **95 [92–97] %** detection (**87 [82–91] %** classification) of White-tailed eagle (*Haliaeetus albicilla*), with detection range

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Infrastructure; Risk Mitigation strategies	Examples where tested	[a]Exp. design	Examples of effectiveness
			300-1000 m, for 1860 measured LRF points from 71 White-tailed eagle flight tracks [77]
Active deterrents:			
Ultrasonic acoustic deterrents (for bats)	Pennsylvania, USA [57]; Illinois, USA [60,181]; Texas, USA [58]; Ohio, USA [36,40].	BACI or CI	Inconclusive (see Fig. 7); species specific responses; potentially also different responses to pulsing or constant signals. Sound attenuation is a major constraint; species that use high frequency echolocation can be within the RSA when their echolocation is jammed – increasing turbine strike for these species.
SafeWind	KNE Competence Centre for Nature Conservation and Energy Transition	VS	**80–100%** detectability for Black storks (*Ciconia nigra*) and Red kites (5% false positive rate) [66].
	Field testing in Mayenne, France.	VS	A false positive rate of 6% was reported initially for bat detections using the infrared configuration, improving and stabilising at around 1% after algorithm refinement [104].
DTBird	1WT at Lower Saxony.	VS	**32%** false triggers [242].
	2 WT at Smøla WF, Norway. 57 individual White-tailed eagles with GPS trackers, and video records also validated with Merlin radar system.	VS	**76–96%** detection across species, **60–88%** of approaching White-tailed eagles (57 individuals with GPS trackers, and video records also validated with Merlin radar system) altered flight paths in response to audible sound deterrents [91].
	14 WT Manzana and Goodnoe Hills WFs, USA [87,92].	CI	**20–30%** reduction in risk for Golden eagles, with effectiveness reaching up to **40%** for birds at higher pre-exposure risk [87].
		VS	Eagle-like UAV flights showed greatest detectability rate (**65%**) within 80–160 m of the turbine [87].
		VS	**63 ± 10%** detection of UAV flights as proxy of eagle-sized birds, triggering a dissuasion signal at an average of 154 m (but ranged from 100 to 240 m) [92]. **36(range 17–57)%** deterrence for all raptors (39% for buteos, 52% for golden eagles) [92].
	1 WT at Haldenstein, Switzerland [78].	VS	Effective deterrence distance was ~100 m from the speakers; collision avoidance primarily achieved through the deterrence system without any change to turbine operation [78]. Activating WT shutdown effectively prevented collisions with medium and large birds (due to curtailment processing time).
	7 WT at Manzana WF, USA [92].	VS	845 triggers of the deterrent signal from 877 detection events of an eagle-like UAV (**96%** detection); however the trial also reported another 11,928 detection events (6264 deterrent signals – i.e. **53%** false triggers), with many detections of Common raven (*Corvus corax*), other non-focal birds, some insects and other aircraft [92].
Nvbird	Combines optical detection with acoustic deterrence.		**97%** detectability and species-level identification capabilities for both bats and birds [74]
SMART	1 WT in southern England [54].		**3.4%** false positive rate of (triggered by noise), **2.2%** false negative rate; **85%** bat protection [54]. Detection accuracy depends on site-specific conditions, e.g., bat community composition, ambient ultrasonic noise, and configuration of alarm criteria. The system is also capable of functioning effectively in environments with mixed bat species or swarming behaviour, without reduction in detection performance.
Passive deterrents:			
Blade painting (1 black blade)	4 WT at Smøla WF, Norway [107].	BACI	**71.9 [61.8–79.1] %** total collision reduction (3.5 years post-painting); no White-tailed eagle collisions compared with 7 before the blade painting [107].
	7 WT at Eemshaven WF, Netherlands ('Dutch Black Blade' study) [243,244].	BACI	**No significant reduction** (2 years post-painting) [106].
Blade painting (1 red patterned blade)	4 WT at Umoya WF, South Africa [108].	BACI	**91%** reduction in total bird fatalities and a **100%** reduction in raptor fatalities (2 years post-painting), with only one bird carcass recorded versus the 11 predicted for unpainted turbines [108].
UV-reflective paint	77 WT at Foote Creek Rim WF, USA [109].	CI	**No reduction** in bird mortality compared to unpainted turbines (1.5 years post-painting), with some species showing increased fatalities at painted WT [109].

MA meta-analysis.
CI control-impact.
BACI before-after control-impact.
VS validation study.
SIM simulation.
[a] Experimental design.
[b] OBS Mitigation not applied, but comparison between WFs with different turbine design.

Data availability

Data is shared as Appendix C

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