



Mitigation Measures for Wildlife in Renewable Energy Projects

Literature review and international practice

Nov 2025

CONTENTS

i. Executive summary.....	4
ii. Methodology	6
iii. Key concepts.....	7
I OVERVIEW	12
1. Introduction.....	12
1.1 Context.....	12
1.2 Objective	13
2. Renewable energy.....	14
2.1 Overview of Renewable Energy.....	14
2.2 General Impacts of Renewable Energy.....	14
II WIND ENERGY	16
3. Overview of Wind Energy Development.....	16
4. Impacts of Wind Energy	16
4.1 Quantifying Collision Mortality.....	16
4.2 Species Most Affected	19
4.3 Types of impacts	22
5. Mitigation Measures for Onshore Wind Farms	28
5.1 Strategic Avoidance	28
5.2 Mitigation Measures During Construction	31
5.3 Operational Minimization.....	32
5.4 Design Modifications	36
5.5 Supporting Measures.....	39
5.6 Measures with limited effectiveness.....	41
III SOLAR ENERGY	43
6. Overview	43
7. Impacts on biodiversity	43

7.1 Estimated mortality	44
7.2 Species Most Affected	44
7.3 Types of impacts	45
8. Mitigation Measures to Reduce Bird and Bat Mortality	47
8.1 Strategic Site Selection	47
8.2 Mitigation During Construction	47
8.3 Panel design modifications	48
8.4 Other Mitigation Measures	48
IV KNOWLEDGE GAPS AND RESEARCH NEEDS	50
V ACKNOWLEDGMENTS	51
VI ANNEXES.....	64

i. Executive summary

This document provides science-based guidance for reducing bird and bat mortality at wind and solar energy facilities in the Czech Republic. Prepared for the Nature Conservation Agency of the Czech Republic (AOPK), the analysis synthesizes peer-reviewed literature, international methodologies, and case studies from European countries with environmental conditions and species assemblages most relevant to Czech landscapes.

The Czech Republic currently generates only 15 to 16 and a half percent of electricity from renewable sources, the lowest share among all twenty-seven EU member states. Meeting the renewable energy target will require substantial expansion of wind and solar capacity. While this renewable energy growth is essential for climate goals, poorly planned facilities create unnecessary conflicts with biodiversity conservation. This guidance document enables Czech authorities, developers, and environmental consultants to implement effective mitigation measures that allow renewable energy expansion while minimizing wildlife impacts.

For wind energy, collision mortality represents the primary conservation concern. European studies document bird fatality rates ranging from 0.4 to 13 birds per megawatt annually, with raptors, vultures, and soaring species facing highest risk due to their flight behavior and low reproductive rates. Red Kites, White-tailed Eagles, and Montagu's Harriers—all present in Czech Republic—rank among Europe's most vulnerable species. Bat mortality at wind facilities has reached crisis levels across Central Europe, with some regions experiencing population declines exceeding fifty percent over two decades. Migratory tree-roosting species including noctules, pipistrelles, and serotines comprise seventy-five to eighty percent of fatalities, with ninety percent of deaths occurring during late July through early October migration and mating periods.

The analysis identifies several mitigation approaches with demonstrated effectiveness supported by rigorous scientific evidence. Site selection provides the foundation for all subsequent mitigation. Avoiding placement in protected areas, known migration corridors, and raptor breeding territories prevents conflicts before construction begins. Strategic siting can reduce collision risk by orders of magnitude compared to poorly located facilities, making this the most cost-effective mitigation strategy.

Operational curtailment emerges as the most effective mitigation for bats. Blanket curtailment strategies that raise turbine cut-in speeds or implement seasonal shutdowns achieve sixty to eighty-five percent mortality reductions at only half to three percent annual energy production losses. Curtailment works because bat activity concentrates during specific weather conditions.

More sophisticated approaches use predictive algorithms incorporating temperature, wind speed, and real-time weather data to curtail only when conditions indicate high bat activity.

Detection-based shutdown systems represent emerging technology for protecting birds, particularly large soaring species. Camera systems use artificial intelligence to identify approaching birds and trigger automatic turbine shutdowns within thirty-five to forty-three seconds. Field studies document fifty to eighty-five percent mortality reductions for golden eagles, white-tailed eagles, and vultures at facilities using these systems. However, detection technologies face important limitations. Smaller, faster-flying species may not be detected at sufficient distances for effective response. Detection systems work best for large raptors in areas with known high collision risk but should not be considered universal solutions.

Visual deterrents like blade painting show mixed results. At Norway's Smøla site, painting one blade black cut bird mortality by 70%, likely by improving blade visibility. Yet trials in the Netherlands found no effect, possibly due to background or species differences. In South Africa, red-striped blades reduced raptor deaths by up to 86%, suggesting pattern design may be key. Given its low cost but inconsistent success, blade painting could be considered for Czech sites with high raptor activity, though not as a primary mitigation measure.

Acoustic deterrents show limited effectiveness despite commercial availability. Multiple recent controlled studies document that ultrasonic bat deterrents provide minimal additional mortality reduction beyond curtailment alone.

For solar facilities, effective mitigation prioritizes site selection (degraded lands/brownfields over natural habitats), agrivoltaic systems combining panels with grazing and native vegetation, wildlife-friendly fencing, and habitat management supporting pollinators and farmland birds. Anti-reflective coatings show promise but require further validation.

No published Czech wind farm mortality studies were identified in this review, creating urgent need for baseline monitoring at representative sites spanning Bohemian and Moravian landscapes. Without local mortality data, Czech authorities must rely on estimates from other Central European countries that may not fully represent local species assemblages or collision risks.

This document provides the scientific foundation for requiring evidence-based mitigation measures as standard conditions for wind and solar facility permits. By implementing the mitigation hierarchy of avoidance through site selection, mortality reduction through curtailment, and ongoing monitoring to verify effectiveness, Czech Republic can expand

renewable energy capacity while protecting its biodiversity obligations under European law and national conservation priorities.

ii. Methodology

This analysis synthesizes peer-reviewed scientific literature, grey literature, and expert consultation to provide evidence-based guidance applicable to Czech Republic renewable energy development. Given the absence of published Czech wind farm mortality studies, the methodology prioritized identifying transferable knowledge from countries with environmental conditions and species assemblages most relevant to Czech landscapes.

Literature Search

Systematic searches of scientific databases and Google Scholar covered publications from 2000-2025, prioritizing the past two decades when renewable energy development accelerated and mitigation technologies matured sufficiently to generate robust effectiveness data. Search strategies combined infrastructure terms (wind turbine, solar panel, photovoltaic) with impact descriptors (bird/bat mortality, collision, mitigation) and functional taxonomic groups (raptors, soaring birds, tree-roosting bats, migratory bats).

Geographic focus emphasized Central and Northern European research—particularly Germany, Poland, Austria, Slovakia, and Scandinavia. German research was prioritized for methodological rigor and long-term monitoring datasets. Spanish studies contributed valuable raptor and bat mitigation data despite climatic differences. North American research was selectively incorporated where it offered transferable insights into detection technologies, curtailment algorithms, and solar polarized light impacts.

The analysis concentrated on onshore wind and ground-mounted solar installations as the technologies most relevant to Czech Republic's geography and development plans, excluding offshore wind and concentrated solar power.

Expert Consultation

Professional consultations with renewable energy and wildlife specialists from Sweden, Netherlands, Ireland, Czech Republic, Spain, and South Africa provided access to unpublished monitoring data, technical reports not indexed in academic databases, and practical implementation knowledge from operational facilities. Experts included academic researchers

conducting long-term monitoring studies, environmental consultants preparing impact assessments, and technology developers implementing detection and deterrent systems at commercial wind facilities.

Grey Literature

Grey literature including technical reports, monitoring studies, and government documents underwent evaluation for credibility and methodological adequacy before inclusion. Reports produced by established conservation organizations including IUCN, BirdLife International, and WWF were included based on organizational reputation for scientific rigor and peer-review processes these institutions employ for major publications.

Language and Translation

Literature was reviewed primarily in English, supplemented by Spanish-language publications. Studies in German, Swedish, Czech, and other Central European languages were incorporated through artificial intelligence translation tools (notebooklm.google.com; claude.ai). This report was originally written in English and translated into Czech by Marie Bostlová (AOPK ČR).

Updating frequency

Given rapid technological development and expanding research, this guidance should be reviewed and updated every 2-3 years to incorporate new evidence.

iii. Key concepts

- **Aposematic coloration**

Warning color patterns in nature (typically combinations of red, black, yellow, or white) that signal danger or toxicity to potential predators.

- **BACI (Before-After-Control-Impact)**

An experimental monitoring design that compares indicators measured before and after an intervention (e.g., commissioning of a power plant) at the affected site, while simultaneously monitoring a non-affected control site. This helps distinguish intervention effects from natural environmental changes.

- **Barotrauma**

Internal tissue damage caused by rapid air pressure changes near rotating turbine blades.

- **Barrier effect**

Obstruction to animal movement patterns causing detours and increased energy expenditure.

- **Biomimetic patterns**

Design approaches that mimic biological warning signals or natural patterns to influence animal behavior.

- **Buffer**

The distances that regulations or guidelines specify wind turbines should be set back from key habitat features.

- **Collision Risk Modeling (CRM)**

Mathematical models estimating collision probability based on flight behavior, avoidance rates, and turbine specifications.

- **CSP – Concentrated Solar Power**

Solar thermal technology that uses mirrors or lenses to concentrate sunlight onto a receiver, generating temperatures up to 800°C to produce steam for electricity generation. Unlike photovoltaic systems, CSP facilities create high-flux zones that can cause direct burn mortality to birds and attract insects.

- **Cumulative impacts**

The combined effects of multiple stressors or developments on wildlife populations over time and space, where individual project impacts may appear acceptable but collectively cause significant harm.

- **Cut-in speed – minimum wind speed for turbine startup**

The minimum wind speed at which the rotor of a wind turbine begins to spin and generate electricity. For mitigation purposes, this threshold can be temporarily increased, preventing the turbine from starting under conditions of high collision risk.

- **Curtailment – limitation or complete stop of operation**

Temporary reduction or full stop of wind turbine (or other power plant) operation to reduce the risk of wildlife injuries.

- **Echolocation**

Biosonar system bats use for navigation and prey detection using ultrasonic calls.

- **EIA – Environmental Impact Assessment**

A project-level assessment that evaluates the potential environmental effects of a specific proposed development before construction approval.

- **Feathering – blade pitch adjustment**

The process of rotating the wind turbine blades along their longitudinal axis to change their angle relative to the wind. Full feathering positions the blades edge-on to the wind, minimizing aerodynamic drag and stopping rotation. Feathering is used both for turbine shutdowns (e.g., for maintenance or collision risk reduction) and for protecting the turbine in high wind conditions.

- **Functional habitat loss**

Reduction in usable habitat due to avoidance behavior rather than physical destruction.

- **Gleaning bats**

Bat species that hunt prey from surfaces rather than in flight

- **Hub – central part of a wind turbine**

The central component of a wind turbine that connects the rotor blades to the main shaft. It transmits the mechanical energy from the rotating blades to the nacelle for conversion into electricity.

- **IBA (Important Bird Area)**

Sites identified by BirdLife International as critical for bird conservation

- **IWT — Industrial Wind Turbines**

Large-scale wind turbines designed for commercial electricity generation, typically with rotor diameters of 80-160 meters and hub heights of 80-200 meters.

- **Lake effect / polarization effect (from PV plants)**

An optical phenomenon in which smooth, dark, and shiny surfaces (e.g., photovoltaic panels) reflect polarized light and mimic water surfaces. This can attract aquatic insects and birds, which may then collide with panels or their structures.

- **Macro-siting**

Strategic site selection at landscape/regional scale to avoid high-risk areas

- **Micro-siting**

Fine-scale turbine placement within a selected wind farm site to minimize collision risk.

- **Migration corridor/bottleneck**

Concentrated routes used by large numbers of migrating birds

- **Mitigation hierarchy**

A sequential decision-making framework that prioritizes actions to address biodiversity impacts: Avoid → Minimize → Compensate for biodiversity impacts.

- **Motion smear**

Visual phenomenon where fast-moving turbine blades appear as transparent blurs, reducing visibility to birds

- **Nacelle**

The housing at the top of the turbine tower containing the generator and mechanical components.

- **Open-space foraging bats**

Bat species adapted for hunting in open air at heights overlapping with turbine rotors.

- **Phototaxis**

Attraction response to light sources.

- **PV – photovoltaic**

Solar technology that directly converts sunlight into electricity using semiconductor materials (typically silicon).

- **Rotor swept zone (RSA)**

The circular area covered by rotating turbine blades where collision risk is highest.

- **SCADA**

Supervisory Control and Data Acquisition system for automated turbine management.

- **Scavenger removal – scavenger bias / carcass persistence**

The rate at which carcasses are removed by scavengers (birds, mammals, insects) from the monitored area. Measured by placing carcasses and observing how long they remain detectable. Used to correct mortality estimates.

- **SEA – Strategic Environmental Assessment**

A systematic process for evaluating the environmental consequences of proposed policies, plans, or programmes before they are approved.

- **Searcher efficiency – carcass detection efficiency**

The percentage of carcasses within the area that a monitoring worker (or dog) actually finds during a survey. Determined by trials where carcasses are placed beforehand in known positions. The value is used to correct estimates of true mortality.

- **Sensitivity mapping**

Geographic identification of high-risk zones based on species distribution and behavior.

- **Shutdown-on-demand – (SDOD)**

An operational regime in which a turbine is stopped immediately after detection of the presence of target protected species or risky behavior (e.g., via radar, thermal camera, or visual observation).

- **Smart curtailment**

Adaptive control of turbine stops based on a combination of current environmental conditions (wind, temperature, day/night) and detection of target species through sensors or risk models. The aim is to minimize wildlife mortality with the least possible loss of energy production.

- **Soaring birds**

Species using thermals and updrafts for energy-efficient flight (raptors, storks, cranes).

- **Volant**

An animal that is capable of flight, typically used to refer to birds, bats, and insects.

I OVERVIEW

1. Introduction

1.1 Context

Czech Republic ranks among the EU's weakest performers in renewable energy deployment, with only 15-16% of electricity from renewable sources—the lowest share among all 27 member states. Wind energy is particularly underdeveloped at just 371 MW capacity (approximately 200 turbines), covering merely 1% of electricity consumption and placing Czech Republic 25th-26th in the EU. Solar capacity has grown more substantially to approximately 5,100 MW by end of 2024 (Costanzo, Brindley & Tardieu, 2025).

This performance contrasts sharply with regional neighbors. Poland expanded from similar starting points to reach 10,276 MW wind capacity—30 times Czech levels—following regulatory reforms in 2019. Germany operates 63,000 MW (185 times Czech capacity), while Austria achieved 3,977 MW (Costanzo, Brindley & Tardieu, 2025).

The National Energy and Climate Plan (*The National Energy and Climate Plan of the Czech Republic*, 2024) sets binding 2030 targets requiring dramatic expansion: wind capacity must increase from 371 MW to 1,500 MW (4x growth), while solar must reach 10,100 MW. Achieving the wind target demands adding 180-190 MW annually—more than 10 times the 2024 installation rate of 16 MW (Costanzo, Brindley & Tardieu, 2025).

The Acceleration Zones Law aims to reduce approval timelines from 7-9 years to 12 months, creating tension between expansion speed and adequate ecological assessment. Under Law 114/1992 on Nature and Landscape Protection, wind projects require mandatory Natura 2000 assessment and landscape protection consent, with authority to prohibit developments threatening protected species. Projects cannot proceed if negative impacts on protected areas are not excluded or adequately mitigated. Furthermore, reactive mitigation implemented after construction proves far more costly and less effective than strategic planning integrated into current expansion blueprints.

This guidance responds to dual legal obligations: EU Nature Directives requiring "favorable conservation status" for protected species versus binding 2030 renewable targets in the December 2024 NECP. Only integrated planning with robust, evidence-based mitigation standards can reconcile these requirements

1.2 Objective

This document serves as technical guidance for evaluating and implementing mitigation measures to reduce bird and bat mortality at wind turbine installations and photovoltaic solar facilities in the Czech Republic. The analysis provides an overview of impact mechanisms, evaluating effectiveness of available mitigation measures, and identifying information gaps that constrain evidence-based decision-making.

The primary objective is to synthesize current scientific understanding of renewable energy impacts on flying vertebrates and translate this knowledge into practical recommendations for Czech conditions. The document examines onshore wind energy development and photovoltaic installations, covering the two renewable technologies experiencing most rapid expansion under Czech Republic's targets.

The analysis serves multiple user groups with distinct information needs by providing evidence-based guidance on wildlife mitigation at energy facilities. For AOPK, it offers scientific justification and effectiveness ratings to evaluate mitigation proposals during permitting and EIA processes. Developers gain insights into cost-effectiveness, production impacts, and implementation costs to integrate suitable measures early and avoid delays or retrofits. Environmental consultants can use species-specific data, technical parameters, and monitoring protocols to design robust mitigation plans and critically assess emerging technologies.

The scope covers direct mortality through collision with turbine blades or solar infrastructure, indirect effects including habitat loss and fragmentation, displacement through avoidance behavior, and barrier effects disrupting migration or daily movement patterns. While the primary focus addresses impacts to birds and bats as the taxa most severely affected by wind and solar development, the document acknowledges broader biodiversity concerns including effects on insects, terrestrial mammals, and ecosystem processes where evidence warrants discussion.

The document addresses knowledge gaps and research priorities to guide future monitoring and impact assessment efforts. By identifying where current evidence remains insufficient for confident recommendations, the analysis helps Czech authorities and research institutions prioritize studies most likely to improve decision-making.

2. Renewable energy

2.1 Overview of Renewable Energy

The European Union has emerged as a global leader in renewable energy deployment, with wind and solar energy reaching unprecedented capacity levels by the end of 2024.

Total EU solar photovoltaic capacity stands at 338 GW, following record additions of 65.5 GW in 2024, (SolarPower Europe, 2024) while wind energy capacity reached 231 GW (210 GW onshore, 21 GW offshore), with 12.9 GW added during the year. Combined, wind and solar now generate approximately 27-28% of EU electricity, contributing to renewables achieving a 46.9% share of total EU electricity generation in 2024, up from 44% in 2023. This substantial growth has enabled the EU to avoid approximately 460 million tonnes of CO₂ emissions between 2019-2024 and reduce fossil fuel dependence to a historic low of 29% of electricity generation (Costanzo, Brindley & Tardieu, 2025).

Globally, renewable energy capacity reached 4,448 GW by end of 2024, with renewables accounting for 92.5% of all new electricity generation capacity additions. Solar photovoltaic led global growth with 452-597 GW added in 2024 alone, bringing cumulative global solar capacity to 2.2 TW, while wind additions totaled 113 GW globally, reaching 1.1 TW cumulative capacity. Together, wind and solar now provide 15% of global electricity generation, up from approximately 2% in 2010 (SolarPower Europe, 2024; Costanzo, Brindley & Tardieu, 2025)

The Czech Republic presents a different situation within the broader European landscape. With renewable energy accounting for only 15-16.5% of electricity generation—the lowest share among all EU-27 member states—the country lags considerably behind its European peers (Costanzo, Brindley & Tardieu, 2025). By the end of 2024, installed capacity reached approximately 4.2-4.8 GW of solar PV alongside a modest 350 MW of wind energy. Recognizing this gap, the Czech National Energy and Climate Plan (NECP), submitted in December 2024, sets ambitious new targets: achieving 30.1% renewable energy in gross final energy consumption by 2030.

2.2 General Impacts of Renewable Energy

Wind and solar energy development generates substantial environmental benefits, particularly in climate change mitigation and air quality improvement. The displacement of fossil fuel generation yields significant greenhouse gas emissions reductions, with each dollar invested in

energy transition producing USD 2-5.5 in benefits from reduced health and environmental externalities according to IRENA 2025 analysis. Solar PV and onshore wind produce lifecycle emissions of 4.6-55.6g CO₂/kWh compared to substantially higher footprints from coal and natural gas generation (Hamed & Alshare, in press).

The EU's renewable energy growth between 2019-2024 avoided approximately €59 billion in fossil fuel imports while eliminating 460 million tonnes of CO₂ emissions. However, renewable energy development also presents environmental challenges requiring careful management: Land use requirements and biodiversity impacts constitute a primary concern. For humans, visual landscape impacts and wind turbine noise contribute to community annoyance, though systematic reviews find no conclusive evidence linking wind noise to serious health outcomes beyond sleep disturbance and annoyance itself (Schmidt & Klokke, 2014).

The social and economic impacts of wind and solar development demonstrate substantial positive contributions alongside localized challenges. **Employment generation** represents a major benefit, with the global renewable energy sector employing 16.2 million workers in 2023, including 7.2 million in solar PV and 1.5 million in wind energy (IRENA, 2024). **Economic cost competitiveness** has improved dramatically, with solar Levelized Cost of Energy (LCOE) declining to USD 0.043/kWh globally (90% reduction since 2010) and onshore wind at USD 0.033/kWh (70% reduction since 2010), making renewables the lowest-cost sources of new electricity generation.

II WIND ENERGY

3. Overview of Wind Energy Development

Wind energy development is globally recognized as a fundamental strategy for combating climate change by promoting a necessary transition away from fossil fuels and reducing greenhouse gas (GHG) emissions. Considered one of the most promising renewable energy sources, the installed capacity of wind power has been expanding rapidly worldwide, with significant growth seen across continents, particularly in Asia, Europe, and the USA (Dai et al., 2015; Estellés-Domingo & López-López, 2025; Katzner et al., 2025).

Although wind energy is widely regarded as one of the healthiest and most environmentally friendly energy options compared to fossil fuels, the increasing scale of onshore and offshore wind farms creates conflicts with wildlife conservation (Saidur et al., 2011; Gartman et al., 2016a; Ferrer et al., 2022). The primary and most immediate impacts of wind power facilities on biodiversity involve the direct mortality of flying vertebrates, especially birds and bats, due to collisions with turbine blades and infrastructure. Addressing these adverse effects through strategic planning, avoidance, minimization, and compensation measures is crucial to ensuring that the expansion of wind energy is sustainable and aligns with biodiversity conservation goals (Garcia-Rosa & Tande, 2023; Katzner et al., 2025).

4. Impacts of Wind Energy

Wind farms are a clean and efficient source of renewable energy. However, they cause negative impacts on biodiversity. The species most directly affected by wind farms are birds and bats, primarily due to their high vulnerability to collisions.

4.1 Quantifying Collision Mortality

4.1.1 Standardization of Mortality Metrics

Bird and bats collision mortality at wind facilities is reported using two primary metrics: fatalities per turbine per year (birds/turbine/year) and fatalities per megawatt per year (birds/MW/year). Mortality rates expressed per megawatt (MW) are generally considered a more standardized measure than rates per turbine, as turbine capacity (wattage) varies substantially (ranging from 0.5 MW to over 5 MW) (Atienza et al., 2014; Garcia-Rosa & Tande,

2023; Lentini, Lumsden & van Harten, 2025). European studies predominantly report per-turbine rates, while North American and other international studies more commonly use per-MW rates. Throughout this document, mortality figures are presented as published in source studies without metric conversion.

4.1.2 Methodological Factors Influencing Mortality Rates

The substantial variability in the following reported collision rates reflects methodological differences as much as biological variation. Three primary factors explain the substantial variability in reported collision rates:

- Carcass persistence: scavenger removal rates vary from hours to weeks depending on local predator communities
- Searcher efficiency: human observers typically detect only 9-65% of small bird carcasses
- Search protocols: radius, frequency, individual bias.

Modern monitoring increasingly employs trained detection dogs achieving 69-96% efficiency regardless of vegetation type (Lentini, Lumsden & van Harten, 2025), while thermal drones show promise for inaccessible terrain. These methodological advances partly explain why recent studies report higher mortality than older research.

4.1.3 Estimated collision mortality

(a) Birds

The fatality rate of birds at wind farms varies widely depending on location, turbine characteristics, and methodology used for estimation. Published estimates globally show significant variation.

- **Per Turbine Rate:** Bird fatality estimates range from less than one up to 21 birds/turbine/year. The highest published rate of 21 fatalities/turbine/year was derived from data in Belgium (Dai et al., 2015; Lentini, Lumsden & van Harten, 2025)
- **Per Megawatt (MW) Rate:** Estimates range from 0.4 to 13 birds/MW/year
 - Overall regional fatality rates in the U.S. ranged from a minimum of 1.0 to a maximum of 4.5 birds per MW per year, with an average of 2.3 birds/MW/year (Bennun et al., 2021; Katzner et al., 2025)
 - South Africa documented rate is 2.0 birds/MW/year (Perold, Ralston-Paton & Ryan, 2020)

- Japan estimated annual mortality 0.4-2 birds/MW/year (Lentini, Lumsden & van Harten, 2025)
- Mexico 9-13 birds/MW/year (Lentini, Lumsden & van Harten, 2025)

Bird fatality rates at European wind farms are highly variable, influenced by factors like location, species composition, and mitigation measures, generally showing a wide range of documented mortalities (Rydell et al., 2017; Garcia-Rosa & Tande, 2023)

- **Spain** reports some of the highest collision rates globally, particularly in southern regions and along major migration routes (Farfán et al., 2023).
 - The highest reported rate in Spain reached 64.26 birds/turbine/year at the El Perdón wind farm in Navarra (Atienza et al., 2014).
 - **Average Regional Rates:** A study of 20 constructed wind farms in southern Spain reported a mean bird mortality rate of 1.33 birds/turbine/year for all species (Dai et al., 2015; Ferrer et al., 2022)
- **Belgium:** Data from Belgium contributed to the upper end of the global range of individual fatality rates, with an estimate of 4-23 birds/turbine/year (Drewitt & Langston, 2006). Most of the recorded fatalities involve seabird species.
- **Germany.** The German research project, "PROGRESS" (Grünkorn, 2016), estimated annual collision rates per turbine for specific common species. These estimates are significantly below the general 5–10 bird/turbine/year average, likely because they are species-specific calculations:
 - Common Buzzard (*Buteo buteo*): 0.433 individuals/turbine/year.
 - Red Kite (*Milvus milvus*): 0.130 individuals/turbine/year.
 - White-tailed Eagle (*Haliaeetus albicilla*): 0.035 individuals/turbine/year.
 - Northern Lapwing (*Vanellus vanellus*): 0.597 individuals/turbine/year.

Country	Fatalities (birds/turbine/year)	Source
Sweden	~5–10	(Rydell et al., 2017)
Netherlands	~28	(Krijgsveld et al., 2009)
Belgium	~21 (avg.; range ~2–43)	(Everaert, 2014)
UK	~6	(Drewitt & Langston, 2006)
Germany	~3–8	(Grünkorn, 2016)
Spain	1.33–64.3	(Atienza et al., 2014; Ferrer et al., 2022)

Table 1. Bird fatalities per wind turbine per year from wind farms across European countries

(b) Bats

Bat mortality rates also vary significantly by geographic location and specific habitat context, but the overall cumulative toll is substantial.

The estimated annual losses of bats killed by wind turbines are about 30,000 bats per year in the United Kingdom, about 50,000 bats per year in Canada, more than 200,000 bats per year in Germany, and more than 500,000 bats per year in the United State (Bennun et al., 2021). The meta-analysis by Rydell et al. (2010) for Northwestern Europe reported habitat-specific ranges, with a maximum of 20 bats per turbine per year. These figures contrast with Spain’s 26–41 and Romania’s 30 bats/turbine/year, indicating that sites located along migratory can experience fatality rates up to an order of magnitude higher than those in temperate Europe.

Country	Fatalities (bats/turbine/year)
North America	12 (Voigt et al., 2022).
Germany	14 (Voigt et al., 2022).
Northwestern Europe	
-Open farmland	0–3
-Complex agricultural landscapes	2–5
-Coastlines, forested hills, and ridges	5–20 (Rydell et al., 2010)
Sweden	10-12 (Rydell et al., 2010)
France	14 (Merlet et al., 2025)
Spain	26-41 (Sánchez-Navarro et al., 2023)
Romania	30 (Măntoiu et al., 2020)

Table 2. Bats fatalities per wind turbine per year from onshore wind farms.

4.2 Species Most Affected

4.2.1 Birds

(a) High-Risk Species in Europe

The wind energy literature consistently emphasizes the high vulnerability of raptors and soaring birds to collisions. Raptors, such as eagles and vultures, are prone to collision due to their soaring flight behavior, long life spans, and low reproductive rates, which makes their populations highly sensitive to increased adult mortality.

Key species frequently studied in Europe include:

- **White-tailed Eagle (*Haliaeetus albicilla*):** Known to be susceptible to collisions, displacement, and reduced breeding success in Norway (Smøla), Sweden, Finland, and Germany (Heuck et al., 2019; May et al., 2020).
- **Red Kites (*Milvus milvus*):** It is considered one of the most susceptible bird species to collisions in Germany. A synthesis of post-construction data from 69 facilities across north-east Germany estimated that ~3% of the breeding population was being killed by collisions annually (Gartman et al., 2016a; Bose et al., 2020a).
- **Montagu's Harrier (*Circus pygargus*):** Faces collision risk, particularly if wind farms are built in core breeding areas. Occasional collision fatalities are reported throughout Europe (Hernández-Pliego et al., 2015; Schaub et al., 2020)
- **Lesser and Common Kestrel (*Falco naumanni*; *F. tinnunculus*):** Frequently reported collision victim in Spain and Germany (Ferrer et al., 2022). Their hunting behavior (hovering while searching for prey) highly increases its collision risk.
- **White Stork (*Ciconia ciconia*):** Despite being identified as one of Europe's most vulnerable soaring birds, White Stork-specific collision rates from Central European wind farms remain unavailable. Swiss modeling shows the species has moderate sensitivity to additional mortality, with 1% additional mortality (Schippers et al., 2020).
- **Common Buzzard (*Buteo buteo*):** A German study calculated 7,800-8,500 annual fatalities in northern Germany alone—representing 7% of the regional breeding population (Grünkorn, 2016).
- **Cranes (*Grus grus*):** Cranes are species with high wing loading (a high-risk factor) and poor maneuverability, which puts them at higher risk of collision (Bennun et al., 2021).

(b) Collision Mortality of Other Bird Groups

While raptors dominate collision literature, other groups are also affected:

- **Small passerine birds** are also vulnerable to collisions but are often under-sampled in studies because they are difficult to find and are quickly scavenged. In the extensive Cadiz study in Spain, a total of 1,352 dead passerine birds were recorded from 2008 to 2020, yielding a mortality rate of 0.386 passerines per turbine and year (Ferrer et al., 2022). Small passerines represented 62.5% of the 4,975 mortalities recorded across 35 studies at IWT farms (Parisé & Walker, 2017)
- **Large Waterbirds/Ground-Nesting Birds:** Species with high wing loading (low maneuverability) are at high collision risk with turbines or transmission lines.
- **Grouse (Tetraoninae):** Research on Tetraonidae reveals displacement and habitat loss as primary impacts, with surprisingly limited collision mortality documentation despite multiple European studies. Vulnerable to tower collisions (Zeiler & Grünsachner-Berger, 2009; May et al., 2020).

4.2.2 Bats

Bat species vulnerable to collision are generally those adapted for foraging insects in open spaces (Thaxter et al., 2017; Gaultier et al., 2020). These high-risk species are morphologically and physiologically adapted for open-air life, featuring long and narrow wings, and using high-intensity echolocation calls. They commonly fly at heights that overlap with the rotor-swept zone (Rydell et al., 2010; Voigt et al., 2024).

(a) Associated Meteorological Conditions

Bat mortality at wind turbines shows extreme temporal concentration, with 90% of fatalities occurring between late July and early October in temperate Europe, coinciding with autumn migration and reproductive swarming. August constitutes the month of highest risk in virtually all European studies. A minor secondary peak (10% of annual mortality) occurs in April-June during spring migration (Rydell et al., 2010; Amorim, 2012; Salguero et al., 2023).

The meteorological factors associated with elevated mortality are consistent throughout Europe: low wind speeds (<5-6.5 m/s), when bats are most active but turbines are still rotating; temperatures above 10-15°C, optimal for insect activity and therefore for bats; absence of precipitation; and low to moderate relative humidity. Mortality is concentrated during nighttime hours, especially the first 4 hours after sunset, when foraging activity is at its peak (Rydell et al., 2010).

(b) High-Risk Species in Europe

Mortality at wind turbines does not affect all European bat species equally. 98% of fatalities involve open-space foraging species belonging to four genera, while the remaining 2% corresponds to species that typically fly below rotor height (Rydell et al., 2010). At least 20 European bat species have been confirmed dead from collisions, and 21 are considered potentially affected (Rodrigues et al. 2008).

High-risk species share common ecological traits: open-space foraging with long, narrow wings adapted for fast flight; high wing loading that requires speed; flight altitudes of 5-150 meters that overlap with the rotor sweep zone (typically 100-200 m in modern turbines); and frequently migratory behavior with displacements of hundreds or thousands of kilometers. Forest-dwelling species with slow, maneuverable flight (long-eared bats, horseshoe bats) mostly avoid collisions due to their different ecology (Rydell et al., 2010; Salguero et al., 2023).

- **Genus *Pipistrellus*** dominates mortality statistics, representing approximately 70% of all fatalities in Spain and over 50% in most European studies (Salguero et al., 2023). Common pipistrelle (*P. pipistrellus*) is the most affected individual species in Central and Western Europe, reflecting its population abundance and high-altitude flight habits (Richardson et al., 2021). Nathusius's pipistrelle (*P. nathusii*) suffers disproportionate rates in migratory corridors, especially Baltic coasts and the North Sea, where it constitutes the main long-distance migratory species (Măntoiu et al., 2020). Isotopic analyses confirm that individuals killed in France, Germany, and Romania originate from northeastern European breeding populations located hundreds or thousands of kilometers away (Merlet et al., 2025).
- **Genus *Nyctalus*** represents the second most vulnerable group. Common noctula (*N. noctula*) constitutes 28% of fatalities in some databases and shows population declines of 53% in France between 2006-2023, potentially linked to wind farm mortality (Salguero et al., 2023; Merlet et al., 2025). Genetic studies reveal that 28-30% of killed noctules are long-distance migrants, with 82% being reproductive females (Merlet et al., 2025). This sex bias has serious demographic implications for source populations.
- **Genus *Eptesicus***, serotine bat (*E. isabellinus* and *E. serotinus*) appear consistently in databases throughout Europe (Rydell et al., 2010; Sánchez-Navarro et al., 2023). Northern bat (*E. nilssonii*) is the most affected species in Scandinavia and the Baltic region (Rydell et al., 2010).
- ***Vespertilio murinus*** (parti-coloured bat) is consistently identified as a high-risk species for collision at wind farms across Europe. Specific collision data compiled up to December 2009 documented 47 dead *V. murinus* bats across Germany (Rydell et al., 2010).

Bats of the genus *Myotis* account for only 2% of fatalities despite their high abundance across Europe. Their typical flight behavior—usually below 20 meters—keeps them largely outside the rotor-swept zone. Similarly, *Plecotus* spp. (long-eared bats), *Rhinolophus* spp. (horseshoe bats), and *Barbastella* spp. exhibit minimal mortality (Rydell et al., 2010).

4.3 Types of impacts

The impact of wind farms on birds and bats ranges from direct physical harm to indirect disturbances that affect habitat quality, behavior, and population dynamics. These impacts occur during all phases of wind farm development, including construction, operation, and dismantling (Atienza et al., 2014; Garcia-Rosa & Tande, 2023)

4.3.1 Direct Mortality

(a) Birds

The most immediate and obvious impact of wind energy on birds is fatality from collisions with turbine blades.

Birds are killed when they fly into the rotating blades within the rotor swept zone (Dai et al., 2015). Collision risk is higher for birds that soar at the same altitude as the blades, such as large raptors (e.g., eagles and vultures) and large broad-winged birds (e.g., storks and cranes), as their flight behavior conflicts with the wind resource used by turbines (Hunt, 2002; Barrios & Rodríguez, 2004)

Although raptors attract the most attention as collision victims, small songbirds actually comprise the largest proportion of wind turbine fatalities. Species that remain in an area for extended periods—whether for breeding, overwintering, or stopover habitat—face significantly higher collision risk compared to birds merely migrating through the landscape (Erickson et al., 2014; Rydell et al., 2017; Bennun et al., 2021).

Collisions are influenced by site-specific factors (e.g., placing turbines on mountain ridges or steep slopes) (Singh et al., 2016), turbine design and layout, and specific behaviors (such as foraging, courtship, or territorial fights) (Percival, 2005; May, 2015; Grünkorn, 2016).

But collisions can also be with static structures at wind farm facilities represent another component of wildlife mortality.

These static structures include the turbine towers, nacelles, and associated power or transmission lines (Marsh, 2007; González et al., 2016). Collisions with turbine towers have been almost exclusively observed in low-flying ground-nesting birds, such as the willow ptarmigan, black grouse, and capercaillie (Zeiler & Grünschachner-Berger, 2009; Stokke et al., 2020). However, birds have also been recorded colliding with turbine towers even when the blades are stationary (Zeiler & Grünschachner-Berger, 2009; Stokke et al., 2020; Lentini, Lumsden & van Harten, 2025).

(b) Bats

Direct mortality through collision with rotating blades is the most visible and widely documented impact of wind energy on bats globally. Wind turbines are now recognized as one of the leading causes of observed mortality of bats worldwide (Frick, Kingston & Flanders, 2020).

Bats are killed by physical contact, suffering **blunt-force trauma** when colliding with the fast-moving rotor blades. Fatalities are closely linked to the movement of the rotors; there is no evidence that bats are killed by non-moving turbine components (Rydell et al., 2010; Hein & Schirmacher, 2016).

For years, there was debate whether barotrauma (internal hemorrhaging caused by sudden pressure changes near the blades) or direct collision with the blades constituted the primary cause of death (Kunz et al., 2007). Current scientific evidence clearly establishes that 90-95% of deaths result from direct traumatic impact, while barotrauma contributes less than 10% and possibly only 5% (Lawson et al., 2020).

Forensic studies by Rollins et al. 2012 found that 73% of 262 bats from wind farms presented lesions consistent with trauma, while only 6% showed ruptured eardrums (an indicator of barotrauma) in the absence of concurrent trauma. The computational fluid dynamics research by Lawson et al. 2020 demonstrated that pressure changes near the blades are 80 times lower than the lethal threshold, concluding that barotrauma does not explain a significant number of fatalities. The Romanian study by (Măntoiu et al., 2020) documented 15 cases of barotrauma versus 34 of blunt-force trauma in a sample of 166 bats.

This clarification has important implications for mitigation: given that direct collision is the dominant mechanism, successful strategies must focus on reducing the probability of encounters between active bats and rotating blades, which is effectively achieved through increased cut-in speed (curtailment) during periods of high bat activity.

4.3.2 Habitat Loss and Degradation

(a) Birds

Wind energy projects can also cause impacts through the physical footprint of the infrastructure and through behavioral responses of birds that reduce the effective usable area of their habitat (Kahler et al., 2004; Smallwood & Thelander, 2008; Dai et al., 2015).

Construction of wind turbines, access roads, and associated facilities results in habitat transformation or clearance (Dai et al., 2015; Bennun et al., 2021) The land occupied suffers a significant reduction in its natural values and is no longer available to birds that previously used it. This loss stems from civil-engineering work, such as foundation excavation, earth movements, and the installation of necessary infrastructure.

Although the direct physical footprint of turbines and access roads typically accounts for only 2–5% of the total project area, the overall facility extends the area affected (Drewitt & Langston, 2006). Associated infrastructure such as roads and power lines contributes to a substantial loss of natural habitats; in Spain, it is estimated that each new wind farm generates around 10 kilometers of new tracks, decreasing local landscape quality (Atienza et al., 2014).

The installation of turbines also entails land conversion, which is particularly damaging in biodiversity-rich areas with little existing infrastructure, where it can lead to the loss and degradation of irreplaceable habitats (Marques et al., 2020; Katzner et al., 2025). During construction, the removal of surface vegetation exposes soil to erosion by wind and rain, while heavy machinery causes soil compaction, burrow collapse, and the crushing of small terrestrial fauna, making this phase one of the most harmful for non-volant species (Lovich & Ennen, 2013). A typical 3-5 MW onshore turbine requires a permanent foundation of 380-640 m², with main crane hardstands adding another 1,200 m² (30m × 40m) per turbine that remains throughout the operational lifetime (Guan, 2022).

Wind farms create physical barriers that disrupt animal movement patterns, affecting both long-distance migration routes and daily movements between foraging and resting areas. For migratory soaring birds, this results in functional habitat loss (Marques et al., 2020). When birds encounter large turbine arrays, they must alter their flight paths to avoid the obstacles, forcing them to travel greater distances (Drewitt & Langston, 2006; Lentini, Lumsden & van Harten, 2025).

(b) Bats

Historically, wind energy development concentrated in open and semi-open landscapes where favorable wind resources, existing infrastructure, and straightforward permitting converged. Yet escalating renewable energy targets are now driving turbine placement into forested terrain and areas often supporting high biodiversity.

Forest clearing for turbine installation permanently converts 0.36 hectares per megawatt in forest habitats, with an additional 1.14 hectares temporarily disturbed. A typical 2.5-megawatt turbine thus directly eliminates 3.68 hectares of forest (Voigt et al., 2024). This deforestation results in the destruction of important foraging habitats, such as tree cavities and standing deadwood, affecting forest-dependent bats.

But the spatial footprint of wind energy development exceeds its physical infrastructure. French researchers monitoring 207 hedgerow sites across 29 wind farms discovered that bat activity declined continuously from 1,000 meters down to turbine bases, with gleaning bats showing 53.8% activity reduction and fast-flying species declining by 19.6% within this radius (Barré et al., 2018).

Wind farms systematically disrupt landscape connectivity for bats. Italian spatial analyses revealed that 54% of existing wind farms interfere with important bat corridors, while 72% of planned developments would create additional fragmentation (Roscioni et al., 2014). These non-lethal effects functionally eliminate habitat for forest specialist bats, fragment migratory corridors across international borders, and have contributed to documented population declines of 53% over 17 years for common noctule bats (*Nyctalus noctule*) in Germany (Merlet et al., 2025).

GPS tracking of common noctule bats in Germany revealed that males make detours around large wind parks rather than flying through them, demonstrating genuine barrier effects (Roeleke et al., 2016). While these detours prove bats can navigate around obstacles, the energetic costs accumulate: forced detours increase flight distances and energy expenditure during critical periods like reproduction and pre-hibernation fattening. For migratory species traveling thousands of kilometers, the proliferation of wind farms along flyways creates an obstacle course with population-level implications.

4.3.3 Displacement Effects

(a) Birds

Disturbance and Avoidance: Displacement varies by species and location. For example, studies have shown raptors may avoid nesting within a 500-meter radius of wind farms (Pearce-Higgins et al., 2009).

1. In Portugal, the installation of wind turbines caused black kites (*Milvus migrans*) to avoid 3%–14% of their previously used habitat in the area (Marques et al., 2020).
2. Studies with White-tailed Eagles (*Haliaeetus albicilla*) at the Smøla wind farm in Norway indicated that the presence of turbines caused displacement from the facility footprint, which subsequently reduced their breeding success in the area (Dahl et al., 2012; May et al., 2013)
3. Large waterbirds like swans, geese, and cranes are observed to have low collision rates, likely due to strong avoidance behaviours (Rydell et al., 2017). Cranes, during

migration, have been reported to be displaced up to 5 km away from wind farms (Tolvanen et al., 2023).

4. For grassland songbirds, wind turbine noise (which often contains low frequencies similar to traffic noise) can directly interfere with acoustic signals vital for survival. Experimental results show that wind farm noise suppresses territorial defense behavior in the European robin (*Erithacus rubecula*) (Zwart et al., 2016)

(b) Bats

The avoidance of wind turbines by bats has been observed for various species and functional guilds, both on farmland (Barré et al., 2018; Leroux et al., 2022) and at forested sites (Ellerbrok et al., 2022; Gaultier et al., 2023)

The lowered activity of bats in proximity to wind turbines is not explained by depletion of local populations from mortality by wind turbines, because avoidance has also been reported for species at low risk of collision, such as forest specialist bats (Ellerbrok et al., 2022). For example, in German temperate forests, narrow-space foraging bats—primarily *Myotis* species and long-eared bats—avoided turbines over distances of at least 450 meters, with activity declining 77% when turbines operated at high wind speeds (Ellerbrok et al., 2022). Finnish boreal forest studies found *Myotis* species required distances ≥ 800 meters from turbines to maintain normal activity levels (Gaultier et al., 2023).

It is likely that the displacement of bats is caused by turbine-generated noise as forest specialist bats only showed avoidance of operating wind turbines at relatively high wind speeds (Ellerbrok et al., 2024). While turbine operational noise (below 2,000 Hz) cannot directly mask bat echolocation calls (20,000-120,000 Hz) due to fundamental frequency separation, it directly overlaps the 100-3,000 Hz frequency range of prey-generated sounds—such as insect wingbeats, walking, and chewing—that gleaning specialists rely upon for hunting (Guest et al., 2022).

Beyond acoustic disturbance, light pollution from aviation warning systems creates additional displacement effects that vary dramatically by species. Light-averse species such as *Myotis* show strong avoidance of artificial lighting at distances up to 50 meters even at illuminance levels below one lux, with avoidance persisting after lights are extinguished. Lesser horseshoe bats exhibit particularly extreme sensitivity, with LED lighting disrupting commuting routes and restricting access to foraging grounds. The spatial scale of light-driven avoidance can extend 600-1,000 meters from illuminated infrastructure for sensitive species.

4.3.4 Attraction (only bats)

Paradoxically, aviation warning lights on wind turbines can attract other species of bats through multiple mechanisms. Experimental studies demonstrate that migratory bats exhibit positive phototaxis (direct attraction) to specific wavelengths, particularly green (520 nm) and red (631 nm) light, but not warm-white light. This attraction occurs independently of foraging opportunities, as bat activity increased 50-73% during light exposure beyond the echolocation detection range for insects (Voigt et al., 2017, 2018).

While some evidence suggests bats forage opportunistically around lights where insects aggregate (Foo et al., 2017), comprehensive reviews conclude that direct phototaxis rather than insect-mediated foraging is the primary driver for the migratory tree-roosting species that comprise 75-80% of fatalities (Guest et al., 2022).

Tree-roosted bat species can also be attracted to wind turbines by mistaking them for tall trees. Turbines resemble tree trunks and crowns, and they create similar airflow patterns that bats use for orientation, especially at low wind speeds when blades move slowly. As a result, bats approach turbines to look for roosts, mates, or insects, showing behaviors such as circling, diving, and inspecting the tower and nacelle at close range (Cryan et al., 2014; Hein & Schirmacher, 2016).

5. Mitigation Measures for Onshore Wind Farms

No single mitigation measure is universally effective. Optimal biodiversity protection requires a site-specific combination of measures informed by pre-construction surveys, species present, and local risk factors. The avoidance-first strategy aligns with the mitigation hierarchy principle, where preventing impacts is prioritized over minimizing or compensating for them.

5.1 Strategic Avoidance

Site selection represents the most effective and cost-efficient approach to minimizing wind energy impacts on biodiversity. By identifying and avoiding high-risk areas during the planning phase, developers can prevent most potential conflicts with birds and bats before they occur. Strategic spatial planning reduces wildlife mortality, decreases regulatory risks, and avoids costly post-construction mitigation requirements (Bennun et al., 2021; Katzner et al., 2025).

5.1.1 Pre-Construction Risk Assessment

Risk assessment is the foundation of effective site selection. This process requires multi-year, multi-season baseline surveys to characterize the presence, abundance, and behavior of birds and bats in proposed wind farm locations. Pre-construction surveys should ideally span a minimum of two years to account for inter-annual variation in species occurrence and migration patterns (Parisé & Walker, 2017). Survey methodologies must include breeding bird surveys during the reproductive season, migration monitoring, and bat activity monitoring. These data inform collision risk modeling (CRM), which mathematically estimates collision probability based on flight height distributions, species-specific avoidance rates, and turbine specifications (Thaxter et al., 2017).

5.1.2 Macro-siting: Exclusion Zones and Buffer Distances

Macro-siting is the process of evaluating geographic areas to select sites where biodiversity impacts are inherently minimized. This process should be guided by tools such as Strategic Environmental Assessments (SEA) and Sensitivity Mapping to identify and exclude high-risk ecological zones (Gartman et al., 2016a).

The objective of macro-siting is to avoid areas where wind infrastructure is likely to cause significant impacts, particularly direct collisions or habitat displacement. It is the most effective strategy for mitigating the adverse impacts of onshore wind energy development on biodiversity, particularly concerning birds and bats (Drewitt & Langston, 2006).

(a) Areas to Avoid

International evidence consistently demonstrates that avoiding protected areas, including Natura 2000 sites, Special Protection Areas (SPAs), and Important Bird Areas (IBAs) prevents 80-95% of conflicts (Gartman et al., 2016a). Specific exclusions should include:

- **Migratory Corridors and Bottlenecks:** Wind facilities should be planned away from major migration corridors and migratory bottlenecks (Barrios & Rodríguez, 2004; De Lucas et al., 2008; Smallwood & Thelander, 2008)
- **Core Breeding Areas:** Development must be precluded from core breeding areas for vulnerable species, which remains the most important mitigation measure for groups like Montagu's Harriers (Schaub et al., 2020).
- **Topography Attractive to Soaring Birds:** Siting should avoid ridges and areas of orographic uplift. These topographical features attract soaring raptors because they deflect air upwards, creating updrafts used for flight, which in turn places them at high risk of collision (Santos et al., 2022).

- **Key Habitat Elements:** For both bats and birds, key features like major feeding, roosting, and resting areas, wetlands, rookeries, waterbodies, and water courses must be avoided. Large river valleys used by migratory bats should be also excluded (Gartman et al., 2016a).

(b) Buffer Distances

The term ‘buffer’ is used to describe the distance that turbines must be set back from key habitat features and resources, such as nesting sites. Buffer distances vary depending on the species group involved, the conservation status of affected populations, turbine dimensions, and local topographic features that influence flight behavior.

Table 3 presents recommended minimum buffer distances for various taxonomic groups and habitat types, based on empirical evidence from displacement studies and documented collision patterns.

Species/Group	Protected Feature	Recommended Distance
Bats	Important habitats (woodlands, hedgerows, waterbodies)	Minimum 500 m ^{1,2}
	Large bat colonies (caves)	More than 5 km away ²
	Forests/Migration corridors	No construction ²
Gleaning and fast-flying bats	Hedgerows	At least 1km ³
Large Eagles	Nests/Communal Roosts	1-3 km ^{4,5,6}
Red Kite	Nesting sites	At least 1 km ⁶
White-tailed Eagle	Nesting sites	At least 2 km ⁴
Peregrine Falcon	Foraging/Nesting Area	2 km to 4 km ⁷

¹(Reusch et al., 2023);²(Voigt et al., 2024);³(Barré et al., 2018);^{4,5,6}(Balotari-Chiebao et al., 2016; Bose et al., 2020b; Salomon, Drechsler & Reutter, 2020);⁷(Rydell et al., 2017).

6.1.3 Micro-sitting

Even after selecting a suitable general location with appropriate buffers from sensitive sites, the precise placement of individual turbines within the wind farm boundary significantly influences collision risk. Micro-sitting involves optimizing turbine layout to minimize wildlife exposure while maintaining energy production efficiency. This process requires detailed understanding of local topography, habitat features, and species-specific movement patterns within the development area.

(a) Turbine Layout and Arrangement

- **Corridors and Alignment:** Turbine groups should be arranged to provide corridors between clusters that are aligned with main flight trajectories, and to avoid alignment perpendicular to expected flight paths (Drewitt & Langston, 2006; Bennun et al., 2021).

Schaub et al. 2020 used high-resolution GPS tracking of Montagu's Harriers (*Circus pygargus*) to quantify collision risk at wind turbines. Their analysis revealed that harriers adjusted flight paths to avoid turbine clusters but still faced elevated collision risk when turbines were densely arranged. The study emphasized that layout optimization can reduce but not eliminate risk for species that forage within wind farm boundaries.

- **Infrastructure Minimization:** The overall development footprint should be reduced (e.g., by siting turbines close together) (Drewitt & Langston, 2006). Crossing a wind farm with a single line of wind turbines is easier for wildlife than crossing farms with several consecutive rows. When turbines are very close together, the risk for wildlife moving between them is greater (Refoyo Román, Olmedo Salinas & Muñoz Araújo, 2020).

Substations and maintenance buildings should be sited to minimize the creation of perching opportunities for raptors near turbines. While raptors sometimes perch on turbine towers themselves, adjacent infrastructure that provides more comfortable perching sites can increase time spent near turbines and consequently elevate collision risk.

(b) Turbine Size - Repowering

The relationship between the size of wind turbines and animal fatalities is complex, generally showing that while larger turbines may kill more individual animals (absolute mortality), they often result in lower mortality rates relative to the amount of energy produced (megawatts) (Rydell et al., 2017).

- **For birds, mortality per MW decreases with larger turbines:** Fewer large turbines kill fewer birds overall than many small turbines generating the same energy, making repowering beneficial for raptors (Gartman et al., 2016a).
- **For bats, the pattern is reversed or neutral:** Mortality per MW remains consistent or slightly increases with larger turbines because taller towers (now up to 200m in Europe) reach the flight altitudes of migratory bats that previously flew above smaller turbines. One repowering study documented bat fatalities increasing nearly 14-fold at new tall turbines despite bird deaths decreasing (Gartman et al., 2016a,b).

5.2 Mitigation Measures During Construction

Avoidance through scheduling is the most effective construction mitigation strategy. Operators should time construction activities to avoid sensitive periods in wildlife lifecycles - particularly bird breeding seasons (March-August), bat maternity colony periods, migration windows for both birds and bats, and amphibian breeding seasons (March-June) (Bennun et al., 2021).

Effective implementation requires detailed site-specific knowledge and coordination. Ecological surveys are needed to identify which species use the site and when their sensitive periods occur - this varies regionally and by habitat type. Close collaboration between construction managers, engineers, and environmental specialists is essential to balance project timelines with ecological constraints (Bennun et al., 2021).

5.3 Operational Minimization

5.3.1 Curtailment Measures for Bats

Curtailment, defined as purposely reducing energy production by stopping turbine blades from spinning, is the most frequently studied and consistently effective mitigation measure identified.

Curtailment measures are the most effective form of operational minimization currently available to reduce bat fatalities at onshore wind farms (Voigt et al., 2024). It operates by restricting turbine operations during conditions associated with elevated bat activity. Two primary mechanical approaches are employed.

(a) Feathering Blades

When environmental conditions fall below risk thresholds, turbine blades are "feathered" — pitched parallel to the wind direction so they generate minimal torque and rotate slowly or not at all. This approach allows turbines to remain mechanically ready for rapid restart when conditions change while preventing the high-speed blade rotation responsible for most bat casualties. Studies demonstrate that feathering alone can reduce bat fatalities by approximately one-third with negligible loss of electricity generation (Behr et al., 2017).

(b) Increased Cut-In Speed

The cut-in speed represents the minimum wind velocity at which turbines begin generating power. Standard cut-in speeds typically range from 3-4 m/s, but bat activity peaks occur predominantly below 6 m/s. By raising the cut-in speed to 4-6 m/s during high-risk periods, operators prevent turbine operation during the wind conditions when bats are most active. Empirical evidence across Europe and North America demonstrates that increasing the cut-in speed by 1.5-3.0 m/s above normal operational parameters can achieve 50% or greater reductions in bat mortality (Lentini, Lumsden & van Harten, 2025).

European curtailment strategies have evolved toward multi-parameter approaches. These parameters include:

- **Wind speed** (measured at nacelle height): Curtailment triggered when wind speed falls below 5.0-6.0 m/s.
- **Temperature**: Curtailment activated when temperature exceeds 10°C (bats inactive during cold conditions).

- **Season:** Curtailment applied April through October in temperate Europe, corresponding to the period between emergence from hibernation and autumn swarming.
- **Diel period:** Curtailment restricted to the period from 30 minutes before sunset until sunrise, when bat flight activity occurs.
- **Precipitation:** Curtailment suspended during rainfall, as bats avoid flying in precipitation.

A Croatian wind farm study (Rnjak et al., 2023) achieved a 78% reduction in bat fatalities by curtailing turbines (turbine height 85 m; rotor blade 51 m) when wind speeds dropped below 5.0-6.5 m/s during the high-risk season (mid-July to October). The curtailment operated nightly from sunset to sunrise. Researchers found 98% of bat activity occurred above 11°C and 97.5% occurred without precipitation

(c) Energy production and economic impacts

Blanket curtailment protocols typically incur 1-4% annual energy production (AEP) losses, with most studies clustering at the lower end of this range (Voigt et al., 2024).

In a simulation study exploring the impacts of different curtailment strategies on annual energy production across the USA, Maclaurin et al. 2022 predicted that increasing cut-in speeds to 6.0 m/s from July-October would result in a 1.3% reduction in annual energy production at the national scale.

The Netherlands offshore study (Boonman, 2018) reported 12% losses for optimized curtailment (5-6 m/s, August 25-October 10), though offshore wind regimes differ substantially from Central European onshore conditions.

(d) Smart and adaptive curtailment algorithms

Smart curtailment using technology recovers 50-100% of energy losses compared to blanket approaches while maintaining equivalent or superior mortality reduction (Rabie et al., 2022)

- **US smart curtailment systems** include the TIMR (Turbine Integrated Mortality Reduction) platform documented by Hayes et al. 2019. Using real-time acoustic detection coupled with 8.0 m/s wind speed thresholds, TIMR achieved 84.5% species-specific mortality reduction (74-91% across 5 species) with $\leq 3.2\%$ annual revenue loss and 48% less curtailment time (hub height 80 m; rotor diameter 82 m) than standard blanket protocols (Rabie et al., 2022).
- In **Europe**, some algorithms have been developed with the same purpose, such as Chirotech® (www.biotope.fr) and ProBat (www.probat.org). ProBat (Germany) integrates real-time weather data with predictive algorithms to determine curtailment necessity on a continuous basis. The system allows operators to balance conservation objectives with energy production through transparent, reproducible decision-making protocols.

- An alternative detection approach using small radar units is being piloted by Dopplium (www.dopplium.com) in the Netherlands and Denmark. Unlike acoustic systems that depend on bat echolocation calls, radar technology detects bat presence within approximately 100 meters of turbines regardless of vocalization behavior, potentially addressing detection gaps when bats fly silently. Field trials with energy companies are currently underway.

6.3.2 Curtailment measures for birds

Bird curtailment differs fundamentally from bat mitigation due to avian behavioral ecology, flight patterns, and visibility. While bats exhibit predictable activity patterns linked to meteorological conditions, bird collision risk varies with species-specific behaviors, migratory phenology, and unpredictable movements (Rydell et al., 2017).

Curtailment efforts for birds primarily focus on large, vulnerable species like raptors and soaring birds. These species are often impacted by collisions because they frequently fly within the rotor-swept zone and may have reduced maneuverability (Santos et al., 2022).

Two primary operational approaches have emerged to address collision risk: Seasonal curtailment and Shutdown-on-Demand (SDOD). Seasonal curtailment targets periods when collision risk is elevated, such as spring and autumn migration pulses when large numbers of birds travel through specific corridors and flyways, or during breeding seasons when raptors concentrate hunting activity near wind farms. In contrast, Shutdown-on-Demand (SDOD) represents a reactive, real-time mitigation strategy where turbines are stopped immediately upon detection of high-risk priority species entering the collision zone. SDOD systems rely on either trained human observers stationed at wind farms or automated detection technologies utilizing radar, camera-based artificial intelligence, acoustic sensors, or combinations thereof.

(a) Effectiveness data and mortality reductions

Spanish studies provide the most extensive effectiveness evidence. De Lucas et al. 2012 documented 65% Griffon Vulture (*Gyps fulvus*) mortality reduction at Tarifa region wind farms (hub heights 106-90 m; rotor diameters 56-90 m) using human observers with SDOD, incurring only 0.07% annual energy loss (average 6 hours 20 minutes curtailment per turbine per year). A subsequent multi-site study across 269 turbines at 20 wind farms (hub height range 60-84m; rotor diameter range 54-88m) achieved >60% mortality reduction for large soaring birds (storks, raptors) with 0.51% energy loss (Ferrer et al., 2022).

(b) Detection technologies

- **Camera-based systems with artificial intelligence** represent the most mature detection technology. **IdentiFlight**[®] (Boulder Imaging, USA) deploys 8 wide-field cameras plus 1 high-resolution stereo camera in 360° coverage, detecting flying objects at ranges up to 1 km. The system's neural network processes 200+ image attributes, classifying detections within 5 seconds against a library of >100 species with 98% protection accuracy. Field validation at Wyoming wind farms (hub height 80 m ; rotor diameters 82,5-101 m) shows 6% false negative rates (9 of 149 eagles missed) and 28% false positive rates (287 of 1,013 non-eagles misclassified as eagles), with detection rates approximately 6-7 times higher than human observers (McClure et al., 2021). With 520+ installations globally across 6 continents, IdentiFlight provides the most extensive operational dataset, though current systems operate daytime only.

Detection-to-safe-passage response times average 35-43 seconds: 5 seconds for detection-to-classification (IdentiFlight), followed by 30-38 seconds for turbine slowdown to $\leq 2-3$ rpm safe rotor speeds. Systems integrate directly with SCADA (Supervisory Control and Data Acquisition) networks for automated curtailment without human intervention, with customizable rulesets including alarm zones, mass migration algorithms, and decision trees. Operators can program shutdown levels from individual turbines to clusters to entire wind farms.

False positive management presents an ongoing challenge. IdentiFlight's 28% false positive rate translates to unnecessary shutdowns reducing operational efficiency, though continuous AI neural network improvements progressively reduce misclassification. Operational targets aim for $\leq 1\%$ energy production losses from SDOD systems, substantially lower than blanket curtailment approaches.

- **DTBird**[®] (Liquen Consultoría Ambiental, Spain) offers modular configurations with HD 360° daylight cameras plus optional thermal imaging for night operations. Operating since 2009 with 500+ units at 110+ wind farms across 16 countries DTBird represents the most widely deployed European system. Norwegian validation studies (May et al., 2012) documented 86-96% detectability for target species.
- **Radar systems** complement cameras for mass detection and night operations. Robin Radar MAX[®] (Netherlands) provides 3D avian radar with simultaneous tracking of thousands of birds, detecting small songbirds at 2-3 km and geese at 5-6 km. Others radar-based systems are MERLIN[®] (DeTect Inc., USA) and MUSE system (DHI, Denmark).

(c) Species-specific effectiveness

Raptors (eagles, kites, buzzards, vultures) show the highest curtailment responsiveness due to predictable soaring behavior and larger body sizes enabling detection at safe distances. Golden Eagles demonstrate 63-85% protection (Huso & Dalthorp, 2023), and Griffon Vultures 65-93% (Spain) (de Lucas et al., 2012; Ferrer et al., 2022).

Large soaring birds including storks and cranes benefit from mass migration detection via radar, with Spanish and Portugal multi-site studies showing 60% reductions (Tomé et al., 2017; Ferrer et al., 2022).

Limitations emerge for smaller, faster-flying species (harriers, falcons, songbirds) where detection distances may be insufficient for 35-43 second response times.

The synthesis of peer-reviewed evidence from 2015-2025 demonstrates operational curtailment as a mature, cost-effective mitigation strategy achieving 50-85% mortality reductions for priority species at 1-3% energy costs.

5.4 Design Modifications

5.4.1 Visual Deterrents

The use of visual deterrents and measures to increase the visibility of wind infrastructure are categorized as minimization techniques aimed at improving a flying animal's ability to detect and avoid collision risk.

(a) Blade Painting

Blade painting emerges as the most cost-effective passive visual deterrent based on field studies. The inspiration came from laboratory studies, particularly involving the American Kestrel (*Falco sparverius*), suggesting that painting one of the three rotor blades black could minimize motion smear and recommended this pattern for field testing to determine efficacy (Hodos, 2003).

The first dedicated *in situ* field experiment using a Before-After-Control-Impact (BACI) approach at the Smøla wind-power plant in Norway demonstrated a significant reduction of over 70% in the annual fatality rate for a range of birds at the painted turbines (4 out of 68), relative to unpainted control turbines (hub height 70m; rotor diameter 80m). This BACI design with 4 painted and 4 control turbines revealed species-specific effectiveness: 100% reduction for white-tailed eagles (6 deaths before treatment, 0 after) and 70-87% reduction for raptors generally (May et al., 2020).

The effectiveness stems from reducing "motion smear"—a visual phenomenon where fast-moving objects appear as transparent blurs to avian eyes. Painting creates dark streaks in the sky that diurnal raptors with superior visual acuity can perceive, enabling collision avoidance.

However, a follow-up BACI study in the Eemshaven wind farm in the Netherlands found no statistically significant effect of the black blade on bird fatalities (including songbirds, gulls, and waders). A possible explanation for this discrepancy is that the single black blade lacked sufficient contrast against the busy background in the Dutch location (Kleyheeg-Hartman et al., 2025).

Laboratory studies have further advanced pattern design by exploring biomimetic approaches. Recent experiments with captive Great Tits tested aposematic warning patterns combining red, black, and yellow—colors. Birds showed greater aversion to these biomimetic patterns and took significantly longer to approach targets compared to uniform white, red-striped, or single black blades, suggesting that contrasting patterns could exploit birds' innate aversion to warning coloration (Hancock et al., 2025).

A 4-year field trial was conducted in South Africa using two broad Signal Red stripes on one blade (rotor diameter 100 m), at four turbines in a species-rich environment. The red color design was influenced by regulatory constraints from aviation authorities, while the patterns were based on two lab experiments by (McIsaac, 2001; Hodos, 2003). This patterning resulted in a significant and median 80% decline in fatalities and an approximate 87% reduction for raptors at the patterned turbines compared to expected pre-treatment fatality rates (Simmons, 2025).

(b) Tower and Base Painting

Painting the bottom 10 meters of the turbine towers at the Smøla wind farm reduced collisions for Willow Ptarmigan (*Lagopus lagopus*) by 48%. This technique helps to increase contrast for low-flying species, especially where the white tower base typically blends with surrounding snow cover (Stokke et al., 2020).

An investigation in Germany suggested that using a green-colored gradient on the tower base fading upwards reduced collisions compared to all-grey or white towers, which is hypothesized to be significant for breeding birds that may not see light-colored turbines as obstacles when taking off from the ground nearby (Gartman et al., 2016a).

5.4.2 Acoustic Deterrence

While acoustic warning systems show behavioral effects in laboratory settings, peer-reviewed evidence from operational wind farms remains scarce for bird-specific applications (Thady, Emerson & Swaddle, 2022).

The DTBird system deployed across Central Europe integrates acoustic deterrents with camera detection, broadcasting species-specific distress calls and warning sounds at 4-8 kHz—optimized for avian hearing above background wind noise. But no published peer-reviewed studies provide specific bird mortality reduction percentages from these commercial deployments.

Bats naturally tend to avoid noise, whether from natural sources (like high frequency sounds from turbulent water or insects) or anthropogenic sources (like traffic noise). This avoidance occurs because ambient noise can impair a bat's use of echolocation for orientation or prey detection, mask sounds made by insect prey, or simply create a disturbing airspace (Gilmour et al., 2020).

Nacelle-mounted ultrasonic devices broadcasting 20-120 kHz frequencies at 120 dB aim to jam bat echolocation or create acoustic discomfort (Weaver et al., 2020), but effectiveness varies dramatically by species and site.

Trials in North America were successful in reducing the number of bat fatalities. For instance, at the Los Vientos wind farm in Texas, USA, acoustic devices resulted in a 50% reduction in overall bat fatalities, including a 54% reduction in fatalities for the Brazilian free-tailed bat (*Tadarida brasiliensis*) and a 78% reduction for the hoary bat (*Lasiurus cinereus*) (Weaver, 2019). Illinois studies showed more modest results of 29-32% reduction in 2014-2015 (Romano et al., 2019).

However, 2025 research from Ohio (Clerc et al., 2025) revealed ultrasonic deterrents doubled mortality for eastern red bats—the high-frequency calling species most commonly killed at U.S. wind farms. This negative effectiveness coefficient suggests deterrents may disorient or attract certain bat species rather than repel them, potentially through sensory confusion or by attracting insect prey responding to ultrasound.

Furthermore, acoustic deterrent systems can cause negative ecological impacts by displacing bats from important foraging areas, commuting routes, or roosting sites, potentially leading to habitat loss, barrier effects, and reduced access to critical resources; additionally, the acoustic signals may induce stress responses similar to those caused by anthropogenic noise (Gilmour et al., 2020).

5.5 Supporting Measures

5.5.1 Habitat Management

The principle underlying habitat management is straightforward: minimizing prey availability and foraging opportunities near turbines reduces the time animals spend in the rotor sweep zone, thereby decreasing collision risk.

(a) On-site Habitat Alteration

- **Reducing rodent populations:** Minimize food resources and availability within the wind facility area to discourage raptors from hunting there has been proved as effective strategy (Garcia-Rosa & Tande, 2023). Short vegetation maintenance, elimination of burrow substrate, access road management, and perch removal reduce rodent population establishment.

Tilling the area around the base of the most problematic turbines reduced fatalities of the Lesser Kestrel (which preys on Orthoptera) by 75–100% across three sites in Spain (average reduction of 86%) (Pescador, Gómez Ramírez & Peris, 2019)

This measure displaces birds and may negatively impact other wildlife. If the area is not significantly modified, birds may still revisit it.

- **For bats,** maintain cleared buffers of 50-100m between forest edges and turbines, remove potential roost trees (large trees with cavities) within 200m of turbines, and carefully manage hedgerows and linear features that channel bat movement toward turbines, though this must balance habitat connectivity needs (Roeleke et al., 2016; Richardson et al., 2021).

(b) Off-site Habitat Enhancement

- Creating or enhancing habitat away from wind farms can redistribute wildlife activity to safer areas. Documented examples include establishing alternative foraging areas for raptors through grassland management that supports prey populations beyond turbine zones; constructing wetlands for waterfowl at locations removed from wind farm flight paths; and installing artificial nest platforms or boxes for raptors and bats in areas away from collision risks.
- Paula et al. 2011 observed golden eagles favoring zones with restored rabbit populations in Spain. To reduce collision risk, facilities should ensure prey is more abundant in enhancement areas than near turbines, as Rasran et al. 2008 found higher raptor fatalities where food availability around tower bases was greater.

Site selection and spatial planning, implemented through comprehensive risk assessment, appropriate buffer distances, strategic micro-siting, and active habitat management, can

prevent 60–80% of potential wind farm impacts on birds and bats. This avoidance-first approach is not only the most effective mitigation strategy but also the most economically efficient, as it eliminates the need for expensive operational mitigation measures and reduces regulatory liability. However, even optimally sited wind farms will not entirely eliminate wildlife impacts, necessitating the implementation of additional minimization measures.

5.5.2 Aviation Lightning

Turbines must be marked with obstruction lights for aviation safety—typically flashing red or white lights—but these mandatory lights can inadvertently attract nocturnal migrants, potentially increasing collision risk. The effects, however, are highly species-specific and inconsistent across studies, complicating mitigation recommendations.

For **birds**, research indicates that nocturnally migrating species show differential attraction to light wavelengths: red (54%) and white (60-81%) lights cause substantially higher orientation responses compared to blue (4-5%) and green (12-27%) lights (Poot et al., 2008). Towers using only flashing lights produce significantly fewer bird fatalities than those with combined steady and flashing lights, leading to recommendations for flashing safety lights during poor visibility periods and preferential use of shorter wavelength radiation to decrease collision risk (Gehring, Kerlinger & Manville II, 2009).

Bat responses present a more complex picture with phylogenetic and geographic variation. Migrating bats exhibit phototaxis toward specific wavelengths—particularly red and green light—but not toward warm white light, though these patterns vary among species and regions (Voigt et al., 2017, 2018). Studies examining individual lit versus unlit turbines within facilities found no clear increase in bat mortality at lit turbines (Arnett et al., 2008). However, this finding may be misleading, as obstruction lights could attract bats to entire wind farms at the kilometer scale relevant to bat visual acuity and navigation, potentially altering flight behavior with erratic and circular patterns near turbines.

Given these uncertainties and species-specific responses, general recommendations remain elusive. Flashing lights over steady lights and shorter wavelengths over red appear generally preferable for reducing bird impacts, though the optimal approach for minimizing combined bird and bat mortality requires further research.

5.6 Measures with limited effectiveness

While certain mitigation measures have proven effective numerous proposed technologies remain unproven, inconsistent, or counterproductive.

5.6.1 Visual deterrents for bats

Field studies show zero mortality reduction using UV deterrents, emerging evidence suggests they may actually attract bats.

The most comprehensive multi-site field trial (Cryan et al., 2021) found no statistically significant difference in bat activity between UV-illuminated and control turbines, while laboratory experiments revealed bats were 2× more likely to approach white reflective blades than darker alternatives. Similarly, UV-reflective paint tested on 105 turbines in Wyoming showed no protective effect for birds (Young et al., 2003).

Groundbreaking research (Jonasson et al., 2025) revealed that hoary bats and silver-haired bats—the two species most killed by American turbines—were at least twice as likely to fly toward white reflective blades versus black blades in Y-maze experiments, challenging assumptions that bats rely exclusively on echolocation. The study demonstrated that bats' excellent dim-light vision and ultraviolet wavelength perception create an "ecological trap" where moonlight reflecting off turbine blades appears as open sky, actively attracting rather than deterring them.

5.6.2 Electromagnetic deterrents

Electromagnetic field deterrents (EMF) remain entirely theoretical with no demonstrated effectiveness at operational wind turbines. The initial promising research from 2007-2009 has led to zero commercial development in the 16 years since.

(Nicholls & Racey, 2007) documented reduced bat activity within 200m of large air traffic control and weather radars (EMF strength >2 v/m) in Scotland across 10 radar stations. However, authors explicitly stated this "has little practical application in preventing bats from colliding with turbine blades." The study conclusion: "Currently there have been no successful attempts to directly mitigate bat collisions with wind turbines." Follow-up testing with portable radar systems found that only fixed-beam antennas at 30m distance showed any effect, while rotating antennas produced no significant deterrence.

The fundamental technical barrier remains unresolved: effective deterrence would require multidirectional EMF signals encompassing the entire rotor-swept zone, consuming substantial power that negates the wind energy benefits. This technology remains at the conceptual stage.

5.6.3 Curtailment

Seasonal blanket curtailment for birds has proven largely ineffective in controlled studies (Smallwood & Bell, 2020).

Furthermore, US research on Golden Eagles generated both compelling evidence and methodological controversy. McClure et al. 2021 reported 82% mortality reduction at Wyoming's Top of the World Windpower Project using 24 camera-based systems (IdentiFlight) units in a BACI design with 44 turbines (hub height 80 m; blade 50,5 m). However, Huso and Dalthorp 2023 identified statistical errors and reanalyzed the data, finding only 50% reduction (with confidence intervals spanning -159% to 89%), substantially diminishing certainty.

Conclusions

Effective mitigation of wind farm impacts on birds and bats requires combining multiple approaches within a site-specific strategy. Strategic avoidance through careful site selection and appropriate buffer distances represents the most cost-effective approach and should always be prioritized during the planning phase. Where avoidance is insufficient, blade patterning can further reduce collisions for certain species. For bats, operational curtailment has proven highly effective at reducing mortality with minimal energy loss. Detection-based shutdown systems offer substantial protection for large raptors, though their cost means they should be considered only in high-risk contexts. The evidence consistently demonstrates that proactive avoidance during site selection prevents far more impacts than any combination of post-construction measures can mitigate.

III SOLAR ENERGY

6. Overview

Solar energy is an important component of the global shift toward a low-carbon future and is key to achieving emissions targets established by the United Nations Framework Convention on Climate Change. Solar photovoltaic (PV) power capacity is increasing globally in response to energy decarbonization and is projected to be the dominant renewable source. Much of this capacity is deployed as ground-mounted solar parks, which represent vast altered landscapes, covering an estimated 37,886 km² (about 0.025% of the world's land area) by the end of 2023. The growth of PV is rapidly surpassing Concentrated Solar Power (CSP) systems.

The rapid transformation of landscapes necessitates urgent research into the biodiversity impacts of solar facilities worldwide. If the implications for the local environment are not considered alongside solar park expansion, development risks trading off climate change mitigation and local ecosystem degradation. Potential impacts include land occupancy and habitat loss, habitat fragmentation, pollution, and direct mortality of wildlife.

There are many studies calling for additional research to fully understand the effects of solar facilities on fauna and develop mitigation strategies. Solar parks can be strategically designed and managed to minimize detrimental environmental impacts and even enhance ecosystem function in intensively managed agricultural landscapes.

7. Impacts on biodiversity

Solar energy facilities cause measurable wildlife mortality, but impacts differ dramatically between technologies and contexts. Solar power generation comprises two main technologies: **Concentrated Solar Power (CSP)** and **Solar Photovoltaic (PV)**. CSP uses mirrors to concentrate sunlight onto central receivers, creating intense heat that drives turbines, while PV panels convert sunlight directly into electricity through semiconductor cells. These technologies differ markedly in their collision risks to wildlife—CSP facilities pose substantially higher mortality threats to birds and bats due to the concentrated solar flux around their towers, whereas PV systems present lower collision risks. Since PV systems now dominate the solar energy sector and are rapidly expanding globally, this report will focus only on this type of solar energy.

7.1 Estimated mortality

Solar photovoltaic facilities impact fauna through several mechanisms, including habitat disruption, attraction to new resources, and direct mortality from collisions with panels mistaken for water surfaces (the "lake effect").

PV facilities cause 1.82-2.49 bird deaths per MW annually in US deserts, with waterbirds most vulnerable to the "lake effect" (Kosciuch et al., 2021), though transferability to Central European agricultural landscapes is uncertain due to different species assemblages and habitat contexts. When habitat conversion mortality is included (loss of breeding birds from land clearance), total bird removals may be 2x higher than collision mortality alone, with ~53% attributable to habitat destruction in California studies (Smallwood, 2022).

Extrapolating data from USA studies, it is estimated that 17.3 million birds die at solar facilities around the world every year (Fleming, 2025).

7.2 Species Most Affected

(a) Waterbirds

PV installations primarily affect aerial insectivores, waterbirds vulnerable to polarized light attraction, and common generalist species. While extensive mortality data exists for US facilities, European evidence remains limited.

Since the "lake effect" represents the primary PV-specific mortality mechanism affecting aquatic bird species (Horváth et al., 2010), waterbirds show dramatic overrepresentation at solar facilities relative to surrounding landscapes. American solar parks documented highest mortality in diving and wading waterbirds, particularly Eared Grebe (*Podiceps nigricollis*, 64% of detections), American Coot (*Fulica americana*), and Common Loon (*Gavia immer*). Furthermore, species like Little Egret (*Egretta garzetta*) and Great White Egret (*Ardea alba*) have been observed attempting drinking behavior at panel surfaces, demonstrating that even species capable of terrestrial locomotion respond to the visual water mimicry (Kosciuch et al., 2020). European ecological equivalents face identical vulnerabilities through shared water-obligate physiology and polarized light detection mechanisms.

Mortality intensifies near actual water bodies, sites proximate to lakes or wetlands recorded substantially higher waterbird deaths than facilities in dry environments distant from aquatic habitats (Kosciuch et al., 2020).

(b) Terrestrial birds

Mourning Dove (*Zenaida macroura*), yellow-rumped (Setophaga coronate) and yellow warblers (Setophaga petechia) were the most commonly species reported dead at solar facilities in Southern California, US (Conkling et al., 2022). These seed-eating and insectivores species likely collide with panels during low-altitude foraging flights.

Central European PV research shows dramatically different patterns than North American deserts, reflecting fundamental differences in landscape context (agricultural versus natural), facility scale (small installations <5.3 ha common), and species assemblages (farmland specialists versus desert/migratory species). Polish agricultural installations (<5.3 ha) recorded a negative reaction of Skylark (*Alauda arvensis*) to the presence of PV (Golawski, Mitrus & Jankowiak, 2025).

(c) Bats

Bats experience severe population-level impacts across European PV installations. UK acoustic monitoring revealed 40-86% activity reductions for Common Pipistrelle (*Pipistrellus pipistrellus*), with all monitored species affected: Soprano Pipistrelle, Noctule, Serotine, Myotis species, and Long-eared bats (Tinsley et al., 2023). Hungarian studies (190 sites) showed synanthropic species (Savi's Pipistrelle, Common Noctule) adapting while conservation priority taxa (Myotis, Barbastelle) declined (Szabadi et al., 2023)

(d) Insects

Insect mortality through polarized light attraction creates cascading trophic effects particularly severe for aquatic taxa. Solar panels at polarization angle produce nearly 100% polarization—substantially exceeding natural water's 30-70%—triggering maladaptive oviposition in mayflies (Ephemeroptera), caddisflies (Trichoptera), and dragonflies (Odonata). Additional affected orders include horseflies (Tabanidae), midges (Chironomidae), and numerous aquatic beetles and true bugs. Reproductive failure occurs when insects deposit eggs on panel surfaces instead of water, causing complete breeding collapse. This creates "mega-traps" where panels attract prey insects, subsequently attracting insectivorous birds (White Wagtail, Yellow Wagtail, Great Tit) that face collision risks while foraging—exposing multiple trophic levels simultaneously (Horváth et al., 2010).

7.3 Types of impacts

7.3.1 Habitat Loss and Transformation

PV installations directly convert habitat through vegetation removal and infrastructure placement. Meeting EU solar objectives would require approximately 3% of European open

habitats (164,789 km²) by 2030. Ground-mounted PV requires 3.2-4 hectares per megawatt (Beatty et al., 2017). In the UK, 95% of solar farms were converted from agricultural land (Kiesecker et al., 2024).

The physical presence of panels creates dramatic microclimate shifts (Li et al., 2025):

- Soil temperature decreases of 4-5°C in summer (increases of 1.7°C in winter)
- Light availability reduced by 43-95% beneath arrays
- Modified precipitation patterns concentrating at panel edges
- Altered humidity and wind speeds

Habitat fragmentation compounds direct conversion impacts. Security fencing surrounds 57% of utility-scale facilities, creating complete barriers to terrestrial wildlife movement. Landscape-scale analyses reveal that medium-sized installations cause disproportionately high fragmentation due to scattered distribution across regions, with cumulative effects often undetected in project-level assessments (Lafitte et al., 2022; Gómez-Catasús et al., 2024).

7.3.2 Direct Mortality

Polarized light pollution ("lake effect") represents the primary **PV mortality mechanism**. Solar panels reflect horizontally polarized light with degrees of polarization approaching 100%, substantially exceeding natural water bodies (30-70%) (Horváth et al., 2010; Fleming, 2025). Birds and aquatic insects evolved to detect polarized light for locating water, making panels attractive as "false water" (Gómez-Catasús et al., 2024).

Water-obligate species like grebes and loons cannot take flight from land; landing attempts prove fatal through collision or stranding (Smallwood, 2022). Aquatic insects attempting oviposition on panel surfaces experience complete reproductive failure as eggs fail to hatch, creating an evolutionary trap (Fleming, 2025). Attraction rates are extreme: panels at optimal angles attract insects 10-26 fold more than actual water (Diehl, Robertson & Kosiuch, 2024).

7.3.3 Behavioral Changes and Ecological Traps

Aquatic insects suffer the most severe maladaptive behavioral responses. Mayflies, caddisflies, tabanid flies, and dragonflies exhibit strong oviposition behavior on panel surfaces where eggs fail to hatch (Lafitte et al., 2022). A Polish agricultural PV study across 43 small sites (<5.3 ha) found positive responses from Corn Bunting (*Emberiza calandra*) and Whinchat (*Saxicola rubetra*), both declining across Europe, while only Skylark (*Alauda arvensis*) was significantly

deterred by PV presence (Golawski, Mitrus & Jankowiak, 2025). (Jarčuška et al., 2024) also found higher species richness and diversity indices at solar sites but (Valera et al 2024) published methodological critique questioning whether single breeding season surveys adequately captured impacts.

Pollinator timing disruption: Delayed plant phenology under panels (blooming postponed by several weeks) disrupts pollinator-plant synchrony (Lafitte et al., 2022). However, Lancaster University research suggests that deploying honeybee hives on every solar farm in England could have resulted in pollination service benefits worth £5.9 million in 2017 (Blaydes et al., 2021).

8. Mitigation Measures to Reduce Bird and Bat Mortality

Mitigation measures aim to reduce the specific hazards posed by solar facility infrastructure and operations. The effectiveness of these measures varies based on the underlying mechanism of mortality they target.

8.1 Strategic Site Selection

Strategic siting prevents 80-95% of wildlife impacts at lowest cost and represents the most effective mitigation approach. Site selection decisions made during planning phases are irreversible and determine all subsequent mitigation needs throughout a facility's operational lifetime.

IUCN guidelines recommend avoiding protected areas, Key Biodiversity Areas, migration corridors, and semi-natural grasslands (Bennun et al., 2021). The most robust strategy involves locating solar projects on land that minimizes new habitat disturbance or utilizes areas already compromised. Developers should prioritize degraded, brownfield, or intensive agricultural lands over semi-natural grasslands. PV facilities replacing previously degraded lands can play an important role in promoting biodiversity (Visser et al., 2019).

8.2 Mitigation During Construction

Construction Timing Restrictions: Scheduling site preparation and main construction outside bird breeding season (March-August), amphibian breeding season (March-June), and reptile hibernation (November-February) eliminates nest destruction and population-level impacts. This requires only planning flexibility with no additional costs, and UK projects demonstrate recovery within 1-3 years when combined with rapid revegetation (Bennun et al., 2021).

Phased Construction: Sequential development of installation zones maintains undisturbed habitat areas throughout construction, allowing mobile species to relocate to undeveloped sections (Bennun et al., 2021).

8.3 Panel design modifications

Anti-reflective coatings provide the only technically proven polarization reduction. Laboratory studies demonstrate ARCs reduce polarization by up to 12%, potentially lowering degree of linear polarization from 80% to 68% (Száz et al., 2016). Commercial panels increasingly incorporate ARCs for energy efficiency, making this a cost-neutral or cost-positive modification. No mortality reduction studies exist at operational facilities comparing ARC-equipped versus standard panels.

Incorporating white, non-polarizing grid lines into solar panel design reduces aquatic insect attraction by 80-95% across multiple taxa (mayflies, caddisflies, midges, blackflies) while reducing solar-active area by only 2-3%. Grid lines between 1-5mm width are effective, with maximum impact occurring when non-polarizing surface covers 2-6% of panel area. Field trials in Europe and North America confirm effectiveness, though no utility-scale validation exists yet (Black & Robertson, 2020).

For bats, whose orientation is impeded by smooth surfaces, placing subtle mechanical surface modifications (e.g., string) across smooth plates can eliminate maladaptive drinking attempts (Szabadi et al., 2023).

8.4 Other Mitigation Measures

8.4.1 Wildlife-Friendly Fencing

Fencing is vital for safety, but non-permeable designs create barriers and can cause entrapment, especially for large-bodied birds or those (like Greater roadrunner) that prefer running over flying. Modify security fencing to minimize barrier effects for small- and medium-sized terrestrial animals (Fleming, 2025)

Creating permeable fencing or leaving specific openings (e.g., 25 cm wide by 18 cm tall) for fauna passage has been trialed successfully at pilot sites in Nevada, allowing movement for tortoises, snakes, and foxes. This modification is effective at reducing the barrier effect and potential entrapment caused by fencing (Fleming, 2025).

8.4.2 Habitat Management

Active habitat management transforms solar facilities from passive infrastructure into biodiversity assets by creating and maintaining high-quality habitats that benefit target species.

Agrivoltaics (dual land use) demonstrates measurable benefits. German 2025 modeling documented 33-88% increases in pollinator supply, 9-22% water retention improvements, and up to 8% carbon storage gains with sheep grazing integration (Ludzuweit et al., 2025).

Wildflower meadow establishment shows quantified effectiveness. Lancaster University research documented 4-fold bumblebee abundance increases with native plantings versus turf grass, with benefits extending 1km beyond facility boundaries (Blaydes et al., 2022).

Hedgerow planting provide connectivity. New hedgerow installations with native species create wildlife corridors, with multiple UK sites showing increased nesting activity. Complementary features include tussocky 4-meter margins for ground-nesting birds, pond creation for amphibians (often integrated with drainage requirements), and hibernacula for reptiles (Montag, Parker & Clarkson, 2016)

Conservation grazing management employs sheep at appropriate timing and stocking density. Removal during April-July allows plant flowering and seed set while preventing ground nest disturbance. Studies demonstrate grazing increases total carbon storage and available soil nutrients. Minnesota research found native habitat under grazed panels supports pollinators and soil health. Panel heights ≥ 70 cm enable sheep access, with smaller breeds selected for confined spaces. Mob grazing (high density, short duration, rotational) optimizes vegetation structure. This approach often generates revenue, creating economically positive biodiversity enhancement (Andrew et al., 2021).

8.4.3 Monitoring

Ongoing monitoring is crucial to ensure mitigation measures are effective. Monitoring data should be comprehensive and standardized (e.g., Before-After Control-Impact studies) to track the effectiveness of interventions and inform adaptive management for the long-term viability of priority wildlife features. This is particularly important since knowledge gaps regarding specific species impacts and effective mitigation across different geographic regions still exist.

IV KNOWLEDGE GAPS AND RESEARCH NEEDS

The evidence base supporting this guidance derives predominantly from research in several countries in Europe but Czech Republic represents a significant gap in the European monitoring network.

No published Czech wind farm mortality studies exist. Without local empirical data, impact predictions rely entirely on extrapolation from other Central European countries that may not represent Czech species assemblages or collision patterns.

Most studies examine single facilities in isolation. As wind farm density increases across Central Europe, cumulative impacts from barrier effects, habitat loss, and mortality across multiple facilities may create population-level impacts not predicted by summing individual facility estimates.

Most mitigation effectiveness studies evaluated turbines with heights 80-120 m and rotor diameters 80-100 m, but modern Czech proposals are 150-200 m hub heights. Collision risk patterns, detection systems, and curtailments effectiveness may differ at these scales.

International studies show that curtailment works, but adaptive algorithms developed in Germany or the US need calibration to local conditions: bat species mix, migration timing, and weather patterns differ enough that imported protocols may not perform optimally. Blade painting needs testing with Czech landscape because results vary dramatically by location—it cut bird deaths by 70% in Norway but showed no effect in the Netherlands, possibly due to different visual backgrounds. Similarly, detection systems like IdentiFlight and DTBird need field validation for Czech species, since their performance depends heavily on bird size, flight behavior, and landscape features that differ between their original test sites and Czech terrain.

Solar energy research lags significantly behind wind energy globally. The "lake effect" mechanism is well-documented, but we lack quantitative data on how insect attraction varies with panel angle, coating type, and surrounding landscape context. Long-term studies on how vegetation management strategies affect biodiversity outcomes at solar parks are virtually absent, despite widespread recommendations for wildflower establishment and conservation grazing. More fundamentally, we don't understand cumulative landscape-scale effects—whether multiple small solar installations cause greater fragmentation impacts than fewer large facilities.

Monitoring protocol standardization represents another critical methodological gap affecting both wind and solar facilities. Reported mortality estimates vary substantially based on search frequency, search radius, scavenger removal correction factors, and carcass persistence assumptions. These methodological inconsistencies complicate cross-study comparisons and meta-analyses, limiting confidence in evidence synthesis.

These knowledge gaps are not unique to Czech Republic. Most European countries face similar limitations: modern turbines are much larger than those used in effectiveness studies, population-level impacts remain poorly understood, and solar energy research lags far behind wind energy globally.

V ACKNOWLEDGMENTS

This report wouldn't exist without the support and expertise of many people who generously shared their time, knowledge, and honest feedback.

First and foremost, my thanks go to Václav Hlaváč, director of AOPK's Vysočina regional office, for commissioning this work and trusting me to tackle such a critical topic. Jitka Uhlíková from the Department of Special Species Protection of Animals deserves special recognition for her patience in helping me understand what Czech authorities actually need, shaping the report's structure, and keeping me on track throughout this process.

I'm also deeply grateful to all the experts who shared part of their valuable time with me to enrich this document. To Dr. Rob Simmons who enlightened me with his recent studies on blades painted with aposematic patterns in South Africa. To Jon Domínguez who gave me tools and information about new trends in technology applied to wind farms. To Tomas Bartonička who provided an exhaustive analysis of the bat situation in CZ and helped me gain the national perspective. To Mårten Hjernquist, whose lifetime of experience with Swedish wind farms has been invaluable. To Ignacio Roldán who opened the doors for me to radars applied to bat detection. And to Brian McGowan for sharing his expert experience across different countries around the world and teaching me how much everything changes with context.

My dear colleague at AOPK Marie Botslová translated this report into Czech with attentive eyes. Thank you so much for your dedication and for always doing everything with a smile.

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VI ANNEXES

The following five tables summarize all mitigation measures for reducing bird and bat mortality at renewable energy facilities. Each table provides the essential information needed to evaluate mitigation proposals during permit reviews:

- Table A: Wind Energy – Birds
- Table B: Wind Energy – Bats
- Table C1 and C2: Solar Energy – Birds and Bats
- Table D: Applicability of mitigation measures on Wind projects
- Table E: Applicability of mitigation measures on Solar projects

Each measure is classified by the quality of scientific evidence supporting its effectiveness (A to D) and by their applicability (1-4):

Level A – Proven Effective

- Tested with rigorous experimental designs (randomized trials or BACI studies with control sites)
- Supported by multiple independent studies

Level B – Strong Evidence

- Clear before-after results or robust statistical models
- May lack control sites but shows consistent patterns

Level C – Limited Evidence

- Single case studies or observational data
- Results may not apply to other contexts
- **Require enhanced monitoring** if approved; use as supplementary measures only

Level D – Unproven

- Expert opinion or theoretical proposals only
- No field validation data
- **Should not be approved** without comprehensive monitoring protocols

Applicability:

1 Generally applicable: Low cost, proven technology, works across most sites.

2 Applicable with conditions: Moderate cost or requires site-specific calibration or needs specialized equipment.

3 Limited applicability: High cost, complex implementation, site-specific constraints.

4 Not generally applicable: Experimental only, prohibitive costs, or only works in very specific conditions.

Measure	Description	Context of use	Expect Effect	Evidence strength	Limitations	Costs	Impact on EP	Additional notes
Macro-sitting	Avoid placement in protected areas, migration corridors, and raptor breeding territories	Pre-construction planning phase	80-95%	A	Reduced available sites for wind development	No costs	0	Most cost-effective measure
Micro-sitting	Arrange turbines to create flight corridors aligned with main bird trajectories	Site development planning after macro-siting selection	20-60%	B	May constrain optimal wind resource utilization	No costs	0	Variable reduction depending on species and site
Shutdown-on-Demand (SDOD)	Camera-based AI or radar systems detect approaching birds	High-risk sites with soaring birds	50-100%	A	False positives; requires 3+ months AI training per site	0.5-2% of the project investment (DTBird) €150,000 (IdentiFlight)	0.014-1.2%	
Seasonal Curtailment	Scheduled turbine shutdown during high-risk periods	Migration corridors; seasonal breeding periods for resident raptors	50-60%	C	Requires grid coordination; climate change may degrade model accuracy over time	No costs	0.12-2%	
Blade Painting	Paint one blade black or use aposematic warning patterns to reduce motion smear	Open landscapes with natural backgrounds	70-87%	A	Heat absorption concerns (monitor for >65°C)	€700-1,700 during manufacturing	0	
Tower Base Painting	Paint lower 10m of tower base with contrasting colors	Sites with low-flying gallinaceous birds	48%	B	Limited to species flying below 15m height	No data	0	Green gradient more effective than grey/white
Acoustic Deterrents	Bio-acoustic systems broadcasting distress calls or predator sounds	Combined with detection systems	33-53%	C	Habituation concerns; potential disturbance to non-target species	€16,500-20,000+ per unit	0	
Habitat Management	Vegetation management at turbine bases	Species attracted by foraging opportunities	75%	B	habitat loss/modification	Estimated hundreds to low thousands €	0	Works best for species attracted by foraging

TABLE A: Summary of mitigation measures for onshore wind farms on birds

Measure	Description	Context of use	Expect Effect	Evidence strenght	Limitations	Costs	Impact on EP	Additional notes
Strategic Sitting	Avoid placement near bat hibernacula, roosts, and major foraging areas; maintain buffer distances	Pre-construction planning phase	20-77%	B	Reduces available land for wind development	-	0	
Blanket Curtailment	Raise cut-in wind speed from 3-4 m/s to 5-6 m/s during high-risk periods	seasonal (April-October in temperate Europe; peak July-October)	60-85%	A	May reduce energy production slightly	-	0.5-4%	Most consistently effective and widely implemented bat mitigation
Smart Curtailment	Predictive models using real-time weather data, acoustic detection, or radar to trigger curtailment	Sites where minimizing energy loss is critical	74-91%	A	Requires 3+ months calibration period; algorithm updates needed	-	≤3.2% annual loss	
Acoustic Deterrents	Nacelle-mounted ultrasonic devices (20-120 kHz, 120 dB) to jam echolocation	-	21-54%	C	May displace bats from important foraging areas	Unpublished	0	Species-specific variation; potential disorientation or prey attraction effects
Habitat Management	Clear vegetation buffers 50-100m from turbine bases	Forested sites	Variable	C	Habitat loss for roosting and foraging	Vegetation clearing/management costs	0	Reduces bat activity near turbines

TABLE B: Summary of mitigation measures for onshore wind farms on bats

Measure	Mechanism	At-Risk Species	Effectiveness	Evidence strength	Costs	Maintenance	Additional notes
Strategic Siting	Avoid placement near sensitive species concentrations	<i>Vanellus vanellus, Alauda arvensis, Emberiza calarina, Milvus milvus, Myotis spp., Barbastella barbastellus, and Rhinolophus ferrumequinum</i>	-	B	0	-	
Prioritizing degraded or brownfield sites	It transforms mitigation from damage limitation to ecological restoration.	<i>Phoenicurus ochruros, Saxicola rubicola, Motacilla alba, Pipistrellus pipistrellus</i>	-	B	No published data	-	Costs are highly variable by contamination level
White grid patterns	It break up the dark polarizing panel surface, helping prevent insects and waterbirds from mistaking it for water	Mayflies, caddisflies, horseflies and all insectivorous birds and bats	10-26 fold reduction in attraction	A	No published data	-	The critical tradeoff involves reduced solar-active surface area
Anti-reflective coatings (ARCs)	Dielectric layers applied to panel glass surfaces. ARCs reduce horizontal polarization of reflected light	Horsefly, duck species, grebes, waders, herons and insectivorous bats	Species-specific responses	B	€50,000-100,000/MW	Every 5 years	3-4% increased electricity generation
Tracking systems	May reduce exposure compared to fixed-tilt panels – mitigate the lake effect	-	-	D	15-25% for single axis 35-40% for dual	Moving parts require additional maintenance	Studies are needed

TABLE C(1): Summary of mitigation measures for Photovoltaic panels

Measure	Mechanism	At-Risk Species	Effectiveness	Evidence strength	Costs	Maintenance	Additional notes
Wildflower meadow establishment	Enhance biodiversity by increasing invertebrates and pollinator habitat on seeding areas beneath and between panels		15-60% increased bird diversity	A	No published data	Sheep annual grazing	Strongest evidence base among habitat management approaches.
Hedgerow and native shrub planting	Native hedgerows at boundaries while creating shrub corridors connecting to surrounding habitats.	<i>Linaria cannabina</i> , <i>Sylvia communis</i> , Long-eared Bat, <i>Myotis</i> spp., and Barbastelle	-	B	No published data	Low cost maintenance	Limitations: land take, establishment lag of several years, and maintenance requirements.
Wildlife-permeable fencing	Larger mesh openings or 20-30cm gaps between fence base and ground, allowing small-to-medium wildlife passage	Foxes, raccoons, rabbits, and squirrels	33% more ungulates successfully; 54% reduced crossing time	B	Installation costs comparable to standard chain-link fencing	-	Birds benefit indirectly through maintained ecosystem connectivity
Agrivoltaic or agri-PV systems	Simultaneous crop cultivation and solar energy production through elevated panels (2-5m clearance)	Common farmland species	No significance in birds species number	B	~33% higher than ground-mounted solar	Panel cleaning and electrical system upkeep	Farmers gain dual income streams and may save on irrigation, plant protection, and herbicides

TABLE C(2): Summary of mitigation measures for Photovoltaic panels

WIND ENERGY MEASURES

Measure	Applicability	Justification
Macro-siting	1	No cost if done at planning stage; uses existing spatial data
Buffer zones from protected areas	1	Standard planning requirement
Micro-siting	2	Requires detailed site surveys; moderate expertise needed
Blanket bat curtailment	2	Proven effective
Smart bat curtailment (ProBat algorithms)	2	Proven effective; requires SCADA programming
SDOD - camera-based (IdentiFlight, DTBird)	3	High cost; needs 3+ months AI training per site
SDOD - radar-based	3	High cost; requires specialized operators; best for large facilities
Blade painting	1	Low cost; proven in open landscapes
UV blade coating	4	Experimental only; no field validation; unknown durability
Acoustic deterrents for bats	4	Mixed results
Construction timing restrictions	1	No cost; easy to implement; standard practice
Lighting modifications (red vs. white)	2	Requires aviation authority approval; low cost
Habitat management around turbines	2	Moderate cost; proven for reducing prey attraction; site-specific design

TABLE D: Applicability of mitigation measures on Wind projects

SOLAR ENERGY MEASURES

Measure	Applicability	Justification
Strategic siting	1	Planning stage; no cost
Anti-reflective panel coatings	2	Standard technology; adds to panel cost
Perimeter fencing	1	Standard practice; low cost
Habitat management	2	Moderate ongoing cost; site-specific plant selection
Pollinator habitat creation	2	Moderate cost; co-benefits; requires maintenance planning

TABLE E: Applicability of mitigation measures on Solar projects