Limiting the impact of offshore wind power on aerofauna: synthesis of recommendations in the absence of effectiveness assessments

Knowledge synthesis

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EXECUTIVE SUMMARY

Background

The climate emergency calls for a rapid reduction in greenhouse gas emissions. As electricity production from fossil fuels is one of the main sources of CO_2 emissions, switching to renewable energy sources is central for achieving carbon neutrality by 2050. The rise in electrification exacerbates this need. In this context, developing offshore wind energy is seen as a viable strategy for meeting the growing demands for carbon-free electricity, diversifying the energy mix, and reinforcing the energy autonomy of countries. In France, this sector is growing rapidly, with a target of 40 GW by 2050 set by the "offshore wind pact". However, despite being beneficial for the climate, offshore wind energy requires large infrastructure that disturb the environment. In this sense, offshore wind energy can pose a threat to biodiversity, for instance through the disturbance of benthic habitats, noise emissions that can harm marine mammals, collisions of birds and bats with wind turbines, ... The "avoid – reduce – compensate" sequence and associated tools (strategic environmental assessments, impact studies) regulate the development of offshore wind energy projects to minimize their negative impact on ecosystems. The real issue now is accommodating the necessary acceleration in offshore wind project deployment with the effective conservation of marine biodiversity; in other words: how do we meet climate objectives without compromising the integrity of ecosystems?

Objectives

The French Foundation for Biodiversity Research (FRB), with the support of the Mirova Research Center (MRC), conducted a Rapid Review (RR) of the literature to assess the effectiveness of measures for minimizing the impact of offshore wind power on aerial biodiversity (birds, bats, and insects). The initial aim was to identify best (evidence-based) practices. However, due to the lack of empirical studies on the effectiveness of these measures in marine environments, we changed the focus of our review to providing a compilation of expert recommendations, to highlight the practices that were deemed most relevant. The main objective of this review was therefore to identify these recommendations in the absence of a systematic assessment their effectiveness.

Methods

A literature review was conducted following the standards and guidelines for Rapid Reviews of the *Collaboration for Environmental Evidence* (the benchmark for evidence syntheses in ecology, https://environmentalevidence.org/information-for-authors/10-guidance-on-the-conduct-and standards-for-rapid-review-of-evidence/). Bibliographic references included scientific (academic literature) and technical articles, as well as reports from databases and specialized websites (grey literature). The collected data were analysed qualitatively using a narrative approach. In the absence of empirical studies on the effectiveness of mitigation measures in marine environments, this review focused on the identification and classification of existing recommendations.

Overview of the selected publications

Bibliographic searches on the measures for mitigating the impact of offshore wind farms on aerial species (birds, bats, and insects) yielded 1,261 references, including duplicates. After conducting an objective, standardized and rigorous selection process, 45 documents were retained.

The selected documents highlighted the following key elements:

- Studies were primarily carried out in Europe (46.7 %) and the United States (26.7 %). The most studied maritime areas were the North Sea (33.3 %), the North Atlantic Ocean (22.2 %), the Baltic Sea (6.7 %), and the Celtic Sea (2.2 %).

- Birds featured predominantly (93.3 % of references, 87.1 % of recommendations). No documents specifically focused on insects. Specific recommendations for birds frequently mentioned marine species (53 %) and migratory species (12 %).
- Among the recommendation categories:
    - planning and impact assessments tools were the most frequently mentioned measures, highlighting the importance of anticipating environmental impacts prior to the installation of infrastructure;
    - wind farm siting and turbine positioning featured in second place;
    - operational modifications (e.g. curtailment) and technical/ technological measures (e.g. acoustic deterrent systems) were also important;
    - research and development (R&D) was frequently recommended, indicating that there is an ongoing need for improving knowledge and solutions;
    - compensatory measures and awareness raising/training (of project holders, instructing services, ...) are seldom (or not at all) mentioned in the recommendations.

Macro-siting (the process of selecting a wind farm's location), integrating environmental analysis tools, long-term studies, and international collaboration, was frequently recommended. Micro-siting (internal wind farm design) complements this approach on a smaller scale. Smart curtailment strategies were also recommended, as well as technical adaptations for improving turbine visibility (light management, painting).
Finally, this review also shows that priority is given to impact avoidance and reduction strategies, and that there is a significant demand for more research and development to assess and optimize the effectiveness of current measures.

Overview of the recommendations from the narrative synthesis and the expert workshop[1]

<u>Colour key by taxon</u>

Birds

Bats

Birds and bats

Insects and bats

For project developers and operators

[1] This overview lists many recommendations, some of which are very specific; however, it is not exhaustive. Complementary measures, methodological variants, and additional details are given in the full report

Project phase	Section	Recommendation	Specific actions
Strategic planning/ construction	Spatial planning & site selection	Preferentially select areas with low environmental risk	- Prioritize state-driven spatial planning based on consolidated environmental data to avoid key biodiversity areas - Use wildlife sensitivity maps and inventories to exclude major migration corridors - Apply a multicriteria risk index (bird density, flight height, bat concentration, light attractivity) in environmental impact assessments (EIAs) - Establish minimum buffer zones around colonies and Natura 2000 sites - Use remote sensing (weather radars, satellite images) to locate migration pathways - Carry out cumulative impact assessments integrating future projects over the long-term
	Temporal planning of work-related activities	Plan intrusive activities outside of sensitive periods	- Establish a local wildlife calendar detailing reproduction, migration, and wintering periods - Schedule pile-driving and cable/mast installation outside of peak sensitive periods for species - Use low noise materials or place mobile noise barriers if work cannot be rescheduled - Install a weather/migration warning system to suspend activities during periods of high passage
	Spatial planning of work-related activities	Map and avoid sectors with high wildlife densities	- Adapt ship and helicopter itineraries to avoid gathering sites
Design/ pre-construction	General wind farm design and site selection (macro-siting)	Optimize wind farm localization	- Exclude critical migration corridors - Exclude high density areas and critical habitats (e.g. colonies, gathering sites, feeding grounds) - Establish safety buffers around sensitive habitats, with distances adapted to species of interest
	Internal wind farm design (micro-siting)	Optimize turbine layout and design	- Adjust the orientation of turbine rows to minimize perpendicular barriers to flyways - Integrate wind flow and flight altitude models to determine the optimal air gap - Increase the air gap to reduce the collision risk to birds flying at low altitude - Plan internal corridors without constructions to allow the passage of aerofauna - Adjust wind farm layout after monitoring (using mobile radars) and modelling flyways for a year - Reduce the number of turbines in previously identified environmentally sensitive areas
Design/construction /operation	Adapt infrastructure and improve visibility		- Paint a single blade black to improve visibility during blade rotation

		Make turbines more easily detectable and less attractive	- Paint a black and white pattern at the base of the mast to make it stand out against the background
			- Adapt the management of nighttime lighting, within the contraints of maritime and aviation security, to limit light attraction
			- Substitute continuous lights with synchronized flashing lights of lower intensity, within the constraints of aviation security
			- Test texturized mast surfaces that limit UV reflection which is attractive to insects
	Deterrent systems	Experiment with complementary deterrent devices	- Install anti-perching spikes on nacelles and maintenance platforms
			- Deploy directional ultrasonic emitters that are automatically activated when wind speeds are below 6 m/s
Operation	Adaptive turbine shutdown	Implement dynamic shutdown based on detection	- Combine scanning radars, acoustic sensors, and thermal cameras to identify approaching wildlife
			- Apply a predictive algorithm (wind, temperature, pressure) to anticipate nighttime risks for bats
			- Programme seasonal nocturnal shutdowns during peak spring and autumn migrations
			- Fix a higher cut-off speed during hot and humid nights when there is more insect activity
			- Raise the cut-in speed to about 5 m/s during bat migrations, and adjust depending on nighttime temperatures
			- Continually optimize curtailment parameters using new data from monitoring and past experiences
			- Implement a standard international curtailment protocol that is reviewed regularly and can be adapted to regional contexts
Operation/ monitoring	Environmental monitoring and model validation (collision risk, distribution/habitat)	Ensure continuous monitoring and improve risk models	- Install a 3D radar system covering the air column to up to 1,000 m
			- Install passive acoustic sensors on masts to measure bat activity
			- Regularly update risk models with new data
			- Publish raw data in an open-access platform, available under a free license
			- Implement robust BACI-type (before/after – control/impact) protocols to scientifically assess the effectiveness of measures
			- Install sensors on lighthouses and other marine infrastructure to follow migratory bats
			- Combine observations from boats, aircrafts, and radars to obtain cover of bird movement at different scales

Wind farm repowering	Repowering of installations	Take advantage of this opportunity to reduce impacts	- Carry out a cost/benefit analysis for wildlife prior to making any replacement - Prioritize the decommissioning of turbines presenting elevated risk as identified by long-term monitoring - Replace blades with certified high visibility rotor blades
Compensation/ post-operation	Environmental compensatory measures	Compensate residual impacts when avoidance is not possible	- Design all compensatory measures in detail: define objectives, indicators, and schedule prior to deployment - Adapt each action to the species and habitats concerned to maximize environmental relevance - Undertake rigorous long-term monitoring to quantify gains and losses, using precise metrics, and verify the effectiveness of compensatory measures - Ensure interregional coordination to create a synergy between different areas of compensation
All phases	Data sharing & shared governance	Set up a regional cooperation framework	- Create a common metadata protocol validated by the authorities - Sign an intercompany agreement to share experiences and pilot schemes - Organize regular industry-academia workshops to update knowledge on mitigation measures and share prior experiences - Maintain a regional database containing mortality and turbine shutdown data - Create a single interoperable portal to centralize environmental data from wind energy projects, managed by a third party - Establish a cross-institutional scientific consortium to coordinate research and harmonize protocols - Authorize and support experimental trials (dynamic lighting, innovative curtailment)
		Offer incentives in favour of biodiversity	- Reintroduce weighted environmental criteria in calls for tender to encourage innovation in favour of biodiversity

For the scientific community

Project phase	**Section**	**Recommendation**	**Specific actions**
Pre-construction/ strategic planning	Research protocol design	Define robust methods to anticipate impacts	- Standardize multi-sensor protocols (visual, aerial, radar) to set a baseline between projects - Systematically apply BACI (before/after – control/impact) designs that are adapted to the marine environment
	Pre-construction knowledge management	Target priority knowledge gaps	- Map areas with the most knowledge gaps - Regularly update the national road map for research priorities, and share with the sector - Carry out BACI experiments at multiple sites to quantify cumulative impacts and test key hypotheses

Construction/ operation	Data collection & monitoring	Harmonize and optimize species monitoring at sea	- Co-create a harmonized international protocol (visual, acoustic, 3D radars, telemetry) with mandatory cross-calibration of methods - Equip wind farms with cutting edge detection devices (vertical/scanning radars, LIDARs, AI-powered cameras) associated with real-time environmental monitoring - Synchronize data collection windows between projects within the same region
	Validation of mitigation measures	Test and quantify measure effectiveness	- Design robust BACI-type experimental protocols to test curtailment, light/acoustic deterrents, air gap size, ... - Publish raw data, methods, and costs in an international database to allow meta-analyses of measure effectiveness - Develop standard metrics (collision rate/MWh, energy cost) to compare measures
Operation/ monitoring	Analyses & modelling	Refine risk and movement models	- Integrate micro-weather and insect density data in bat activity models - Continuously recalibrate collision risk models with new telemetric data for different species - Update sensitivity maps and cumulative analyses on a regional scale yearly to guide the adaptation of measures - Publish each model update with its source code and associate dataset - Create a single interoperable portal managed by a third party, to centralize environmental data
End-of-life/ repowering	Prior experiences & prospects	Capitalize on decommissioning and repowering	- Monitor changes in the use of space by wildlife after decommissioning - Measure the effects of new high visibility designs installed during repowering - Carry out meta-analyses on multiple decommissioned or repowerd wind farms to identify trends in potential impacts and benefits for biodiversity over the long-term
All phases	Scientific coordination & governance	Reinforce the organization of research programmes	- Maintain and support the annual conference “Conference on Wind Energy and Wildlife Impacts” (CWW) bringing together academics, institutions, and industry to align protocols and priorities - Maintain and support the Offshore Wind Energy Observatory (*l’Observatoire de l’Éolien en Mer*) as a cross-institutional scientific consortium to coordinate projects, funding, and knowledge capitalization - Ask for the reintroduction of weighted environmental criteria in calls for tender to help fund applied research - Set up support funds for the publication of studies on offshore wind farms in open-access journals

For government agencies

Project phase	Section	Recommendation	Specific actions
Before calls for tender/strategic planning	National planning framework	State-led spatial planning to avoid sensitive areas	- Draw a national map of migration corridors and include it in calls for tender - Publish exclusion and caution zones prior to any competitive tendering procedure - Regularly update environmental data and make them accessible to candidates
	Project selection criteria	Reintroduce weighted environmental criteria in calls for tender	- Define minimum percentage points awarded to biodiversity commitments - Publish a national bonus point rule for ambitious mitigation measures (air gap, curtailment, BACI studies)
Authorization and regulation	Relax trial regulations	Facilitate trials of innovative solutions	- Deliver temporary authorizations for dynamic lighting and adaptive curtailment
Construction/ operation	Monitoring and control	Increase the means of instructing services to control the implementation of measures	- Hire and train specialists in marine ecology
Operation/ monitoring	Protocol normalization	Harmonize the monitoring protocols imposed on project holders	- Publish national methodological guidelines (radar, acoustic, data collection) - Impose standardized protocols and procedures nationwide (even internationally), and ideally BACI-type designs to assess measure effectiveness
	Data management	Centralize and environmental data accessible	- Require that raw data be deposited in a standard format - Create a single interoperable portal managed by a public body to ensure data is accessible
All phases	Research – state – industry coordination	Organize applied research via a consortium	- Fund a pluriannual programme dedicated to the effectiveness of mitigation measures - Set up a cross-institutional consortium with the purpose of 1) identifying priority research questions, and 2) for each question, design a harmonized monitoring protocol and pool results
	Support environmental innovation	Provide financial incentives for ambitious measures	- Use grants and tax incentives to stimulate research and development into mitigation technologies

INTRODUCTION

The climate crisis calls for a significant reduction in greenhouse gas emissions to mitigate the impact of climate change. According to the IPCC (the Intergovernmental Panel on Climate Change), global temperatures could increase by 1.5°C by 2030, 2°C by 2050 and could reach 3°C by 2100 (IPCC, 2023). The effects of climate change are serious, affecting biodiversity, ecosystems and human well-being (IPBES, 2019). In 2024, CO_2 emissions from electricity generation represented ~ 36 % (about 13.8 Gt) of global CO_2 emissions from power generation (37.8 Gt) (International Energy Agency, 2025a; International Energy Agency 2025b). In 2023, emissions from electricity generation in France fell to 16.1 $MtCO_2eq$, representing ~4.2 % of total national emissions (385 $MtCO_2eq$) (Ministère de la Transition Écologique, 2024; RTE, 2024). The energy transition, by reducing the use of fossil fuels and developing renewable energy sources, is therefore crucial to achieve carbon neutrality by 2050, a target adopted by many countries within the framework of the Paris Agreement (UNFCCC, 2015). To reduce the use of fossil fuels beyond electricity production, it is also necessary to switch to electric wherever possible. This makes it even more necessary to develop renewable energy production above current levels to meet the growing demands for carbon-free electricity. In parallel, businesses, in accordance with target 15 of the Kunming-Montreal Global Biodiversity Framework, need to reduce their negative impact on biodiversity, including the impact stemming from measures for mitigating climate change (target 8). Energy production, like all other human activity, needs to become more sustainable, and limit its impact on biodiversity (Decision 15/4, U.N. doc. CBD/COP/DEC/15/4 (2022), Stephen, 2023).

Wind power plays a key role in sustainable energy transition. Worldwide, wind power has increased rapidly over the past decades, becoming a major feature of the energy plan of many countries (REN21, 2021). In France, the total electricity production capacity of offshore wind farms has been multiplied by three in the last three years, reaching 1.5 GW in 2025 (Direction générale de l'énergie et du climat, 2025). In 2022, the offshore wind energy sector and the French government signed an "offshore wind pact" (*pacte éolien en mer*), which aims to attribute 2 GW per year to new offshore wind projects starting from 2025, and achieve 18 GW capacity by 2035, and 40 GW by 2050 (État français & Filière industrielle de l'éolien en mer, 2022). Offshore wind power is not only an alternative to fossil fuels, but also a means for reducing the dependency on other countries for energy and diversifying energy sources. However, the rapid and intense development of these energy sources (referred to as renewable) needs to be accompanied by a comprehensive assessment of their impact on biodiversity. This complies with target 8 of the Global Diversity Framework, which states that it is crucial to "increase the resilience of biodiversity by mitigation, while minimizing negative and fostering positive impacts of climate action on biodiversity".

Despite its advantages, offshore wind power poses environmental challenges on many fronts. For instance, it affects the sea floor by disturbing sediments and producing underwater noise, notably during the construction phase, which can affect fish and invertebrates (Andersson & Stanley, 2020). The presence of turbines can also modify currents and affect phytoplankton productivity, with consequences on pelagic ecosystems (van der Molen et al., 2014). Some positive effects have been observed, such as the "artificial reef effect" resulting from the colonization of these structures by various marine organisms (Degraer et al., 2020). Other impacts, such as those associated with electromagnetic fields generated by power cables or light emissions require further study (BOEM, 2023). In this complex context, this paper focuses on the risks posed to aerofauna (birds and bats) (Galparsoro et al., 2022). Impacts on these species may be direct, such has collisions resulting in injury or death, or indirect, such as behavioural changes, displacement, and habitat modification (Perrow, 2019). These effects are particulary worrying as many species are already in decline and subject to different levels of protection (Dias et al., 2019; Frick et al., 2020; Neate-Clegg et al., 2020). The impact of collision is very well documented for certain species on land (Perrow, 2017), but remains more difficult to study at sea, due to limitations associated with the methods used for observation and the impossibility of doing carcass surveys. However, a few direct observations in Europe have confirmed that collisions do occur between seabirds and offshore wind turbines (Hüppop et al., 2016 ; Skov et al., 2018 ; Bowgen & Cook, 2018). Risks arise mainly from the presence of these structures at sea but can also be exacerbated by induced attraction behaviours and changes to the availability of prey near wind turbines. Behavioural changes are significant, ranging from avoidance to attraction, or even displacement of species away from their preferred area (Dierschke & Garthe, 2016). In Europe, several studies have observed these behaviours in different species of seabirds. The extent and the type of avoidance strongly depend on the species, as well as on the location and the design of the wind farm (Dierschke et al., 2016; Lamb et al., 2024). Attraction can be induced by the artificial lighting of wind turbines and power stations, by the artificial reef effect increasing the availability of prey (Rebke et al., 2019; Degraer et al., 2020), but also by the "reserve effect" produced by the creation of no-take zones within wind farm boundaries, which contributes to the protection and accumulation of biomass locally (van der Molen et al., 2014 ; Hammar et al., 2016). Artificial light, notably continuous white light, frequently attracts and disorientates nocturnal migratory birds, resulting in collisions or fatal exhaustion (Gauthreaux & Belser, 2006; Montevecchi, 2006). This phenomenon is also documented in bats, mainly via the attraction of insects to light sources (Rydell, 1992; Azam et al., 2015; Cravens & Boyles, 2019). Finally, the impacts associated with habitat modification, or effects induced by the environment, include changes to the physical environment and the availability of food resources. These effects can arise from perturbations such as the introduction of invasive species, sea floor erosion, the artificial reef effect induced by the structures themselves (Adams et al., 2014; Degraer et al., 2020; Nielsen et al., 2024; Reubens et al., 2013), or even the "reserve effect" (Gill et al., 2020). These modifications can alter the distribution, abundance, and community structure of prey, and thus indirectly impact aerofauna. However, these impacts remain difficult to measure and are generally poorly known. In the light of persistent uncertainty regarding the extent of these impacts in the marine environment, it is crucial to follow a rigorous hierarchy of mitigation measures, i.e. avoidance, reduction, and as a last resort, compensation.

The "avoid – reduce – compensate" sequence, also known as the mitigation hierarchy, is a central approach for reducing the impacts of offshore wind power on aerofauna (Croll et al., 2022; BOEM, 2024; REWI, 2022). Although experiences accumulated in Europe, where the offshore wind industry is the most developed, provide early indications as to the nature and mechanism of these impacts, many uncertainties persist as to their actual magnitude. As a result, a rigorous application of the "avoid – reduce – compensate" sequence appears essential to regulate and mitigate the impacts of offshore wind farms. Priority is given to the "avoid" step mainly during the planning process, with the aim of locating offshore wind farms away from critical areas for wildlife, such as migration corridors and breeding grounds (Croll et al., 2022). When impacts cannot be avoided, approaches based on the second step ("reduce") of the hierarchy are used, mainly during the design and operation phases, for instance by adjusting technical (e.g. micro-siting, turbine height, deterrent devices) and operational (cut-in speed, lighting) parameters in order to minimize collisions and disturbances (Croll et al., 2022). Finally, if there are residual impacts despite these measures, compensation must be carried out in the form of corrective actions for restoring or improving the state of biodiversity in environments that are functionally similar to the impacted areas. For instance, this could be the creation of new nesting or wintering grounds, the restoration of degraded habitats, or actions against invasive species (Arnett & May, 2016; Natural England, 2022; DEFRA, 2025; BOEM, 2024). The ultimate objective is to counterbalance the losses to achieve "no net loss" in biodiversity, or even a gain in biodiversity, as stipulated in article L. 110-1 of the French Environmental Code, aligned with the principles of the mitigation hierarchy (Croll et al., 2022; BOEM, 2024).

In the context of these uncertainties and to ensure that conservation targets are reached, many have highlighted the need to assess the effectiveness of mitigation measures. This approach will determine whether the strategies adopted provide the expected environmental benefits and allow practices to be adjusted in the light of these results to continually improve the environmental management of offshore wind farms.

Offshore wind energy: the application process

The installation of offshore wind farms within the French public maritime area is subject to: (i) an environmental authorization under articles L.181-1 ff. of the Environmental Code (Légifrance, 2024); (ii) a concession for the right to use the public maritime domain provided for in article L.2124-3 the General Code of Public Property (Légifrance, 2020); and (iii) an operating license delivered in accordance with article L.311-5 of the Energy Code (Légifrance, 2024). Beyond territorial waters, these decisions are fused into a single authorization as per ordinance no. 2016-1687 of December 8, 2016 (Légifrance, 2016). Prior to that, any offshore wind energy project or programme must be subject to a strategic environmental assessment in accordance with articles L.122-4 et R.122-17 (Légifrance, 2023), and individual wind farms must be subject to an environmental impact assessment as required by article L.122-1 (Légifrance, 2024). The authorization process must involve public consultation to ensure public access to information and participation, in accordance with article L.123-1 (Légifrance, 2024), and must be compatible with the maritime spatial planning plan set by the Sea Basin Strategy Documents under articles R.219-1-7 ff. (Légifrance, 2017).

MAIN OBJECTIVE OF THE REVIEW

The French Foundation for Biodiversity Research (FRB) decided to carry out a review of the scientific and technical literature on the effectiveness of measures for reducing the impact of offshore wind farms on aerofauna. This project is part of a larger programme funded by the Mirova Research Center, which aims to encourage the adoption of effective practices and the de-implementation of ineffective practices, and provide operational recommendations based on solid scientific evidence to improve the conciliation of wind power development and biodiversity.

This programme relies on close collaboration between different specialists and has three complementary areas of activity. First, it involves the production of scientific knowledge syntheses, including updates of previously published syntheses, on the impact of renewable energy – onshore wind power, offshore wind power, and solar power – on biodiversity, as well as three review papers on the effectiveness of the measures in place for minimizing these impacts. Second, it offers research funding opportunities: four innovative projects that will provide new knowledge on this topic have recently been funded. Finally, expert-led workshops are organized to provide an opportunity for scientists, government agencies, regulators, and project developers and operators to meet. These workshops aim to foster dialogue, inspire new ideas and optimize biodiversity conservation practices.

This programme stands out by its use of an integrated and holistic approach for tackling the environmental challenges posed by the development of renewable energy. The impacts of the main technologies (onshore and offshore wind power, solar power) are reviewed based on rigorous scientific evidence to propose effective mitigation measures. Moreover, by funding innovative research, the programme demonstrates its commitment to the production of new knowledge.

The FRB, in association with the Mirova Research Center, is responsible for providing a synthesis (a "rapid review") of the interactions between wind power development and biodiversity. The programme's scientific committee has steered this review towards a review of the academic and technical literature on the effectiveness of mitigation measures and the practices in place to minimize the impact of offshore wind power on aerial species (birds, bats and insects). A rapid review, an abridged version of a systematic review, aims to provide relevant information in a condensed format (best practices, success, failures and knowledge gaps). This overview is essential for guiding policy and future practices, as well as for optimizing the selection of projects where financial investments will be steered toward practices that support biodiversity conservation.

However, early in the literature search, it became rapidly apparent that studies that specifically investigated the effectiveness of mitigation measures in relation to offshore wind energy were extremely rare, even non-existent, in the databases queried. There were no readily accessible studies that provided a direct answer to this question. This observation was corroborated by a recent review entitled “Strategies for Mitigating Impacts to Aerofauna from Offshore Wind Energy Development: Available Evidence and Data Gaps” by Gulka et al. (2024). In their review, the measures that were put forward as being effective had never been assessed specifically in the context of offshore wind farms. Instead, evidence came from studies carried out in other contexts, including terrestrial wind facilities. Because of this, we changed the focus of our review to be a compilation of recommendations from the scientific community. The objective was therefore to identify the mitigation measures that were deemed pertinent by experts and assess the general trends in best practice recommendations, despite a lack of systematic assessment of their effectiveness.

Therefore, the main question of this Review is the following: “What are the recommendations for mitigating the impacts of offshore wind farms on aerofauna, despite the lack of effectiveness assessments?”.

Note to readers:

For details of the methods used in this review, see the appendices (Appendix I-III). The bibliographic search strategy and the criteria for selecting documents are described in the Methods section. The approaches used for the narrative synthesis are also given. This information provides a complete description of the methods used to ensure the scientific rigour and robustness of the conclusions presented here.

DESCRIPTIVE ANALYSIS OF THE SELECTED DOCUMENTS

Search and selection

Bibliographic reference selection process

Records were retrieved from different online publication databases and search engines: 460 records from Web of Science, 401 from BASE, and 400 from Google Scholar.

Of the initial 1,261 records, 688 unique references were retained after removing duplicates (Figure 1). 391 citations were retained after assessing titles and abstracts. Full texts were not available for 20 references (5.1 %). After assessing the full texts, 45 relevant articles were selected, consisting of 34 original research articles and 11 review articles. Full texts were excluded mainly because of inappropriate interventions[2] (72.4 %), or because populations[3] (18.7 %) were not considered relevant.

Sources and types of references selected

All selected articles were retrieved through the main online publication databases, primarily Web of Science (39 articles, 86.7 %) (Figure 2). Among these, except for one book chapter, all were scientific articles, indicating that this database is particularly rich in peer-reviewed academic papers. Four additional references (8.9 %) were retrieved from BASE: a research paper, a Master’s thesis, a Ph.D. thesis, and a technical report. It is important to note that most of the records retrieved from BASE were discarded because they were duplicates of those from Web of Science. This suggests that BASE is an important source of unpublished and grey literature, offering a complementary perspective to scientific articles. Two references (4.4 %) were retrieved using Google Scholar, both of which were scientific articles. Like BASE, many records from Google Scholar were duplicates of those from Web of Science and/or BASE. These results indicate that, although Google Scholar can find a considerable number of references, the added value it provides is relatively low compared to Web of Science and

[2] When an action or an intervention described in a paper does not correspond to the subject of the review; for instance, the study of measures on land.

[3] When an article focused on a population that “deviates” from the target groups, i.e. species other than birds, bats, and flying insects.

BASE. However, it is still a useful source for getting access to references that may not be indexed in other academic databases. Additional searches of websites dedicated to renewable energy or wind power did not provide any other sufficiently informative references. It is worth noting that the Mitigation Practices Database (MPD) Tool, which was queried, does not list any studies assessing the effectiveness of measures for mitigating the impact of offshore wind power on aerofauna. This absence is particularly significant because this database was developed following a literature review commissioned in 2018-2019 by the New York State Energy Research and Development Authority, to compile and assess the options for mitigating the effects of offshore wind power on fisheries and marine wildlife, both aerial and subaquatic.

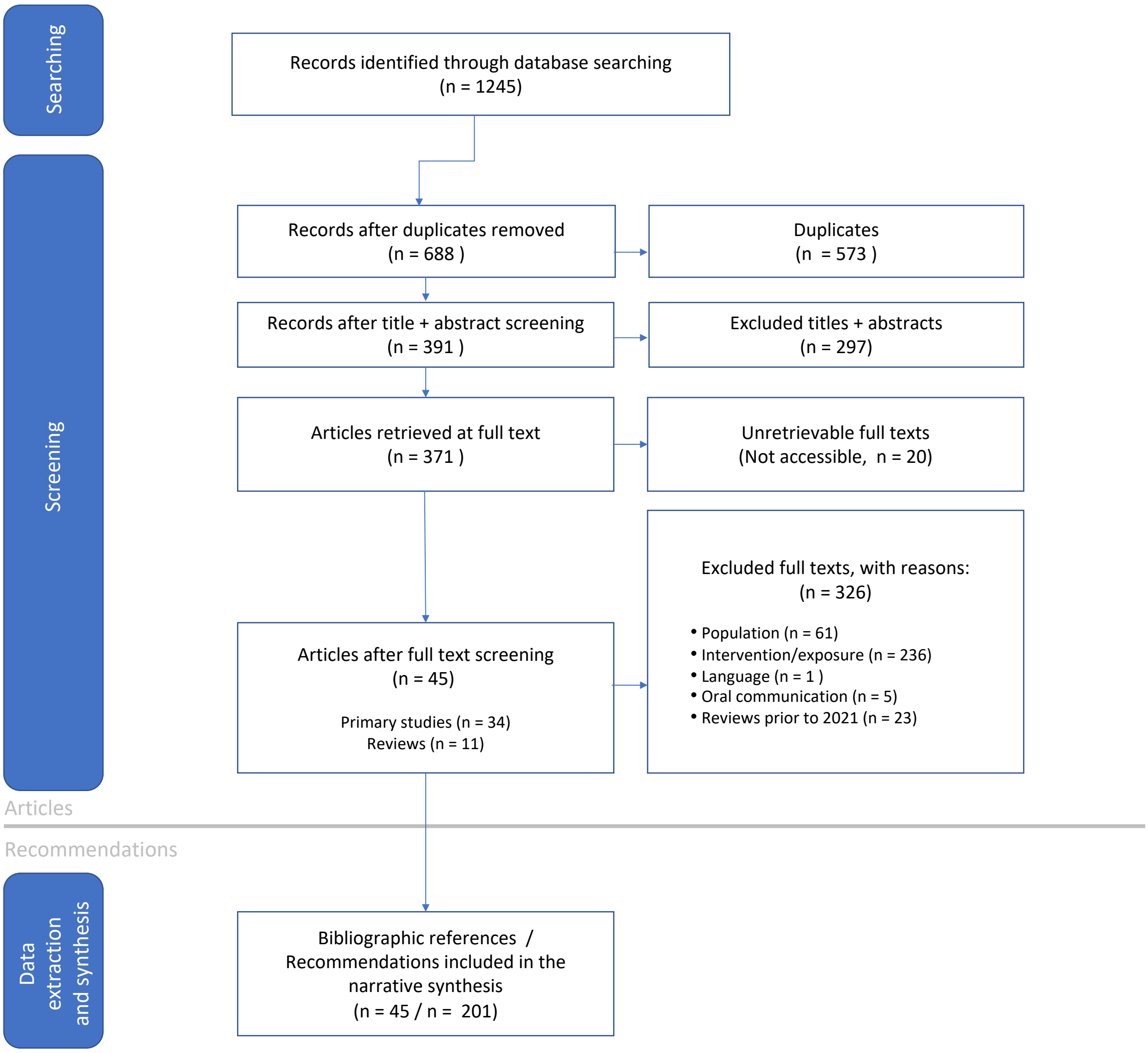

Figure 1. ROSES flow diagram of the selection process of bibliographic references included in the systematic mapping study.

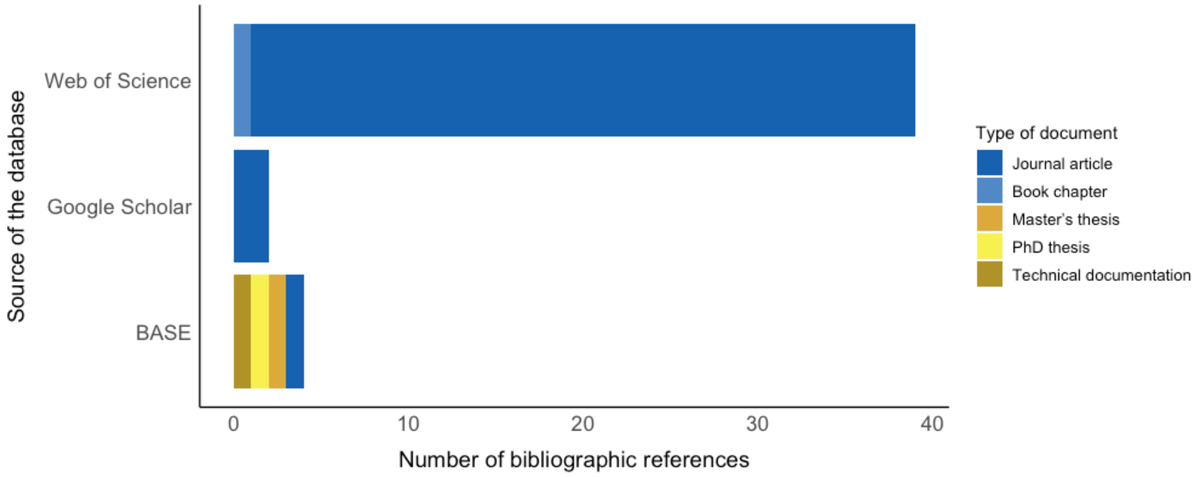

Figure 1. Number of selected bibliographic references by source and document type.

Key characteristics

Temporal evolution

The earliest selected publications date from 2004, indicating that awareness of the need to mitigate the impact of offshore wind power on aerofauna is relatively recent and still limited (Figure 3). Indeed, the number of "primary research articles" referenced each year between 2004 and 2018 varied between zero and three. From 2019, there was a slight increase in the number primary research studies published, plateauing at four per year. Even if we include review papers, the total number of documents does not exceed seven per year. This trend indicates that research efforts to assess and improve the effectiveness of measures for mitigating the impact of offshore wind power on biodiversity have only slightly intensified. Wind power has grown rapidly in the last few years, and its impact on biodiversity has only been acknowledged recently. Whereas mitigation measures are increasingly studied in the context of onshore wind power, the situation for offshore wind power, where scientific data is still scarce and many gaps exist, remains worrying. Indeed, we were unable to find any scientific study that assessed the effectiveness of mitigation measures specifically in the context of offshore wind power. Note that our bibliographic search was carried out in mid-September 2024, thus the numbers are incomplete for that year.

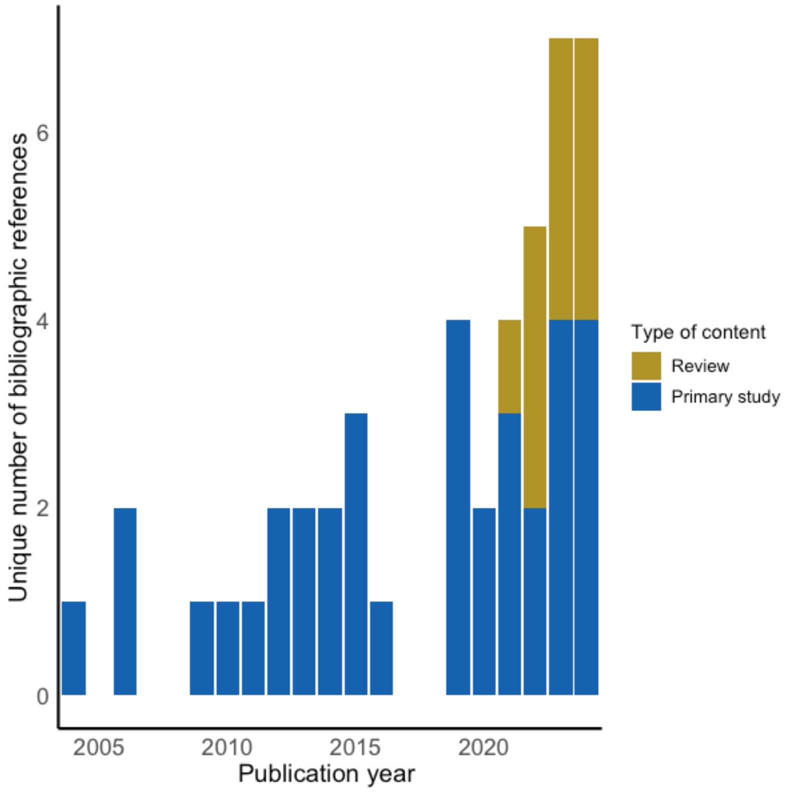

Figure 2. Number of selected bibliographic references per year. The search was carried out mid- September 2024.

Geographic distribution

When specified (80 %), studies were mainly carried out in Europe (46.7 %) and the United States (~26.7 %), while other regions were notably under-represented (**Erreur ! Argument de commutateur inconnu.**). In other parts of the world, data was either absent or very limited (one document). In terms of maritime areas, most studies were concentrated in the North Sea (33.3 %) and the North Atlantic Ocean (22.2 %), areas where offshore wind power is particularly well established and in constant development. These areas, benefiting from favourable wind conditions and the political will to promote renewable energy production, concentrate a large proportion of wind power projects and, consequently, of the recommendations. In the same part of the world, the Baltic Sea (6.7 %) and the Celtic Sea (2.22 %) also appear in publications, but to a lesser extent. This distribution illustrates the evolution of research efforts in relation to the dynamics of offshore wind energy development.

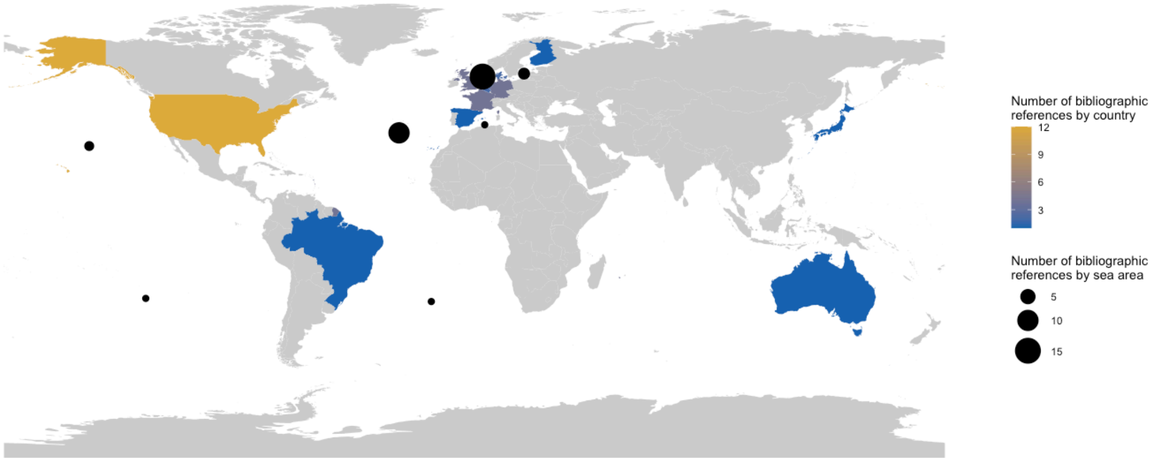

Figure 3. Geographic distribution of the selected bibliographic references by country or by sea/ocean. Note: France does not have any bibliographic references but has been coloured in to help visualize the number of studies carried out in Europe sensu lato.

Taxonomic groups studied

Recommendations were unevenly distributed between the different taxonomic groups (Figure 5). Bats featured in 12 bibliographic references comprising 45 recommendations (representing 26.7 % of the references and 22.5 % of the recommendations). By comparison, birds featured predominantly in the literature, with 42 bibliographic references and 175 recommendations, representing 93.3 % of the references and 87.1 % of the recommendations, respectively. There were no recommendations for insects. When specific characteristics were specified for bats (80 % of cases), these were exclusively related to their migratory status. For birds, nearly 53 % of recommendations targeted “seabirds”, whereas ~12 % targeted migratory species (Figure 6).

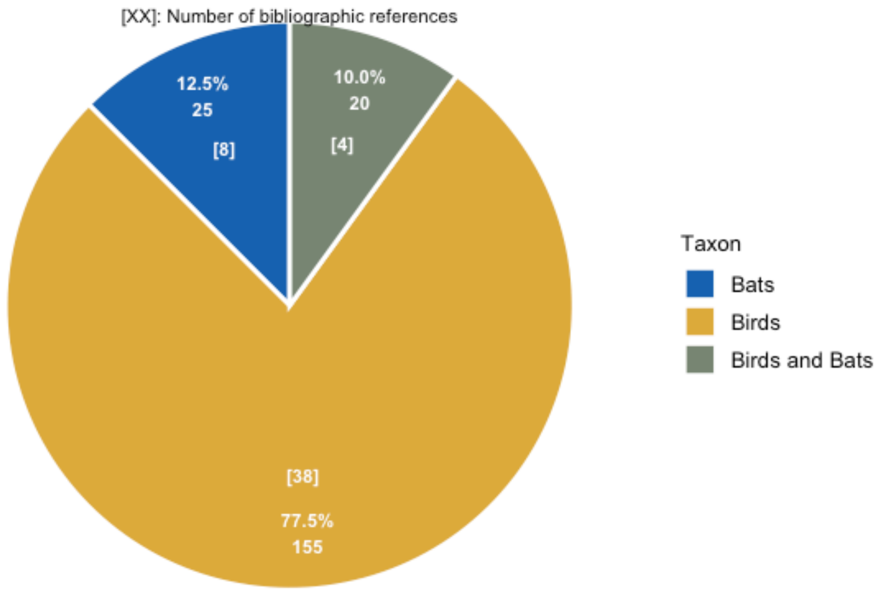

Figure 4. Number of recommendations and bibliographic references (in brackets) for each taxonomic group.

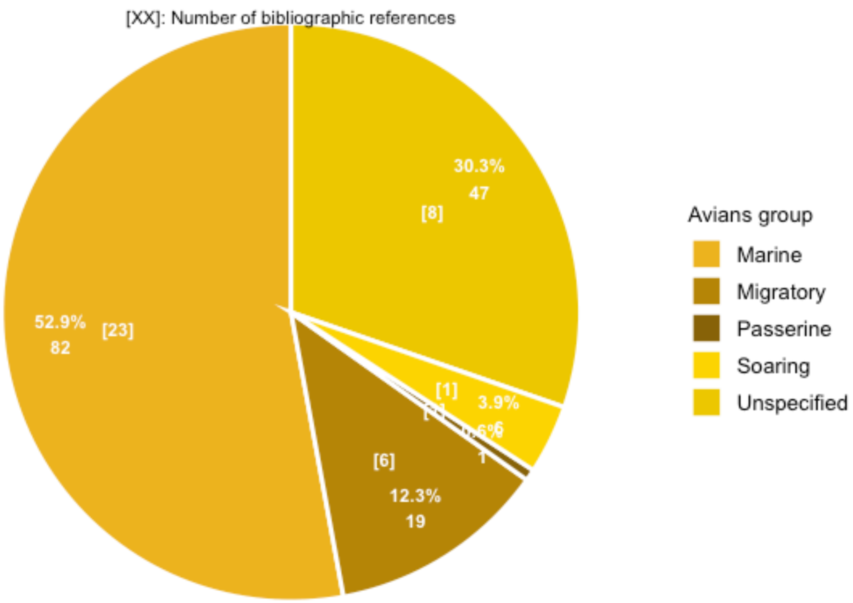

Figure 5. Number of recommendations and bibliographic references (in brackets) for each bird group/type.

Recommendation characteristics

The most frequent recommendations centred around "planning and impact assessment tools", which were mentioned in nearly half of the bibliographic references (Figure 7; see Appendix I: Methods for a definition of the different recommendation categories). "Turbine location and positioning" were also frequently mentioned (13 references), this category being directly derived from the first, being implemented with the help of planning tools. Altogether, these types of recommendations represent the most frequently cited approaches for anticipating and limiting environmental impacts prior to the installation of infrastructure. "Operational modifications" and "technical or technological measures" were mentioned in a relatively high number of references (17 and 16, respectively) and represent a significant portion of all recommendations. These two categories include turbine curtailment measures, such as temporary shutdown during migration periods, and the use of technology to adjust operations to reduce the risk to wildlife. "Research and development (R&D)" were mentioned in 16 references, highlighting the need for continuously improving knowledge and solutions for mitigating the impacts of offshore wind farms. "Infrastructure adaptation" includes measures for improving visibility and was mentioned in ten or so references. "Collaboration and integrated management" were mentioned in significantly fewer references even though it is a complementary lever for impact mitigation. Finally, "environmental compensation" was the least common, indicating that compensatory measures are seldom cited in the recommendations we examined. Note that "training and awareness raising" was not mentioned at all, suggesting that this approach has not been considered in the selected literature.

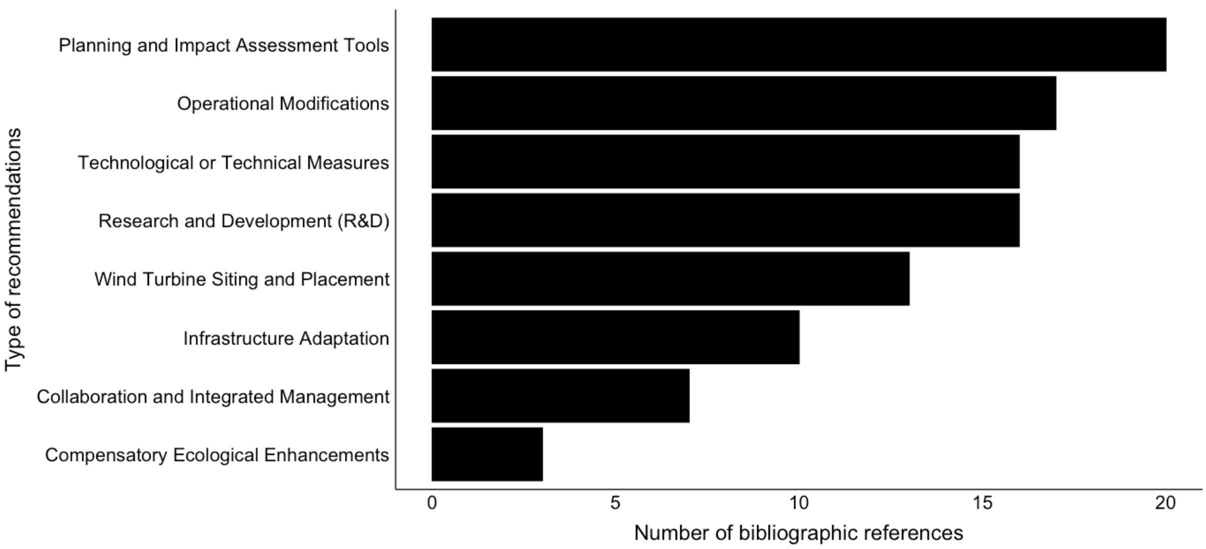

Figure 6. Number of bibliographic references for each main type of recommendation.

The distribution of the number of bibliographic references per type of measure reflects the importance of the type of recommendation (Figure 8). From our analysis, the most frequently cited measures corresponded to the siting process (both macro and micro-siting). Macro-siting, i.e. the process of selecting the geographic location of the site based on environmental considerations, was mentioned in 30 references, while micro-siting, i.e. the process of determining the internal characteristics of a wind farm, was mentioned in five references. This trend illustrates the importance given to planning and impact assessment tools as well as to the location and positioning of wind turbines, which have been identified as major components of the mitigation strategy. The second-most frequently cited measures were turbine curtailment options, which were mentioned in over 21 references, highlighting the attention given to operational as well as technical and technological solutions, e.g. making operational adjustments such as stopping turbines during critical periods for wildlife. Turbine visibility was mentioned in 12 references, illustrating the interest for making turbines more visible to wildlife by modifying their design or using specific visual signals. Deterrence strategies (e.g. the use of ultrasonic deterrents for bats), temporal planning, compensatory measures, and wind farm repowering were less frequently mentioned, each being cited in five or less references.

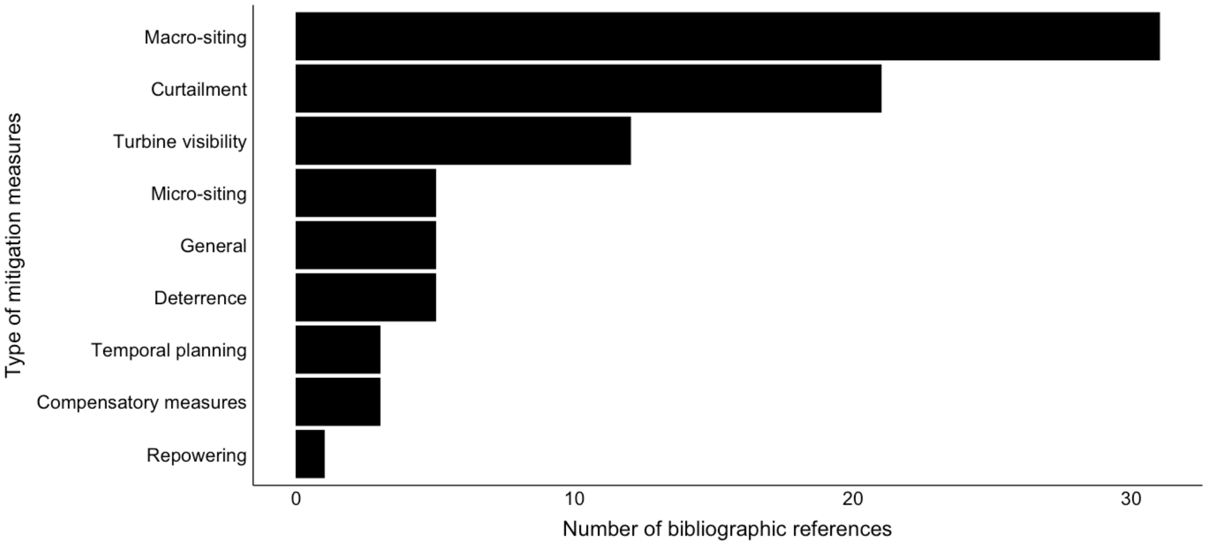

Figure 7. Number of bibliographic references for each type of measure.

The table below (Table 1) lists all the measures associated with the recommendations identified in the scientific literature. This summary shows that there are a variety of approaches within each broad category of measures, but also that certain specific categories have received more attention from the scientific community.

In relation to macro-siting, several points were emphasized. First, long-term analyses are considered essential for effective planning, allowing more precise predictions of the environmental impacts of offshore wind farms to be made. Moreover, impacts need to be assessed using a precise methodological framework that integrates the different tools of Environmental Impact Assessments. Transnational and multipartite collaboration is also mentioned, as it fosters data sharing and the development of standardized practices. The establishment of exclusion zones is among the preferred strategies for mitigation: it aims to preclude wind farm installations in areas that are particularly important for wildlife.

On a more local scale, the micro-siting process focused on two elements: wind farm design, which considers site characteristics to optimize turbine arrangement, and migration corridors, which need to be considered to avoid interfering with bird/bat flyways.

Turbine curtailment was also frequently mentioned, involving mainly two types of strategies. First, there is smart, or dynamic, curtailment, which relies on detection systems that trigger real-time adjustments to turbine operations in response to the presence of at-risk species. Second, seasonal curtailment involves the temporary shutdown of turbines during critical periods such as bird and bat migration periods.

Finally, turbine visibility is an important area of research, with several recommendations made for making turbines more visible to aerofauna. We found three main strategies in the literature: adjusting the lights on wind turbines to attract birds and insects less, adjusting elements of turbine size as they can influence species' perception and behaviour, and painting turbines with different colours or motifs to improve blade visibility and reduce bird collision risk.

In summary, the distribution of bibliographic references per recommendation and measure category shows that priority is given to the “avoid” step of the “avoid – reduce – compensate” sequence, while compensatory measures are marginal in the current literature. Mitigation strategies, such as turbine curtailment or visibility, are also important. Moreover, research and development (R&D) efforts are often mentioned, emphasizing the need to improve knowledge of the impacts of offshore wind farms on wildlife, develop solutions to minimize these impacts, and assess the effectiveness of these solutions.

Table 1. List of the characteristics of the recommendations for mitigating the impact of offshore wind farms on aerofauna, compiled from 45 research articles and other types of documents. 201 entries were classified into 9 broad measure types, 68 measure subtypes, and 8 recommendation categories.

Measure type	Measure subtype	Recommendation	Taxonomic group	Number of references	References
Macro-siting	Flight altitude	Research and development (R&D)	Birds	2	Reid et al. (2023); Watts et al. (2022)
	Holistic analysis	Planning and impact assessment tools	Birds	2	Reid et al. (2023); Fox et al. (2006)
	Long-term analysis	Planning and impact assessment tools	Birds	6	Goyert et al. (2016); Winiarski et al. (2014); Thaxter et al. (2019); Thaxter et al. (2015); Croll et al. (2022); Abramic et al. (2022)
	Framework for impact assessments	Collaboration and integrated management	Birds	2	Busch et al. (2013); Walsh et al. (2024)
			Bats	1	Walsh et al. (2024)
		Operational modifications	Birds	1	Grover (2023)
		Planning and impact assessment tools	Birds	9	Christel et al. (2013); Reid et al. (2023); Lapeña et al. (2010); Fox et al. (2006); Nebel et al. (2024); (Best et Halpin, 2019); (Desholm, 2009); Grover (2023); Croll et al. (2022)
	Transnational and multipartite collaboration	Collaboration and integrated management	Birds	3	Busch et al. (2013); Walsh et al. (2024); Gulka et al. (2024)
			Bats	2	Walsh et al. (2024); Gulka et al. (2024)
	Data collection	Planning and impact assessment tools	Birds	1	Reid et al. (2023)
		Research and development (R&D)	Birds	1	Cleasby et al. (2015)
	Migration corridors	Turbine location and positioning	Bats	1	O'Neil (2020)
			Birds	3	Hüppop et al. (2006); Walsh et al. (2024); Abramic et al. (2022)
		Planning and impact assessment tools	Birds	3	Christel et al. (2013); Hüppop & Hilgerloh (2012); Grover (2023)
		Research and development (R&D)	Bats	2	True et al. (2023); O'Neil (2020)
	Exclusion zones	Turbine location and positioning	Bats	2	O'Neil (2020) ; Gulka et al. (2024)
			Birds	5	Hüppop et al. (2006); Watts et al. (2022); Croll et al. (2022); Abramic et al. (2022); Gulka et al. (2024)
	Scientific expertise	Planning and impact assessment tools	Birds	2	Lieske et al. (2019); Croll et al. (2022)

	Impact assessment tool – Collision risk model	Research and development (R&D)	Birds	1	Croll et al. (2022)
	Impact assessment tool – Deterministic model	Planning and impact assessment tools	Birds	1	Lapeña et al. (2010)
	Impact assessment tool – Species-specific sensitivity index	Planning and impact assessment tools	Birds	2	Obane et al. (2024); Garthe et Hüppop (2004)
	Modelling	Research and development (R&D)	Birds	2	Fox et al. (2006); Croll et al. (2022)
	Impact assessment tool	Research and development (R&D)	Birds	1	Nebel et al. (2024)
	Impact assessment tool - Sensitivity map	Planning and impact assessment tools	Birds	2	Reid et al. (2023); Thaxter et al. (2019)
	Impact assessment tool – Ecological niche modelling	Planning and impact assessment tools	Birds	2	Lemos et al. (2023); Nebel et al. (2024)
	Data sharing	Collaboration and integrated management	Birds	2	(Grover, 2023); Croll et al. (2022)
	Standardized protocols and procedures	Collaboration and integrated management	Birds	2	Fox et al. (2006); Busch et al. (2013)
	Behavioural research	Research and development (R&D)	Bats	1	O'Neil (2020)
			Birds	3	Schwemmer et al. (2023); Grover (2023); Green et al. (2022)
	Species distribution	Turbine location and positioning	Birds	1	Loring et al. (2014)
		Planning and impact assessment tools	Birds	2	Goyert et al. (2016); Winiarski et al. (2014)
	Buffer zones	Turbine location and positioning	Bats	2	Brabant et al. (2021); Gulka et al. (2024)
			Birds	2	Nebel et al. (2024); Gulka et al. (2024)
	Cumulative impact assessment	Planning and impact assessment tools	Birds	2	Thaxter et al. (2019); (Grover, 2023)
Micro-siting	Data collection	Research and development (R&D)	Birds	1	Masden et al. (2012)
	Wind farm design	Turbine location and positioning	Birds	3	Masden et al. (2012); Hüppop et al. (2006); Gulka et al. (2024)
			Bats	1	Gulka et al. (2024)
		Planning and impact assessment tools	Birds	1	Masden et al. (2012)
	Migration corridor	Turbine location and positioning	Birds	3	Goodale & Milman (2020); Hueppop et al. (2006); Gorman et al. (2023)

			Bats	1	Gorman et al. (2023)
	Impact assessment tool – Bird movement model	Planning and impact assessment tools	Birds	1	Masden et al. (2012)
Temporal planning	Adaptive planning and temporal avoidance	Operational modifications	Birds	3	Perrow et al. (2011); Croll et al. (2022); Gulka et al. (2024)
			Bats	1	Gulka et al. (2024)
Curtailment	Adapted to regional migration periods	Operational modifications	Birds	1	Machado et al. (2024)
	Predictive “smart curtailment” algorithms	Technical or technological measures	Bats	1	True et al. (2021)
		Research and development (R&D)	Bats	1	True et al. (2021)
	Targeted curtailment	Technical or technological measures	Bats	1	Bach et al. (2022)
		Operational modifications	Birds	1	Bradarić et al. (2024)
		Research and development (R&D)	Birds	1	Bradarić et al. (2024)
	Raising the cut-in speed	Technical or technological measures	Bats	2	Brabant et al. (2021); True et al. (2023)
		Operational modifications	Bats	1	Gulka et al. (2024)
	Weather-based curtailment	Operational modifications	Birds	2	Grover (2023); Schwemmer et al. (2023)
		Research and development (R&D)	Birds	1	Grover (2023)
	General curtailment	Operational modifications	Birds	1	Croll et al. (2022)
	Detection-based smart curtailment	Technical or technological measures	Bats	1	Willmott et al. (2015)
			Birds	2	Willmott et al. (2015); Nebel et al. (2024)
	Predictive smart curtailment	Technical or technological measures	Bats	1	True et al. (2023)
			Birds	5	Weiser et al. (2024); Hüppop & Hilgerloh (2012); Hüppop et al. (2006); Walsh et al. (2024); Machado et al. (2024)
		Operational modifications	Bats	2	Solick & Newman (2021); Gulka et al. (2024)
			Birds	2	Brabant et al. (2021); Gulka et al. (2024)
	Seasonal curtailment	Operational modifications	Birds	2	Schwemmer et al. (2023); Gulka et al. (2024)
			Bats	1	Gulka et al. (2024)

	Seasonal curtailment / Targeted shutdown	Operational modifications	Birds	2	Reid et al. (2023); Watts et al. (2022)
	Transnational and multipartite collaboration	Collaboration and integrated management	Birds	1	Machado et al. (2024)
	Migration corridor	Research and development (R&D)	Birds	1	Machado et al. (2024)
	Continuous optimization of curtailment protocols	Operational modifications	Birds	1	Machado et al. (2024)
	Data sharing	Collaboration and integrated management	Birds	1	Machado et al. (2024)
	Standardized protocols and procedures	Collaboration and integrated management	Birds	1	Machado et al. (2024)
	Behavioural research	Research and development (R&D)	Birds	1	Machado et al. (2024)
	Site-specific monitoring	Technical or technological measures	Bats	1	True et al. (2023)
	Risk assessment and adaptive curtailment	Operational modifications	Birds and bats	1	Gorman et al. (2023)
Turbine visibility	Turbine size adjustment	Infrastructure adaptation	Birds	4	Reid et al. (2023); Cleasby et al. (2015); Goodale & Milman (2020); Gulka et al. (2024)
	Rotor blade design	Infrastructure adaptation	Birds	1	Nebel et al. (2024)
	Lighting management	Infrastructure adaptation	Birds	3	Gulka et al. (2024); Grover (2023); Croll et al. (2022)
		Operational modifications	Birds	6	Rebke et al. (2019); Goodale & Milman (2020); Hüppop & Hilgerloh (2012); Hüppop et al. (2006); Walsh et al. (2024); Gulka et al. (2024)
			Bats	1	Gulka et al. (2024)
		Research and development (R&D)	Birds	1	Hüppop et al. (2006)
	Turbine painting	Infrastructure adaptation	Insects (indirectly bats)	1	Gulka et al. (2024)
			Birds	1	Martin & Banks (2023)
		Research and development (R&D)	Birds	1	Grover (2023)
	General visual stimuli	Infrastructure adaptation	Birds	1	Croll et al. (2022)
Deterrence	Anti-perching system	Infrastructure adaptation	Birds	1	Grover (2023)
	Acoustic deterrents	Technical or technological measures	Birds	2	Gulka et al. (2024); Croll et al. (2022)

	Ultrasonic acoustic deterrents	Technical or technological measures	Bats	2	Solick & Newman (2021); Gulka et al. (2024)
		Research and development (R&D)	Bats	1	O'Neil (2020)
	Light deterrents	Technical or technological measures	Birds and bats	1	Gulka et al. (2024)
	UV light deterrents	Infrastructure adaptation	Birds	1	Gulka et al. (2024)
		Technical or technological measures	Bats	1	Solick & Newman (2021)
	Texturized surfaces	Infrastructure adaptation	Bats	1	Solick & Newman (2021)
	Electromagnetic signals	Technical or technological measures	Bats	1	Gulka et al. (2024)
Repowering	Micro-siting	Turbine location and positioning	Birds and bats	1	Gulka et al. (2024)
Compensatory measures	Habitat-based compensation	Environmental compensation	Birds	3	Reid et al. (2023); Croll et al. (2022); Gulka et al. (2024)
			Bats	1	Gulka et al. (2024)
	Financial compensation (non-applicable in France)		Birds	2	Croll et al. (2022); Gulka et al. (2024)
			Bats	1	Gulka et al. (2024)
	Targeted conservation measures		Birds	2	Gulka et al. (2024); Croll et al. (2022)
	Planning and assessment of compensatory measures		Birds	2	Reid et al. (2023); Croll et al. (2022)
Misc.	Data collection	Technical or technological measures	Birds	2	Grover (2023); Croll et al. (2022)
	Development of collision risk mitigation measures that are specific to the marine environment	Research and development (R&D)	Birds	1	Croll et al. (2022)
	Effectiveness and cost of mitigation measures and monitoring	Research and development (R&D)	Birds and bats	1	Green et al. (2022)
	Adaptive strategies	Technical or technological measures	Bats	1	O'Neil (2020)
	Minimization strategies	Infrastructure adaptation	Birds	1	Abramic et al. (2022)
		Research and development (R&D)	Birds	1	Croll et al. (2022)

NARRATIVE SYNTHESIS

Spatial planning

Spatial planning is an essential part of offshore wind farm development. During the planning stage, prior to the installation of any infrastructure, the most severe impacts on aerofauna (mainly migratory marine birds and bats) can be avoided. Planning revolves around the identification, on a regional or local scale, of sensitive areas (e.g. migration corridors, critical habitats, high abundance areas) to guide the choice of future wind farm sites, and the establishment of exclusion zones and protected areas. This preventative approach is based on the principles of ecosystem-based management (Douvere, 2008), and is informed by a combination of ecological knowledge, spatial modelling, monitoring data, and concertation between actors. It aims to reconcile as best as possible the objectives of energy development with the necessity to conserve biodiversity.

Collaboration and data sharing

Several recent documents have identified active collaboration and transparent data sharing as key elements for optimizing the spatial planning strategies for minimizing the impact of offshore wind farms on marine aerofauna.

Soliciting expert opinion is mentioned as a valid approach when data are insufficient or incomplete, notably on a regional or global scale. Lieske et al. (2022) found that integrating local expert knowledge improves the performance and robustness of predictive models. They show that the systematic qualitative synthesis of expert knowledge using the Analytic Hierarchy Process (AHP) was useful for in-depth assessments of seabird sensitivity to different environmental risks. This approach allows the integration of a wide range of knowledge sources, including direct and indirect observations, professional experience, as well as the substantial amount of information provided by unpublished data and grey literature, which would be missed in conventional literature searches. Moreover, expert review is an essential step in the validation of predictive ecological models, as it can help identify model failures and improve performance (Croll et al., 2022).

For data management, several authors strongly recommend that data be shared publicly. Grover (2023) stresses that government agencies should make systematic public sharing of the data a condition for the approval of offshore wind energy projects. Transparent data sharing provides the opportunity to pool knowledge and thus facilitates informed and consensual decision-making. For the same reason, it is recommended that access to model code be open to ensure transparency and resolve concerns surrounding uncertainty and variability of available input parameters (Croll et al., 2022). This would help identify and resolve model and data limitations where possible.

Finally, several studies stress the need to reinforce transnational and multipartite collaboration in the context offshore wind development. Greater cooperation between neighbouring countries is considered an essential lever to ensure coherence in the way environmental targets for offshore wind projects are taken into consideration (Busch et al., 2013). There is also a need for enhanced transboundary cooperation between economic actors, consenting authorities, policy-makers, and researchers at the scale of the Greater North Sea, to ensure a realistic and robust assessment of the cumulative effects (Walsh et al., 2024). Moreover, early engagement with local stakeholders and institutions, such as local communities, and state or federal agencies, is advised to minimize potential impacts, particularly with regards to siting (Gulka et al., 2024).

Standardized protocols

Standardizing protocols and procedures at the regional and even international level is an essential complement to data sharing: without harmonized methods, between-site comparisons lose their scientific value. Fox et al. (2006) stress the need for the adoption of common, preferably international, best practice standards to enable standard collation of data and ensure the most effective cross comparison of experiences acquired on different offshore wind farms. They also make the case for a centralized data handling facility to collate and curate data and ensure experiences and scientific data are made available to all stakeholders. Similarly, Busch et al. (2013) advise harmonizing offshore wind farm national approval procedures, and environmental assessment and monitoring protocols. However, they also warn of the risks associated with harmonization, including the lowering of existing national environmental standards and targets, as happened with the European common fisheries policy. Harmonization therefore requires a clear governance framework that guarantees that minimal standards will not be lowered.

Research and monitoring

Environmental and ecological data collection, behavioural monitoring, the analysis of bird and bat flight altitudes, long-term studies, and predictive modelling were identified as essential avenues for research and monitoring to optimize the spatial planning of offshore wind farms.

Several articles emphasize the need for different and complementary data collection methods. Reid et al. (2023) highlight the importance of combining boat-based visual surveys (precise but limited in spatial and temporal coverage), aerial surveys (greater spatial coverage but lower taxon identification resolution), radar (extensive temporal coverage but no taxon identification), and, for more precise flight altitude and trajectory information, animal-borne devices (GPS, altimeters), to obtain a complete view of the use by birds of offshore areas considered for wind farm projects. Cleasby et al. (2015) stress the need for more species-specific data, for example for gannets and other high-priority species such as large gulls, to refine collision-risk estimates and sustainable mortality thresholds needed to assess long-term population viability.

Further research on the migratory behaviour of seabirds near offshore wind farms is urgently required to support planning decisions based on solid evidence (Green et al., 2022). Schwemmer et al. (2023) indicate the need to quantify the energetic costs to migratory birds of the cumulative barrier effects of offshore wind farms. To continuously monitor bat movement patterns offshore, a network of preexisting offshore structures can be employed, which would significantly improve our understanding of bat migration patterns (O'Neil, 2020). Grover (2023) recommends carrying out more surveys, studies, and modelling, to ensure the lowest possible number of collision events in the California offshore wind area, and future projects around the world.

The acquisition of species-specific flight altitude data is addressed in two articles, which consider flight altitude to be key factor in collision risk. The lack of empirical altitude data is emphasized, and the collection of species-specific data is seen as a priority to improve our understanding of vertical exposure to offshore wind turbines (Reid et al., 2023; Watts et al., 2022).

Goyert et al. (2016) stress the need to integrate mid- to long-term spatio-temporal variability in impact assessments, given the ongoing changes in climate and environmental conditions. Winiarski et al. (2014) support this recommendation by highlighting that multi-annual surveys are needed to effectively integrate the variation in spatial distribution models. Prolonged monitoring thus provides a better understanding of behaviour and wildlife-wind farm interaction variability (Thaxter et al., 2015; Thaxter et al., 2019) and allows the incorporation of intra- and interannual variability to improve predictive models in the light of climate change (Croll et al., 2022). These assessments must also be based on historical time series to reflect the current real state of the marine environment (Abramic et al ., 2022).

Finally, the continuous development of modelling tools is crucial for assessing the impact of offshore wind projects on biodiversity. Fox et al. (2006) stress the importance of having models that can convert measurements of local effects into impacts at the population level, to assess the impact of offshore wind farms on migrating species. Croll et al. (2022) emphasize the need for species distribution models that link environmental covariates and telemetry data to inform siting. However, these authors add that certain methodological limitations associated with modelling spatio-temporal and interaction data need to be overcome to improve the predictive accuracy and ecological relevance of these models.

Note to the reader:
Additional methods (assessing monitoring effectiveness, BACI studies, continuous adjustment of impact models) are described in the "impact assessment of wind energy development" section below, where they are discussed in the context of their applications.

Impact assessment of wind energy development

The methodological framework for assessing the ecological impact of offshore wind farms is crucial for the planning process. Various articles give different recommendations for improving the process's robustness, reliability, and operational pertinence.

According to Christel et al. (2013), this framework must be based on explicit concern levels. Concern levels are defined from the main risks to seabirds: primarily collision with turbine blades and habitat loss. Each level should have its own standard monitoring protocol tailored to the intensity of the risk. For instance, an accurate assessment of collision risk should include flight height and trajectory data obtained by visual transects, radar, GPS, or infrared cameras. As a complement, pre- and post-installation monitoring is needed to validate the initial predictions made by the environmental impact assessment and adjust practices accordingly.

This approach is like that of Fox et al. (2006), who highlight the critical role played by Strategic Environmental Assessments (SEAs) during the planning stage of offshore wind farm development. According to the authors, as part of SEAs, extensive mapping of the seasonal densities of seabirds could help identify sensitive areas. The objective is to avoid discovering at a later stage, during environmental impact assessments (EIAs), previously undetected high bird densities, which could lead to environmental conflicts and major operational delays. They also recommend using weather and military surveillance radar to define bird migration corridors and contribute to robust GIS databases that will enable the analysis of cumulative impacts over the long term.

Cautious planning involves the integration of the precautionary principle in environmental assessments and the systematic use of a power analysis framework to measure the uncertainty of impacts that have remained undetected in the available survey data. Even without a statistically significant[4] result, this approach would determine the probability that a real effect remains statistically undetectable and allow environmental managers to be explicit about which risk they are willing to take for a certain size impact (Lapeña et al., 2010). The early identification of ecologically sensitive areas is critical: the production of maps that compare the economic potential of offshore wind power development and the environmental risks to birds could help the planning process. Ideally, these tools should also estimate the numbers of animals affected and the consequences on populations, to best inform policy decisions (Best & Halpin, 2019).

As a complementary approach, Desholm (2009) proposes a framework for ranking bird species according to their relative abundance and demographic sensitivity. This approach is considered appropriate for wind farm management, as it offers a practical solution to the problem of limited resources for monitoring and conservation, by directing efforts towards ecologically important species. Grover (2023) emphasizes the need for integrating the region-specific flight behaviour and avoidance rates of local species in preliminary impact assessments. These data would produce more reliable vulnerability models, adjusted to the exact technical specifications of the project. Wildlife sensitivity maps, combining species distribution and species sensitivity scores, provide an intuitive and practical way for visualizing potential impacts on a regional and local scale (Reid et al., 2023).

4. In statistics, saying that an effect is "**statistically significant**" amounts to saying that the probability of observing this effect by chance is very low (generally set at less than 5 %). In other words, the data provide enough evidence for the effect to be considered real rather than being due to chance.

Moreover, preliminary assessments should consider the cumulative impacts across neighbouring countries (Busch et al., 2013; Walsh et al., 2024). This broad-scale ecosystem-based approach to marine management also requires adopting a precautionary approach in the absence of complete information. According to these authors, this approach ensures that the cumulative ecological impacts of multiple offshore wind farm projects do not compromise the “good environmental status” of the marine ecosystems in question.

Finally, Nebel et al. (2024) add that moving construction sites to a priori less sensitive areas appears to an effective conservation strategy but requires careful evaluation of the possible effects on other vulnerable species. They recommend an assessment framework that can weigh the environmental pros and cons to determine the optimal siting of wind farms.

The accuracy and pertinence of environmental impact assessments for offshore wind farms rely on the use rigorous methodological tools that are adapted to the marine environment. The authors stress the importance of continually developing and improving these tools to obtain reliable assessments that will inform environmental decision-making.

Spatial planning needs to consider species distribution, both to avoid areas of high ecological value and anticipate potential impacts on bird and bat communities. This approach depends on fine-scale knowledge of relative abundance, spatial distribution, and environmental factors that determine the presence of species in areas considered for development. Species Distribution Models (SDMs) predict the spatial and temporal distribution of birds using survey data crossed with environmental covariates (e.g. depth, surface temperature, primary productivity, distance from the coast). For instance, Winiarski et al. (2014) suggest combining a spatial conservation prioritization approach based on SDMs and ecosystem-based marine spatial planning to identify sensitive areas that should be avoided until the effects of offshore wind energy development on bird population demographics are better understood. SDMs should, however, be founded on robust systematically collected survey data. Data collecting methods must be diverse and complementary: aerial surveys and animal-borne devices provide good taxonomic resolution but are limited in their spatial and temporal coverage, while radar data provides continuous coverage, notably at night, but no taxonomic data. Moreover, a plane’s GPS helps provide the precise geolocation of each observation and facilitates future data combination. One strategy involves combining data from these sources to produce predictive SDMs for the most sensitive species. This approach showed that shallow nearshore habitats were important for certain species of sea ducks such as the black scoter. These specific habitats (hard-bottomed or coarse-sand substrate, < 20 m deep) concentrate high levels of winter foraging activity. The creation of offshore wind farm exclusion zones is a direct application of spatial planning based on bird distribution (Loring et al., 2014). However, species distributions cannot be considered solely from punctual observations. Due to the spatio-temporal dynamics of marine populations, influenced by seasonal and interannual cycles, and climate change, these models must be considered as evolving tools that need to be updated regularly with monitoring data. As Goyert et al. (2016) stress, it is important to identify not only where species are, but also why they are there, by integrating the ecological factors that determine their distribution. This understanding is crucial for evaluating the actual exposure to offshore development and for carrying out credible risk assessments. As for Lemos et al. (2023), they recommend using ecological niche modelling (ENM) in environmental impact assessments. These models, which are particularly useful for areas where data are scarce, assess in a prospective manner the likely distribution of sensitive species and identify higher-risk sites. The authors also suggest the use of a species “richness index” (RI) to identify the seasons and areas with greater ecological vulnerability. In the specific context of sensitive area identification, species distribution modelling (SDM) and ecological niche modelling (ENM) can be considered equivalent.

Carrying out continuous environmental assessments and monitoring is recommended to adapt conservation measures (Nebel et al., 2024). Using habitat models together with cumulative impact assessments is also recommended to better understand the effects on vital demographic rates on a large scale, notably for species at risk of collision such as gliders. These models need to be regularly updated with collision event and ecological data. This recommendation echoes that of Thaxter et al. (2019), who emphasize the strategic importance of producing vulnerability maps based on the actual movements of seabirds using GPS telemetry. Unlike other approaches based only on bird abundance, these tools integrate the movements of individuals, which could help identify areas where the collision risk may be the greatest, and where appropriate mitigation measures such as adjusting the turbine cut-in speed could be implemented. Similarly, Reid et al. (2023) strongly recommend the use of wildlife sensitivity maps, where a risk score based on the conservation status and susceptibility of the taxa present is assigned to each grid cell. These maps, which can be used at different spatial scales, are presented as useful for local spatial planning. According to these authors, sensitivity maps represent a natural progression from the very large-scale regional ecological risk assessment approach and provide a solid basis for identifying and avoiding sensitive areas in the early stages of planning. These tools should not replace, but rather be used in conjunction with field surveys, to optimize the allocation of resources for environmental monitoring. In addition, Croll et al. (2022) highlight the importance of having rigorous empirical validation of collision risk models (CRM), in particular by using empirical data of actual collision events. This validation would ensure the inclusion of the right parameters to predict risk and thus reduce the structural uncertainty of predictive models and reinforce their credibility in the eyes of environmental decision-makers. Lapeña et al. (2010) present a method for assessing the effectiveness of monitoring systems. Their statistical approach considers sampling effort and the limits of monitoring systems, providing environmental managers with clear operational information for designing optimal and reliable monitoring systems. As a complementary approach, Obane et al. (2024) compared several impact models to assess the robustness and consistency of model predictions for seabirds. This comparative approach allows us to better understand methodological differences and how they affect the results, thus limiting the risk of interpretation errors in the final assessments. Finally, Garthe and Hüppop (2004) developed a wind farm sensitivity index for seabirds, combining distribution and abundance data with detailed behavioural studies, to act as a basis for the selection of offshore wind farm locations. Although this index is particularly useful for large-scale strategic assessments, it does not replace detailed local assessments. The authors stress the need to systematically integrate extensive baseline studies into environmental impact assessments to contextualize local results within a larger and more complete regional perspective.

Taking cumulative impacts into account in environmental assessments of wind energy projects is a way to ensure the sustainability of offshore wind energy developments. Indeed, although the effects of a single wind farm may seem negligible, their repetition or combination on a regional scale, over time, or in association with other man-made pressures, may result in significant consequences for populations of seabirds and other sensitive species. Of greatest concern is the accumulation of collision events, disturbances linked to habitat loss or degradation, and increased pressure on migration routes.

Thaxter et al. (2019) reiterate that the displacement effect caused by a wind farm can also modify the way birds interact with other nearby wind farms, e.g. by modifying flight patterns, foraging behaviour, or the search for resting sites. These behavioural changes, when repeated on a large scale, can affect the physical condition of individuals and ultimately compromise the viability of populations. Cumulative analyses require a change of scale for wind project planning and assessment. Rather than assess the impact of individual wind farms in isolation, Reid et al. (2023) call for a coordinated regional-scale approach, including detailed sensitivity maps at the scale of entire regions such as the Bass Strait region, where the concentration of offshore wind energy projects implies adopting a coordinated approach to data and risk management. This approach would not only identify areas with existing high wind farm concentration but also anticipate the cumulative effect of new projects still at the planning stage. In addition, Fox et al. (2006) emphasize the need for the collation and analysis of data at different spatial and temporal scales to address the strategic impact of wind farms. Before/after studies and control site monitoring are required to detect delayed or indirect effects, which may be hard to detect from a single localized impact assessment. The authors thus recommend the adoption of common robust comparative protocols at the national and international level.

As an example, the case described by Grover (2023) in California provides a clear illustration of this issue. Although offshore wind energy development in California is still in its infancy, the author recommends not only investigating the impacts of current projects, but also the long-term cumulative effects of future projects. Anticipating future impacts is crucial to ensure that the expected benefits of renewable energy developments do not come at the expense of marine biodiversity.

Wind farm macro-siting and spatial exclusion

Wind farm macro-siting, the process of selecting the geographic location of future wind farms, is important to avoid the most critical areas for aerofauna. Recommendations in the literature converge towards adopting a spatial planning strategy based on knowledge (of migration corridors, critical use areas) and the application of the precautionary principle (exclusion and buffer zones).

Every year, millions of individuals follow migration corridors to reach breeding, wintering, or roosting grounds. The installation of wind farms on these flyways increases collision risk, disturbs migration, and may induce a barrier effect, reducing the connectivity between habitats that are essential for species to complete their life cycles.

One of the most important vulnerability factors is migration density. Coastal and offshore areas with the most passage, notably near breeding colonies and important migration routes, are particularly sensitive. The abandonment of wind farm projects in areas with dense migration is recommended by several studies, some advising that wind farms be excluded from areas with both high density and unfavourable weather conditions such as drizzle or mist, which decrease visibility and thus the ability to avoid wind turbines (Hüppop and Hilgerloh, 2012; Hüppop et al., 2006).

The avoidance principle is applied when planning strategies exclude areas situated on crucial migration corridors, including for short distance commutes between breeding and foraging grounds, or for the seasonal migration of tree bats (Grover, 2023; True et al., 2023). It has also been suggested that turbines be grouped to provide aerial corridors between clusters (Abramic et al., 2022).

More prospectively, several studies emphasize the need to map migratory movements, including altitude, on a large scale using remote sensing, radar, or telemetry data (Walsh et al., 2024; O'Neil, 2020). This approach helps anticipate conflicts of use between energy production and migration, while considering the spatio-temporal variability of wildlife migration patterns.

The impact of offshore wind development is not limited to birds: migratory bats, although long-overlooked in the context of offshore wind projects, are increasingly the focus of attention. Understanding their movements is crucial for assessing their potential exposure to risk and guide offshore wind farm development towards less frequented areas (True et al., 2023).

In parallel to the identification and preservation of migration corridors, the literature also recommends the proactive exclusion of areas of high ecological value. These two strategies follow the same logic of preventive spatial planning and contribute to selecting sites that are more compatible with biodiversity conservation objectives. "High value" areas are generally defined as having high densities and/or critical habitats for sensitive species. These include areas where individuals are known to congregate, breeding colonies, and foraging and resting areas, as well as ecologically sensitive areas such as undisturbed areas, shallow waters, waters in proximity to the shore, and areas of high prey density (Gulka et al., 2024; Abramic et al., 2022).

Recommended measures also include avoiding the construction of wind farms between resting and foraging grounds (Hüppop et al., 2006), and near bird activity centres, notably for shorebird species that depend on these areas for their survival (Watts et al., 2022). In some cases, these priority habitats have a recognized status, such as Important Bird Area (IBA) or other national or European conservation area designation, and are protected by regulation (Gulka et al., 2024).

The distance from the shore is often used as an indirect indicator of environmental importance, notably for migratory bats, the activity of which decreases with distance from the coast. This is an argument for not building wind farms in coastal and nearshore areas, where flight activity and prey density, notably insects, are high (Brabant et al., 2021; O'Neil, 2020).

The creation of exclusion zones prior to any installation is a way to optimize spatial decisions between energy production and biodiversity conservation. It can reduce the probability of major conflicts by considering both the available ecological data and the technical and financial constraints of wind farm development. The aim is to reduce the need for costly corrective measures (such as curtailment or compensation) by prioritizing impact avoidance in the planning process (Croll et al., 2022).

Besides complete exclusion, safety buffers can also be created around sensitive habitats or areas of high bird activity. Buffer zones are established at the boundary of sensitive areas following a logic of precaution and gradual risk mitigation. This approach reduces the edge effect and allows species mobility and variability of use of space to be taken into account.

Several authors recommend adjusting the minimum distance for wind farm installation according to the species at risk and the ecological significance of the area. For example, Nebel et al. (2024) suggest increasing the radius of the buffer zone around nesting sites of white-tailed eagles to > 5 km. This safety buffer is larger than the current guideline of 2 km used in Finland and would encompass foraging areas and reduce collision risk around nesting sites. The study shows that this measure could reconcile the conservation of species with large home ranges with the constraints of spatial development.

Brabant et al. (2021) show that there is a marked decline in migratory bat activity away from the coast. The negative correlation between distance from the coast and bat detection frequency is presented as a practical tool for selecting the locations of offshore wind farm projects, especially in the early planning stages. Siting wind farms away from the coast would not only reduce their effects on bats, but also on shorebirds, and is coherent with other maritime activities (navigation, fishing). Gulka et al. (2024) specify that buffer zones can be defined from different environmental criteria, including the proximity of breeding colonies and nesting areas, bat hibernacula, or frequently used feeding grounds. They stress the importance having context-specific buffer zones, i.e. adjusted to the species, critical period (nesting, migration), and local habitat configuration.

Wind turbine micro-siting

Micro-siting, the process of optimizing the arrangement of wind turbines within a wind farm, is another measure for mitigating the impact of offshore wind farms on aerofauna. Unlike macro-siting, which determines the geographic location of a wind farm, micro-siting focuses on its internal configuration: parameters include layout, turbine orientation, turbine spacing, and flyway location. This is a two-step process: (i) exploit empirical data to characterize the use of space by wildlife, then (ii) based on this knowledge, optimize the spatial arrangement of wind turbines to minimize the risk to wildlife.

First, reports highlight the need for more empirical post-construction data, which are currently insufficient to adequately assess the effects of turbine layout on flying species. This lack of data hinders the effective improvement of future designs. Targeted monitoring is required to fill these gaps and develop evidence-based micro-siting strategies (Masden et al., 2012). Bird movement models are presented as a particularly promising tool in this context. By calculating the probability of birds passing between turbines under different configurations, they can help reduce collision risk. These models use data from environmental impact assessments to predict the effects of turbine spacing, wind farm size, and even wind direction (Masden et al., 2012). Thus, this type of approach allows the direct integration of components of animal behaviour and ecology into wind farm design. Once data are gathered and models are designed, the question then turns towards the physical configuration of the wind farm.

The preservation of migration corridors, both within and between wind farms, is a frequent recommendation. Various authors stress the importance of maintaining free migration corridors, several kilometres wide, between wind farms to ensure the safe passage of migratory species (Hüppop et al., 2006; Goodale et Milman, 2020; Gorman et al., 2023). These corridors limit cumulative barrier effects, particularly when installation on a flyway cannot be avoided. Special attention should be given to the spacing between turbine blocks, as it contributes to the permeability of the area for flying species. Thus, having several smaller wind farms may have advantages over one larger densely packed wind farm when barrier to movement is the main concern (Masden et al., 2012).

In terms of configuration, it is recommended that turbines be aligned in rows that are parallel to the main migration direction, and not perpendicular to the birds' main flyways, which would accentuate the barrier effect (Hüppop et al., 2006; Abramic et al., 2022). These configurations help birds and bats avoid obstacles, while preserving migration corridors. This type of recommendation is an example of micro-siting: here, choosing the orientation of the turbines within a preselected site. Other parameters include turbine density and spacing. For instance, leaving a larger gap between turbine rows in the direction of prevailing winds, notably when it coincides with that of migration, opens passages for flying species (Gulka et al., 2024). Positioning must also take daily flight paths to foraging, breeding, and roosting sites into consideration, to avoid intercepting regular movements. In addition, the total number of turbines, their distribution within the marine area, and their configuration (clustered or spread out), influence the visual and auditory perception of flying species, and thus whether these species will display an avoidance behaviour. Micro-siting strategies need to be based on in-depth knowledge of flight behaviour on a local and regional scale, by integrating for instance the results of telemetry and acoustic surveys.

Take home message

Spatial planning *is a major lever for avoiding the environmental impacts of offshore wind energy development on marine birds and migratory bats. All studies examined here converge towards using a precautionary, collaborative, evidence-based approach to spatial planning.*

Spatial planning rests on several complementary pillars. First, ***robust data acquisition and data sharing*** *are the foundations for informing siting decisions. They rely on targeted research, standardized monitoring protocols, and open collaborative platforms. Next,* ***environmental impact assessments tools****, such as mapping, statistical tools, and modelling, can prospectively evaluate risks and identify areas of high vulnerability for flying species.*

Strategic ***macro-siting measures****, such as the exclusion of sensitive areas, the establishment of buffer zones, and the preservation of migration corridors, reinforce the principle of impact avoidance. On a more local scale,* ***micro-siting*** *allows the adjustment of a wind farm's internal configuration to improve its environmental permeability, while optimizing energy production.*

This process cannot be effective without ***transnational coordination, multi-stakeholder engagement, and continuous adaptation*** *based on prior experience and new knowledge. Faced with the rapid development of offshore wind energy and the complexity of marine ecosystem dynamics, spatial planning appears not as a simple technical step, but as an integrated process where science, environmental governance, and sustainable development of the marine environment meet.*

Temporal planning

Temporal planning involves scheduling disruptive activities, such as construction, maintenance, and boat traffic, in a way that avoids critical periods for sensitive species, such as marine birds and bats.

The recommendations of Perrow et al. (2011) are based on a field study that was carried out near an important colony of little terns (*Sternula albifrons*). The construction of an offshore wind farm coincided with a significant decline in the abundance of young herring, which are the dominant component of the chicks' diet. This decline could not be explained by environmental factors and is thought to have been caused by the installation of monopiles during the winter spawning period, resulting in a significant decline in foraging and reproductive success in the colony. The authors urge the adoption of a precautionary approach to the timing and duration of pile-driving activity, accompanied by long-term targeted monitoring. These recommendations have since led others to support the seasonal planning of human activities. More generally, according to Gulka et al. (2024), planning should not only avoid the breeding season, but also migratory and wintering periods, depending on the taxa and location. Additionally, they recommend careful scheduling of maintenance vessel and helicopter activity, which can also significantly disrupt behaviour. Croll et al. (2022) add that reducing the intensity and adjusting the timing of activities may help minimize certain displacement impacts for vulnerable species.

In summary, this measure relies on available data and follows the precautionary principle. However, its implementation requires detailed knowledge of the spatio-temporal dynamics of the species in question and needs to be supported by robust monitoring programmes. These are still lacking for marine environments.

<u>A rare example of field experience:</u>

A single mitigation measure was employed at the Kentish Flats offshore wind farm area in the U.K. to reduce disturbance to divers during construction: it involved scheduling construction activity outside of peak diver season (Kentish Flats Ltd, 2007; Office Français de la Biodiversité & Biotope, 2025). According to the authors, disturbance to populations of divers was avoided by scheduling pile-driving operations and turbine installation outside of the wintering period. Post-installation monitoring from boat and aerial surveys did not find any significant long-term effects on bird populations. It was concluded that this strategy of adjusting the timing of construction activity had been effective for avoiding disturbance to divers in the area.

<u>Take home message</u>

Temporal planning *is a practical mitigation measure that is complementary to spatial planning. Using knowledge of the seasonal activity of sensitive species, the timing of the most intrusive phases of wind farm construction and operation can be adjusted to limit their impact.*

Available data show that disturbances during critical periods can have significant ecological effects, such as a decrease in reproductive success or a change in foraging behaviour. Therefore, careful scheduling of human activities appears to be a promising measure for avoiding impacts. It relies on detailed knowledge of local species and rigorous environmental monitoring.

Turbine curtailment

Turbine curtailment is one of the main levers mentioned in the literature for mitigating the impact of offshore wind farms on marine birds and migratory bats. Curtailment measures, which consist in adjusting or temporarily shutting down turbine activity under certain weather conditions or during specific periods, are seen by the scientific community as the main operational lever for mitigating the impacts that could not be avoided during the planning process (considered to be the first line of defence). However, the implementation of these operational measures requires in-depth knowledge of the migratory behaviour and the spatio-temporal distribution of impacted species, as well as the environmental conditions that directly influence collision risk.

Behavioural research and site-specific monitoring

In the recommendations, behavioural research and site-specific monitoring constitute prerequisites for the design and implementation of effective turbine curtailment protocols.

In their review, Machado et al. (2024) stress the importance of undertaking comprehensive and continuous monitoring of migratory marine bird behaviour, including activity patterns, flight height and direction, and reactions to wind turbines. They recommend the systematic collection of detailed behavioural data, which will serve as the basis for elaborating curtailment strategies that are adapted to the species' migration pattern and behaviour. These data should ideally be collected in all countries with offshore wind projects. The objective of this approach is to acquire comprehensive knowledge of migration patterns on a regional or international scale.

Site-specific monitoring is considered a fundamental step by True et al. (2023), notably for migratory bats. They advise offshore wind farm managers to implement site-specific observation protocols to better understand the risk of collision and mortality for different bat species. According to these authors, the visiting rate of migratory bats could vary significantly from one offshore wind site to the next, especially compared to typical onshore installations. Thus, precise monitoring would allow managers to identify critical periods of bat activity, and avoid unnecessary or ineffective turbine curtailment, and thus optimize the economic and environmental effectiveness of this measure.

The complementarity of these two approaches (behavioural research and site-specific monitoring) lies in their ability to provide robust and precise data, which are needed to adjust curtailment measures. Indeed, without prior knowledge of migratory behaviour and local activity, it becomes difficult to identify the period or the weather conditions where turbine curtailment would be required. Targeting situations where birds and bats are really exposed to collision risk not only improves the effectiveness of species conservation but also avoids the energetic and economic losses associated with unnecessary curtailment.

Raising the cut-in speed

Raising the cut-in speed (i.e. the minimum wind speed at which turbines start rotating to generate power) is an operational measure that has been proposed to reduce bat collision risk at offshore wind farms.

Surveys in the North Sea (Brabant et al., 2021) showed that most migratory bat activity (61 to 70 % depending on the site) occurred when wind speeds were lower than the usual cut-in speed for offshore wind turbines (generally between 3 and 4 m/s). Increasing the cut-in speed to 5 m/s would allow up to 80 % of bat activity to take place when turbines would be inactive. These authors also recommend being flexible and adjusting the cut-in speed according to other environmental parameters such as ambient nighttime temperature. Thus, this measure could be abolished when ambient nighttime temperature is below 13 °C, when bat activity decreases significantly. This type of approach could significantly reduce the number of fatalities, at a minimal economic cost for offshore wind energy producers.

True et al. (2023) support this conclusion: increasing the cut-in speed of wind turbines is a potentially viable method for reducing bat collisions at offshore wind farms, with results comparable to those seen at onshore wind farms. According to their observations, most collisions occur under conditions of low wind speed, high temperature, and good visibility - conditions that would warrant the application of curtailment measures. Therefore, they advise raising the cut-in speed of offshore wind turbines to significantly reduce bat mortality, while noting that financial losses should remain minimal due to the intermittent nature of bat activity.

Finally, Gulka et al. (2024) also confirm this recommendation, noting that raising the cut-in speed of offshore wind turbines is often recommended in the literature as a potentially effective mitigation measure for reducing bat collisions. Moreover, the effectiveness of this measure has been proven on land.

These different articles clearly indicate that raising the cut-in speed is a feasible and promising operational measure for protecting bats in offshore environments, provided specific local conditions and other key environmental parameters (temperature, season, weather conditions) are considered. They highlight the need for more studies within offshore wind farms under real conditions to fully confirm the effectiveness of this strategy.

Seasonal curtailment

Seasonal curtailment involves reducing or stopping turbine operations during selected periods, for instance when bird migration is particularly intense, and when collision risk is at its highest.
Several recent studies advocate this approach. The analysis of Eurasian curlew (*Numenius arquata*) flight tracks showed that a high proportion of individuals crossed offshore wind farms at rotor level (Schwemmer et al., 2023). The collision risk was significantly higher in autumn than in spring. The authors recommend seasonal turbine curtailment during the more intense autumn migrations. Reid et al. (2023) agree that seasonal adjustments of wind farm operations could be effective for reducing collisions, provided the timing coincides with previously identified critical periods. Detailed knowledge of when and where such periods of elevated risk may occur is therefore essential for the implementation of viable and targeted seasonal mitigation measures. In the review by Gulka et al. (2024), several studies suggest that seasonal restrictions of wind farm operations during periods of elevated risk, such as peak migration, could reduce the mortality rate of certain bird species. Finally, Watts et al. (2022) state that for offshore wind facilities that have already been approved or built, seasonal curtailment (including time of day restrictions) is the main operational option available for mitigating collision risk.
These articles concur that seasonal curtailment is a potentially effective operational mitigation measure, although this has been shown in the context of onshore wind farms. Its effectiveness relies on the precise identification of critical migration periods, which can be complex given the temporal variations among species. It is therefore important to clearly identify which species need to be protected as a priority and undertake regular and in-depth environmental assessments of the sites in question.

Adaptive and smart curtailment based on specific conditions, predictive approaches, or direct detection

Adaptive and smart curtailment systems can respond to weather conditions, the direct detection of animals, high intensity bird migration periods identified by real-time monitoring, or predictive models of bird activity. They are frequently suggested for reducing marine bird and migratory bat collisions. These strategies often rely on dynamic technological solutions that adjust turbine operation in real-time or anticipate turbine shutdown in response to the detected or predicted presence of sensitive species.

Certain weather conditions (fog, rain, storms) affect the ability of birds to detect and avoid wind turbines (Grover, 2023; Schwemmer et al., 2023). Schwemmer et al. (2023) recommend investigating behavioural reactions during different weather situations, to identify when birds are most vulnerable. Grover (2023) also stresses the importance of better understanding visibility conditions at offshore wind farms, so that this information can guide curtailment measures.

Smart curtailment based on predictive models uses environmental data to predict the presence of animals near wind turbines. Continuous monitoring systems (radars or acoustic sensors) combined with meteorological data can be used to anticipate periods of high collision risk, such as periods of high migration intensity in adverse weather conditions (Hüppop & Hilgerloh, 2012; Hüppop et al., 2006). In the Netherlands, a protocol was developed for offshore wind turbines in the North Sea, based on predictive models combining radar and meteorological data to preventively trigger turbine curtailment (Walsh et al., 2024). The predictive accuracy of the model is expected to improve over time as it is trained with new data continuously. The main challenge, according to Brabant et al. (2021), is warning offshore wind farm operators 24 to 48 hours in advance if turbines need to be idled for the sake of the stability of the electricity network. This is why models need to be robust. True et al. (2023) as well as Weiser et al. (2024) mention that predictive models must combine temperature, wind speed, and visibility data to identify periods of elevated risk. Gulka et al. (2024) also stress the high potential of this approach for migratory bats, notably by integrating wind speed and temperature thresholds to minimize economic losses and maximize animal protection.

Risk assessments and selective curtailment rely on the continuous monitoring of collision risk and the implementation of adapted curtailment measures when risks increase, allowing for a flexible response (Gorman et al., 2023). This approach is currently used in the Netherlands for migratory birds (Bradarić et al. 2024). In their paper, the authors describe how targeted curtailment is triggered by precise bird migration forecasts during nights of intense migration, a strategy already deployed by military aviation. However, it requires knowledge of hourly flight altitude distributions (a parameter that depends on wind direction and the time of night), to precisely select curtailment windows. Thus, better knowledge of migration patterns will minimize unnecessary curtailment, and still protect birds effectively. Meanwhile, Bach et al. (2022) highlight the importance of targeted curtailment schemes for migratory bats. They recommend monitoring bats at the level of the nacelle and at the bottom of the blade swept zone to determine when curtailment is required. Although this strategy is already implemented in a few areas, such as the Netherlands and the coastal waters off Germany, the authors make the case for expanding these mitigation schemes across the whole of the North and Baltic Seas. Their study shows that migratory bats are generally only active a few nights a year, when wind speeds are low.

Smart curtailment based on the direct detection of animals relies on automated systems that detect the presence of birds or bats in real time and trigger immediate turbine shutdown. Willmott et al. (2015) developed an Acoustic and Thermographic Offshore Monitoring (ATOM) system that transmits in real time the density of activity, flight height, and direction of travel of birds and bats, to inform dynamic curtailment decisions. Automated detection technologies and human observers have already been used in certain onshore wind farms. Thus, Nebel et al. (2024) show that this system effectively protects white-tailed eagles by stopping turbines when an individual is detected nearby. In general, this approach is thought to be effective for threatened species, notably when turbines can be shut down quickly to avoid a collision without affecting energy production (Croll et al., 2022). These authors suggest that it would be worth adapting these systems to marine environments. Although transposing these systems poses technical challenges, due to weather conditions and maintenance issues, targeted curtailment systems that work on land could be adapted to the specific requirements of the marine environment (Reid et al., 2023). Constraints associated with the larger size of offshore wind turbines, which makes curtailment systems less reactive and increases the risk of mechanical problems due to repeated shutdowns, accentuate these difficulties.

In their review, Machado et al. (2024) stress the importance of continually improving curtailment protocols to maintain an optimal balance between bird conservation and energy production. This optimization implies integrating new data and technological advancements and regularly adjusting curtailment strategies from experience.

These curtailment strategies share the same operational logic based on a dynamic and predictive adaptation to real or foreseen conditions to effectively protect animals, and at the same time minimize as much as possible energy production losses. They highlight the need for an integrated and adaptive approach, combining advanced monitoring technology, robust predictive models, and continuous adjustments of mitigation strategies.

Collaboration and integrated management

Effective reduction of the impacts of offshore wind farms on migratory species depends on a collaborative and integrated approach, involving transparent data sharing, transnational and multipartite cooperation, and standardized procedures and operational protocols. A recent literature review highlights the importance of these strategies for the sustainable management of the impacts on flying species (Gulka et al., 2024).

Active and systematic data sharing between stakeholders (e.g. wind farm owners, environmental authorities, research institutes) is a key measure for improving our understanding of bird and bat migration dynamics in marine environments. Machado et al. (2024) recommend encouraging data sharing to improve knowledge of migration patterns and thus facilitate the implementation of coordinated curtailment efforts. Pooling together data would ensure that a robust and up-to-date body of data would be available for making informed and coherent decisions.

Implementing effective transnational and multipartite cooperation between different parties, including national environmental authorities, wind farm owners, non-governmental organizations, academia, and transmission system operators, is another key recommendation. The establishment of a committee comprising representatives from every country involved in the development of offshore wind energy has been suggested to coordinate and supervise sea-basin level curtailment initiatives, oversee implementation, address challenges and ensure adherence to established guidelines and protocols. In addition, they advise forming stakeholder groups to foster collaboration, consensus-building, and shared responsibility, and optimize mitigation strategies.

For maximal effectiveness and operational coherence on a regional and international scale, it is essential to design and make freely accessible standardized curtailment protocols and procedures. Machado et al. (2024) propose the establishment of clear curtailment rules, which can be adapted to specific local conditions, based on available data and recommendations from previous studies. These protocols need to be regularly updated in the light of experience and scientific advancements, and be clearly communicated to all stakeholders to ensure a uniform and coordinated approach. In addition, international cooperation is essential to ensure that curtailment procedures are harmonized across borders, thus facilitating the sharing of best practices and the implementation of of consistent standards for the protection of migratory species in the marine environment. Although the standardization of protocols is crucial for ensuring the coherence of measures across borders, regional specificities also need to be considered. Indeed, critical migration periods and seasonal dynamics may vary considerably depending on the region and the species. Consequently, curtailment rules and procedures must be flexible enough to align with site-specific migration dynamics to maximize their ecological relevance while remaining coherent at the international level.

Take home message

*The different **curtailment strategies** described in the scientific literature, whether general or targeted, adaptive or predictive, have been shown to be indispensable tools for the effective mitigation of the effects of offshore wind farms on flying species. However, their operational success relies on in-depth knowledge of species behaviour, and rigorous and continuous monitoring of their effectiveness in situ. Three conditions are necessary: 1) the deployment of state-of-the-art detection technology; 2) the generalization of site-specific behavioural and environmental assessments; and 3) the implementation of integrated and collaborative management practices on a regional and international scale. In time, these approaches will not only significantly reduce the environmental impact of offshore wind farms but also improve the public and economic acceptability of these projects, in a perspective of long-term sustainability.*

Turbine visibility

Different approaches can be used to increase turbine visibility to birds and bats, including lighting management, blade design, painting, and modifying turbine size. Their actual effectiveness in offshore wind farms remains poorly documented, although some of these strategies have been shown to be effective on land or in other types of marine infrastructure.

Lighting management

Offshore wind turbines are illuminated at night for the safety of maritime traffic and aviation. However, these lights can also attract nocturnal species, notably during migration periods or adverse weather conditions (e.g. fog, heavy rain), which in turn increases the risk of collision, disorientation, and exhaustion (Rebke et al., 2019; Hüppop et al., 2006; Croll et al., 2022).

One of the most frequent recommendations is reducing artificial lighting as much as possible. This can involve limiting the number of lights or reducing their intensity or the length of time they are switched on (Rebke et al., 2019; Gulka et al., 2024; Grover, 2023). Walsh et al. (2024) specify that German authorities recommend only switching lights on when necessary (for instance for aviation and marine navigation safety), to significantly reduce the level of continuous artificial light exposure of birds and bats at night.

The use of automated Aircraft Detection Lighting Systems (ADLS) that switch on lights only when an aircraft is detected, also avoids unnecessary continuous lighting. This approach was highlighted by Gulka et al. (2024) and is required for all commercial-scale offshore wind farms planned in the United States. A similar approach can be applied to maritime traffic, where structures are illuminated only when ships are approaching in low visibility conditions (Rebke et al., 2019).

The type of signal also plays a critical role in bird attraction. Several studies conclude that intermittent or flashing lights are less attractive than continuous light (Hüppop et al., 2006; Rebke et al., 2019; Gulka et al., 2024; Croll et al., 2022). Studies onshore show that the use of short intermittent flashes and a longer time interval between flashes were better for reducing bird collisions (Gulka et al., 2024). By contrast, fast stroboscopic lights should be avoided due to their lack of effectiveness and their potential effect on people (blinding, disorientating maritime operators).

Adjusting light orientation (down-shielding) is also recommended. Directing light downwards minimizes the attraction of birds that are far away (Grover, 2023; Croll et al., 2022). This practical measure is particularly relevant for safety lights on platforms and bridges on offshore installations. However, mandatory aviation warning lights are under strict regulations that leave little room for manoeuvre for the application of this measure.

Light colour is a parameter that strongly influences attraction. Several European studies show that white lights are highly attractive to nocturnal migratory birds (Gulka et al., 2024; Rebke et al., 2019). Several experimental studies (some of which were carried out in the Netherlands) tested the effect of different colours on birds: red, green, and blue lights were generally less attractive than white light (Gulka et al., 2024). Other studies in the United States showed that intermittent red light attracted far fewer birds than continuous red light (Gulka et al., 2024). However, discrepancies persist in the literature: some studies suggest that green or blue light would cause less disturbance, while others find that red light is the least attractive (Gulka et al., 2024). Thus, the optimal colour remains to be determined and may vary depending on the species and weather conditions.

Authors agree on the need to avoid using floodlights at offshore wind farms. Such intense lighting may massively attract birds during nocturnal migration and in poor weather, resulting in numerous collisions or serious disorientation (Hüppop et al., 2006; Gulka et al., 2024; Croll et al., 2022).

Finally, lighting only the outer turbines in an array, and thus reducing the overall lit surface, was also suggested to minimize the impact on wildlife (Gulka et al., 2024). This practical and relatively simple measure could effectively reduce total light exposure.

Rotor blade design

A recent study suggests that rotor blade design could play a role in reducing bird collisions, notably for raptors such as white-tailed eagles. Modifying the blade profile or shape could make blades more visible to birds and thus change their approach behaviour (Nebel et al., 2024).

Turbine painting

Increasing the visibility of offshore wind turbines by changing their appearance, for instance by painting turbine blades and structures, is frequently mentioned in the literature to reduce bird collision risk. For bats, the effect would only be indirect: colours could reduce the attraction of insects and thus reduce the presence of bats nearby.

High contrast patterns applied to turbine blades and pylons may enhance their detectability by marine birds. A review of vision-based wind turbine collision mitigation measures suggests using achromatic (black and white) patterns on blades and masts (Martin et Banks, 2023). The internal visual contrast produced by these patterns remains effective under a wide range of light levels and ambient conditions and can be detected at a sufficient distance to allow approaching birds to change their course. The authors stress that these patterns need to be integrated into the design or during the construction of turbine parts to ensure a maximum and long-lasting effect, although they must comply with the statutory requirements for aviation and marine navigation safety. They recommend applying an alternating black and white pattern to the blades and alternating vertical bands of black and white to the pylons to produce a flickering effect that is highly visible to birds. These suggestions are corroborated by Gulka et al. (2024) who describe an experimental study at an onshore wind farm in Norway. This pilot study (May et al., 2020) found that painting one blade black significantly reduced the annual bird mortality rate by over 70 %, with raptor mortalities showing the highest reduction. However, these results are preliminary: only four wind turbines at a single site were studied. Additional research is needed before concluding the effectiveness of this measure, especially in marine environments. Moreover, Grover (2023) highlights the need for more studies to determine which colours and patterns at the most visible to marine birds under different weather conditions and light levels. So far, black is still the colour that maximizes the contrast with the background and shows the best overall effectiveness in making blades more visible. However, other colours and reflective pigments still to be investigated, since chromatic perception varies from one species to the next: for instance, some species cannot detect certain wavelengths, while others have tetrachromatic vision that include UV receptors. The application of highly reflective paints, notably in the UV spectrum, is regularly suggested (Croll et al., 2022; Gulka et al., 2024; Grover, 2023). This measure remains species-specific: birds lacking sensitivity to UV light or other wavelengths would not benefit, and this approach would only protect a fraction of the species at risk. Nonetheless, as stated by Croll et al. (2022) and Gulka et al. (2024), the effectiveness of UV-reflective paint in mitigating the impact of wind development has not been clearly demonstrated, especially offshore, even though it is an established method for preventing birds from flying into windows.

Moreover, Gulka et al. (2024) mention that other strategies, such as texturizing turbine blades or using colours that are less attractive to insects (and thus less attractive to bats) have been tested on a small scale on land, with inconclusive results.

Several authors recommend carrying out rigorous and carefully controlled experimental studies under real offshore conditions (Martin et Banks, 2023; Gulka et al., 2024; Grover, 2023). Experimental validation is essential before making any generalization or large-scale operational recommendation, notably because of the variability of maritime weather conditions, the diversity of species affected, and the specific constraints of maintenance at sea.

Turbine size

"Turbine size" refers to multiple turbine characteristics, such as overall height, the distance between the surface of the water and the lowest edge of the rotor-swept area (called the air gap), rotor diameter, and the spacing between individual wind turbines.

Increasing the air gap has been suggested to reduce the mortality of species that fly close to the water's surface, such as albatrosses, puffins, and petrels. Reid et al. (2023) suggest that this could be an effective measure for directly reducing collision risk for these types of birds. Building taller turbines could sufficiently clear the way above the sea-surface to reduce collision risk. Cleasby et al. (2015) recommend raising the minimum permitted clearance of turbine blades from 22 m (the lowest blade clearance currently permitted) to at least 30 m above sea level, especially at sites with high collision risk. Another trend in wind turbine development is using turbines with a larger rotor, which can produce more energy per turbine (Abramic et al., 2022). Goodale and Milman (2020) indicate that installing larger turbines requires placing them further apart to avoid negative aerodynamic interactions. This effectively decreases turbine density, which could indirectly reduce collision risk as well as the risk of displacement or disturbance for marine birds. Gulka et al. (2024) stress that the relationship between turbine size and collision risk is complex and varies depending on the species and context. Having taller turbines can reduce the number of turbines required in a wind farm, and thus reduce turbine density, but it can shift the rotor-swept zone to a different altitude: species that previously flew above, or below, the rotor could now be exposed, in particular species that migrate at high altitude, or conversely, low altitude if the rotor height is lowered. The potential impact depends not only on flight patterns, but also on local weather conditions and the ecological context of the area. Using collision risk models to optimize turbine height would minimize the impact on specific species. However, these models remain to be validated in marine environments. It is also difficult to accurately predict the impact of replacing existing turbines with larger models. The determining factor is not so much rotor diameter as the total swept area and where it is positioned in relation to the air column, two elements that are crucial to apprehend collision risk (N. Hette-Tronquart, pers. comm., April 2025). A wind farm with fewer turbines does not automatically pose less risk, and reverse may be true if the new rotors have a larger rotor-swept area than before.

Even though measures based on turbine size seem promising, their effectiveness offshore needs to be validated experimentally. The available studies highlight the potential variability of results depending on the species and local ecological context (Gulka et al., 2024). Moreover, the technical and economic feasibility of installing larger, more spaced-out turbines need to be considered, as this can pose serious challenges offshore, including because of greater technical and logistical constraints.

Take home message

*Measures for increasing **turbine visibility** are based on a precautionary and anticipatory approach: the aim is to design infrastructure that can be more easily detected by sensitive species, using detailed knowledge of their sensorial specificities and flight behaviour. Measures mentioned in the literature include light management, the application of high contrast patterns, less attractive colours, and adapting turbine size elements such as air gap size and rotor diameter. These measures, derived for the most part from interdisciplinary research in sensory ecology, engineering, and flight biomechanics, still require empirical validation in the context of offshore wind farms.*

For operators, these elements provide opportunities for technical innovations, within the constraints of safety requirements and regulations. For scientists, they open an area for applied research that is indispensable for assessing the interaction between species and infrastructure. For decision-makers, they reinforce the idea that wildlife-friendly wind farm design requires the inclusion of ecological knowledge when making technical choices.

In this perspective, turbine visibility is a complementary lever for risk mitigation that needs to be considered alongside other, more structural, measures such as micro-siting, curtailment, or spatial planning.

Deterrence measures

Few recommendations exist regarding the use of deterrence measures for mitigating the impact of offshore wind farms on flying species. Most of the recommendations identified were only briefly mentioned in literature reviews on the potential impacts of offshore wind energy development, and their possible solutions. The effectiveness of such measures was only tested in the context of wind farms on land, highlighting the need for carrying out specific research in the marine environment.

Ultrasonic acoustic bat deterrents

Ultrasonic auditory deterrents broadcast high frequency sound signals that disrupt the ability of bats to receive and interpret echolocation calls, thus reducing their activity and presence near wind facilities. This measure is the most common "deterrence measure" mentioned in the literature. Studies found a decrease in bat mortality of up to 64 % at treatment turbines on land (reviewed in Gulka et al., 2024). However, results vary depending on the species, year, and method used (Solick & Newman, 2021). Note that these devices have a limited range and that their effectiveness decreases rapidly with distance (Gulka et al., 2024). Despite being a promising measure in certain contexts on land, the effects of transposing this measure to marine environments remain highly speculative. A better understanding of the behavioural responses of specific bat species in marine environments is required before considering implementing this measure. Thus, O'Neil (2020) recommends focusing research and funding resources on ways to improve the practicality and applicability of these systems.

Acoustic bird deterrents

Acoustic bird deterrent systems emit recorded alarm, distress or predator calls, (bioacoustic deterrents), or artificial impulsive sounds. Results were highly variable and species-dependent, with rapid habituation reported (Gulka et al., 2024). Moreover, recent reviews find that its effectiveness in deterring birds from approaching wind turbines is generally weak (Croll et al., 2022). These measures have not been tested at sea, and the response of marine birds remains largely unknown, indicating a need for detailed behavioural studies (Croll et al., 2022).

UV light deterrents

UV light deterrents emit dim or flickering UV light to reduce the number of birds and bats near wind turbines. This measure was mentioned in two review articles (Solick & Newman, 2021; Gulka et al., 2024). Experiments on land produced highly variable results: some studies found a significant reduction in bat activity levels despite an increase in insects (prey), whereas other studies found no difference in bat mortality rates between illuminated and non-illuminated turbines (Solick et Newman, 2021; Gulka et al., 2024). Although UV lights were found to reduce bird collision with electrical lines, additional data is needed on the utility of UV lights in the context of offshore wind farms (Gulka et al., 2024).

Visible light deterrents

Deterrent systems that use visible light to deter birds and bats from wind facilities include devices that emit lasers, stroboscopic lights, or flashing lights. These measures are only mentioned in one review. Studies show that this measure can be effective at first, but animals tend to rapidly become habituated, which reduces its effectiveness in the long term (Gulka et al., 2024). Moreover, constraints due to navigation safety regulations make it difficult to implement this type of measure in marine environments. There are currently no data available that are specific to offshore wind farms to validate this approach; targeted studies are therefore needed to assess its effectiveness in this context (Gulka et al., 2024).

Texture coating

Texturizing is a measure for reducing bat collisions whereby the surface of turbine blades is modified to make blades less attractive or more easily detectable by bats. This approach is currently being tested on land, and studies for assessing its effectiveness in marine environments are strongly encouraged (Solick & Newman, 2021).

Electromagnetic bat deterrents

Electromagnetic signals are used to deter bats by disrupting their behaviour through the emission of specific electromagnetic waves. This measure is mentioned in the review by Gulka et al. (2024). Studies in Europe have shown that bat activity levels were reduced when high intensity electromagnetic waves were emitted, for instance by radars. However, although this approach is promising, it has not yet been assessed in the context of offshore wind facilities, and warrants additional research (Gulka et al., 2024).

Seabird anti-perching designs

Anti-perching designs aim to prevent marine birds from perching or roosting on wind turbines and thus reduce the risk of collisions and negative interactions. It is recommended that anti-perching designs be included from the first turbine deployments (Grover, 2023). Although considered potentially useful, this measure has not been evaluated in the context of offshore wind turbines.

Take home message

*The effectiveness of **deterrence methods** for limiting the interaction of flying species with offshore wind turbines is still poorly known. Most systems (acoustic, light, texture, electromagnetic) have been tested on land and have not been studied in the marine environment. Their effectiveness varies depending on the species, and there is a risk of rapid habituation. Certain solutions, such as ultrasound emissions or anti-perching designs, seem promising, but need to be tested offshore, while others, such as systems using lasers, textured surfaces, or UV lights, are still in the prototype stage.*

In this context, deterrent devices must be considered as potential complements to other proven mitigation measures (e.g. spatial planning, micro-siting, curtailment). Their future development will depend on investments in applied research and linked to current knowledge of species ecology and the constraints of offshore wind energy operation. Developers and decision-makers should actively pursue this area by supporting pilot projects and scientific validation programmes to determine if certain approaches can be effectively integrated in the next generation of offshore wind farms.

Wind farm repowering

Wind farm repowering is the process of replacing older turbines with newer, more efficient, models, and is often accompanied by a revision of wind farm layout or design. This approach is mentioned in one review paper which suggests that it could be a strategic opportunity to limit the impact of wind farms on flying species (Gulka et al. (2024).

This review identified micro-siting as an important mitigation measure, via the targeted revision of wind farm layout or the decommissioning of turbines that have a disproportionate environmental impact. These actions must be informed by precise data, such as the specific collision rate for each turbine. However, this strategy requires having high-resolution data, which are generally more accessible for terrestrial wind energy projects than for offshore wind projects. Indeed, monitoring collision rates or the use of space by flying species is particularly difficult in marine environments, due to technical and logistical constraints.

Although this mitigation measure seems promising in principle, it has not yet been applied or evaluated in the context of offshore wind farms. Significant effort is needed in terms of ecological monitoring at sea to allow the effective and evidence-based application of repowering as a mitigation measure.

Take home message

***Wind farm repowering** offers a new opportunity for integrating more effectively the demands of nature conservation into the long-term management of offshore wind energy infrastructure. By allowing the spatial and technological reconfiguration of wind farms, this phase provides an opportunity to implement targeted mitigation measures based on the latest scientific evidence, such as micro-siting or the decommissioning of turbines that have a disproportionate environmental impact.*

However, for this strategy to be effective in reducing the impacts on aerofauna, continuous and robust environmental monitoring protocols that can identify the most problematic turbines must be in place. However, acquiring data in marine environments remains a major challenge. The success of repowering as a mitigation measures hinges on greater investment in offshore environmental monitoring and a governance framework that encourages the exploitation of these data during phases of reconfiguration of wind farm projects.

Compensatory measures

Compensatory measures aim to counterbalance the residual negative environmental effects of offshore wind farms on bird and bat populations which cannot be avoided or minimized. Measures primarily involve (i) the creation and restoration of suitable habitats, (ii) conservation actions for the most affected species, and when legally allowed (iii) financial compensation. In addition, strategic planning and rigorous assessment are applied to each type of action mentioned above, as a framework to ensure its coherence, track its implementation, and ensure its effectiveness over the long term.

Planning and assessment of compensatory measures

Papers on this topic emphasize the need for undertaking rigorous planning and effectiveness assessment of compensatory measures. Reid et al. (2023) highlight the challenges associated with assessing the actual environmental and economic benefits of these measures, this assessment being necessary to ensure that the measures taken avoid unexpected or unintended outcomes that undermine the initial objectives. Croll et al. (2022) recommend using a globally unified approach on a broad regional, even international, scale, given the long distances covered by migratory birds.

Habitat-based compensation

This approach may include measures such as habitat restoration, enhancement of existing habitats, and habitat creation, which are either directly implemented by the project holder or via permittee-responsible compensation. These measures can improve the environmental conditions of impacted populations (Gulka et al., 2024). As an example, Reid et al. (2023) cite the creation of sanctuaries and nature reserves away from wind farms, which can act as effective refuges for vulnerable species.

Species-specific compensatory measures

Conservation measures targeting specific species affected by offshore wind farms are mentioned in two review papers. Gulka et al. (2024) discuss the removal of invasive terrestrial predators near seabird breeding colonies. Results from published studies are mixed and depend on the species targeted: for instance, this measure had a positive effect on razorbill (*Alca torda*) and Atlantic puffin (*Fratercula arctica*) breeding numbers, whereas it had no clear effect on other species such as guillemots (*Uria* spp.). Croll et al. (2022) mention that this approach is commonly used worldwide and its efficacy is well established: globally, there have been 1,550 eradication attempts, of which 88 % significantly reduced adult mortality and increased reproductive success. These gains can indirectly compensate the losses due to collisions or other effects of wind turbines. The authors stress that compensatory measures must be selected on a species-by-species basis for maximal efficacy. They suggest the establishment of new colonies in biosecure (predator-free) areas through social attraction and/or translocation. Site selection should prioritize predator-free islands over fenced areas that require long-term maintenance and periodic replacement. They also recommend supporting compensatory measures for reducing other threats to marine birds, such as the incidental capture of non-target species (bycatch) by fishing boats. These measures, by supporting the costs and implementation of regulatory changes and techniques for reducing bycatch, could compensate for the losses caused by offshore wind farms. Moreover, the establishment of formal protected areas around nesting sites, and the active management of local threats are recommended to maximize the survival of populations impacted by offshore wind farms.

Financial compensation

This measure relies on financial mechanisms to indirectly offset the impacts of offshore wind farms. Mechanisms include mitigation banking, whereby environmental credits can be earned through the conservation of habitats or species, which can be then used to offset negative impacts in other areas. Another similar approach is the establishment of in-lieu fee programmes, where direct financial contributions fund conservation actions for specific species or habitats to offset impacts to the same species or habitats occurring elsewhere (Gulka et al., 2024). Croll et al. (2022) specify that these financial mechanisms must be integrated into existing regulatory frameworks and be applied to cover at the appropriate scale to cover the range of cumulative impacts of offshore wind energy projects. These authors also mention allocating funds to reduce alternate threats to bird and bat populations on a regional or global scale, beyond the direct impacts of offshore wind farms.
However, current French regulation on environmental compensation (inscribed in the “avoid – reduce - compensate” sequence), does not permit direct financial compensation. According to the French Environmental Code, all compensatory measures must take the form of concrete environmental restoration or rewilding actions, which must be cumulative, measurable, and long lasting (Légifrance, 2016). Thus, direct financial compensation is not legally permitted (Cerema, 2021). Moreover, ministerial guidelines explicitly prohibit the use of purely financial compensation to meet the obligations associated with the residual environmental impacts of projects (Ministère de la Transition écologique, 2025).

Take home message

Compensatory measures *are a last resort in the mitigation hierarchy and serve to counterbalance the residual impacts of offshore wind farms on birds and bats, after all other possible impact avoidance and reduction measures have been used. Their implementation relies on a range of complementary approaches: habitat restoration, targeted conservation actions, and strategic planning.*
These measures must be carefully designed, adapted to focal species, and assessed over the long term to ensure they effectively compensate environmental losses. Actions such as the removal of invasive predators, the establishment of protected colonies, and allocating funds to alternative conservation programmes, are practical solutions that could boost the resilience of impacted populations.
However, their success is not guaranteed and hinges on strict conditions: rigorous monitoring, interregional coordination, being part of a global environmental strategy. It is crucial that these compensatory measures are not seen as a substitute for avoidance measures, but as a complement, to be deployed with precaution and transparency, and with long term conservation as its goal.

CONCLUSION

It is evident that no single measure can resolve all the issues associated with the impact of offshore wind farms on aerofauna. Differences in behaviour, habitat, and sensitivity impose a combination of complementary and adaptable strategies. As highlighted by O'Neil (2020) in her thesis on the potential of utrasonic acoustic deterrent technology for reducing bat mortality at offshore wind farms:

"*Overall, one mitigative strategy or technology may not be applicable in all scenarios. A mixture of smart curtailment, AI image recognition, acoustic detection, UADs* [ultrasonic acoustic devices]-*both nacelle-and blade-mounted, and working with industry to allow for construction modulation to wind turbines for the addition of external deterrent and monitoring equipment could be introduced to pre-construction EIA* [environmental impact assessment]*/ES* [environmental statements] *permitting language. Pre-construction monitoring and EIA should be a requirement for each specific project including siting, habitat, seasonal and migratory corridors, species type, and prey availability for each species. Risk assessment language based on CEA* [cumulative effect analysis]*, resilience indices, and species vulnerability on an ecosystem level is a new systems-thinking process that could prove effective in reducing bat fatalities at wind energy sites."*

This perspective shows the importance of using a large-scale integrated approach for aerofauna as a whole. Indeed, the current state of knowledge makes it clear that the mitigation hierarchy (avoid – reduce – compensate) needs to be followed from the first stages of project development: first, avoid sensitive areas – in particular migration corridors, breeding colonies, and feeding grounds; then, apply operational mitigation measures and technological solutions that are adapted to each situation. Simultaneously applying smart curtailment, advanced acoustic or visual detection systems, and various deterrent devices that could be directly integrated into the design of offshore wind farms, would reinforce the protection of sensitive aerial species. Moreover, our analysis shows that there an urgent need to develop tools and standardized methods to assess the environmental impact of offshore wind farms, with the systematic inclusion of precise criteria such as cumulative effect analyses and ecosystem-scale species resilience. These tools will not only make interventions more targeted, but also clearly identify current knowledge gaps, such as the critical lack of empirical and post-construction data, especially for bats and insects – taxonomic groups that are still largely neglected in the current literature. This systematic approach also highlights the need for rigorous protocols from the environmental impact assessment stage, with the inclusion of monitoring and risk analysis criteria at the scale of ecosystems, to reconcile offshore wind energy development and the conservation of aerial marine biodiversity. Finally, close collaboration between researchers, developers, and public authorities seems crucial to proactively guide investments towards innovative, sustainable, and evidence-based solutions, to ensure that offshore wind energy development is harmonious and environmentally sustainable.

EXPERT OPINION

In a collaborative effort to assess and improve the effectiveness of measures for mitigating the impact of offshore wind power on aerofauna, experts were invited to a meeting to discuss the results of this synthesis. This meeting enabled representatives of the wind farm sector (operators, consulting experts), public bodies such as the French Environment and Energy Agency (ADEME), and international organizations in the field of nature conservation such as the IUCN, to interact directly and exchange constructively on experiences of offshore wind farm operation. Although no research institute representative could attend the meeting, they were able to contribute by answering the written questionnaire which was handed out to all participants and identified partners. This aim of this questionnaire was to provide further feedback on the intermediary report and on mitigation practices: their practical implementation, their perceived effectiveness, the obstacles encountered, as well as the needs in terms research, coordination, and regulation.

By combining the outcomes of the meeting and the answers given in the questionnaire, this "Expert Opinion" section of the report presents the various viewpoints, identifies consensuses and disagreements, and contributes to final recommendations by having better understanding of the practices, constraints, and expectations in the field.

Selection and effectiveness of mitigation measures: a diversity of practices and approaches

A diversity of context-dependent measures, and a universal recognition of the key role of planning

The mitigation measures that are implemented or considered for reducing the impact of offshore wind energy projects on aerofauna differ considerably depending on who is involved and the context of the project. Developers, faced with the financial and technical realities of the project, generally prefer solutions that are seen as both effective and compatible with energy production. For instance, increasing the air gap, i.e. the distance between the surface of the water and the lowest edge of the rotor, is often mentioned. This measure, which is not considered costly in terms of production but is difficult from a technical and structural point of view, limits the collision risk for birds flying at low altitudes.

Turbine curtailment, notably during periods of high bat activity (low winds, mild temperatures), is also seen as a measure that can be transposed to offshore wind farms, with some adaptations. Protocols for this measure are largely derived from results at onshore wind farms, even though their transposition to offshore environments is still at the experimental stage. Certain pilot projects use automatic bird/bat detection systems to activate curtailment, although the readiness of this technology and its actual effectiveness remain to be proven.

Consulting experts propose using an integrated approach: early in the planning stage, they combine measures such as orienting turbine rows with respect to flight paths, reducing turbine numbers in sensitive areas, and the sustainable management of lighting within the limits imposed by maritime and aviation safety regulations.

Although opinions on the technical measures to be used vary, there is strong consensus on the importance of spatial planning. During this process, which is perceived as robust, pertinent, and potentially important for future outcomes, key biodiversity areas can be avoided, which reduces the need for reduction or compensatory measures later. However, certain participants highlighted that this is primarily within the state's competency, and current planning strategies are too disconnected from environmental realities. This disconnect can be explained not only by the lack of environmental data available when calls for tender are issued, but also because economic and technical constraints often take precedence over environmental issues.

Different actors apply different selection criteria

Mitigation measure selection depends on several and sometimes conflicting criteria. For developers, the deciding factor remains the balance between putative environmental benefit and economic viability. Decisions (e.g. air gap vs. curtailment) are often made based on internal cost/benefit analyses, which are integrated into tender applications. However, some have expressed their dissatisfaction that, since the release of the call for tender no. 9 (AO9; one of the most recent releases by the French government for the attribution of fixed offshore wind sites), environmental criteria are no longer weighted in the selection process. While these criteria were important in previous calls for tender and allowed candidates to capitalize on ambitious environmental mitigation measures, their removal is seen as disincentivizing. This contributes, according to some developers, to basing applications solely on economic criteria (cost per MWh) at the expense of innovation benefitting the environment.

By contrast, researchers (for instance from the Centre for Functional and Evolutionary Ecology (CEFE)) and public institutes (such as the French Office for Biodiversity (OFB)) prioritize criteria of evidence-based environmental effectiveness and are concerned by the implementation of measures that have no scientific backing.

The difficulty in documenting effectiveness offshore

The real effectiveness of mitigation measures is open to debate, notably because of a lack of consolidated studies offshore. While measures such as curtailment have been validated by certain studies on land, their transposition to the marine environment suffers from a lack of long-term time series, harmonized protocols, and open data.

Currently, assessments are most often carried out by developers or their contractors, within the framework of legally required post-construction monitoring. These assessments, despite the existence of official guidelines, differ greatly in their methodologies, and are thus difficult to compare, which hinders cumulative impact and measure effectiveness assessments. The OFB controls the conformity of measures with the operating license (e.g. effective implementation of curtailment, declared activation) but is not responsible for assessing the environmental impact of these measures. Researchers in academia request that a more rigorous approach be taken (BACI (before/after – control/impact) studies) but highlight the technical and logistical difficulties for carrying out these studies in the marine environment.

Obstacles and dampeners: a shared diagnosis

Despite a stated willingness to reduce the impacts of offshore wind farms on aerofauna, feedback obtained during the workshop and from the questionnaire converge towards the same conclusion: the implementation of mitigation measures is hindered by a series of technical, economical, scientific, regulatory, and institutional obstacles. These hurdles, although they differ in nature depending on the professional sector, contribute to slowing down the adoption and consolidation of good practices.

Technical and economic dampeners

For developers, the most important obstacles are of a technical and economic nature. Some structural measures, such as increasing the air gap or installing adaptive curtailment systems, generate considerable expenses and and may be difficult from a technological point of view, which can affect a project’s profitability or even its technical feasibility. The installation of bird/bat detection systems (radars, visual sensors, LIDARs) is considered too expensive to become widespread, notably in complex marine environments where sea conditions, corrosion, and energy autonomy constitute major challenges.

These costs are particularly significant as economic competitiveness remains the main selection criterion in recent calls for tender, such as the AO9. Since environmental actions no longer carry any weight, voluntary measures that benefit biodiversity are hard to justify economically, unless they are legally required.

Regulatory and legal obstacles

Several respondents, either developers, consultants, or researchers, mentioned obstacles related to the regulatory framework. The precautionary principle, as it is interpreted in some cases, is considered too restrictive: it prevents the implementation of experimental measures due to a lack of evidence but also makes it difficult to obtain evidence the absence of authorized trials. This paradox contributes to the stagnation of practices and discourages the development of innovative solutions.

Sector-specific regulations (notably from the French Civil Aviation Authority (DSAC), and maritime authorities) are also seen as hurdle. For instance, they do not authorize any dynamic modulation of wind turbine lighting, even though this measure could limit the attraction of birds to wind farms. Moreover, modifying a prefectural order, e.g. for introducing a new measure or adjusting a monitoring protocol, often entails an administrative process that is seen as a complex, costly, and the outcome of which is uncertain.

Scientific and methodological obstacles

Scientific hurdles are a critical problem. The lack of harmonized protocols, common methodological standards, and usable data prevent a rigorous and cumulative assessment of measure effectiveness. Projects have their own indicators and use formats that are often not interoperable, which significantly limits the ability to derive consolidated conclusions at a national or European level.

Researchers also highlight the fact that robust BACI-type protocols are complex, logistically cumbersome, and are difficult to apply in marine environments without significant resources and easy access to sites and data. In addition, this type of applied research is not academically attractive, and lacks dedicated long-term funding. These factors hinder the development of ambitious collaborative projects.

Cultural and institutional obstacles

Finally, several barriers stem from institutional or cultural factors. Mistrust between the science community and industry was mentioned during the workshop and in the questionnaire. Several researchers expressed their increasing reluctance to take part in industry-led projects. In addition, there is a lack of academic recognition given to applied research within industry, which makes these collaborations an unattractive option when pursuing an academic career. Conversely, some representatives of the offshore wind energy sector expressed their difficulty in forming ties with research groups. They mention a lack of availability of researchers, their excessive caution towards industrial projects, and sometimes their lack of knowledge of the constraints surrounding the development of complex offshore wind projects. This perception can foster a sense of aloneness in the face of academia, or misunderstandings of how academia works.

These mutual criticisms reveal a break in trust that is detrimental to the development of ambitious joint projects. Without a secure, long-lasting, and mutually beneficial collaborative framework, the potential for co-construction between science and industry remains largely untapped. These communication difficulties are all the more problematic because tackling the impacts of offshore wind energy on biodiversity requires a wide range of skills, improved data accessibility, and pooled expertise over the long term.

In parallel, public institutions and management authorities (e.g. the Regional Office for the Environment, Planning and Housing (DREAL), the OFB) lack the human and technical resources to analyze the environmental data produced by various projects and cannot fulfil their role as third party supervisor. This situation produces an imbalance between the formal obligations imposed on project holders and the capacity of administrations to effectively follow up projects and contribute to strategic reflections on the evolution of practices.

In addition to technical and regulatory obstacles, cultural and institutional hurdles contribute to a fragmented landscape, where cooperation between different sectors is still not the norm. Shared governance, neutral coordinating bodies, and clarified collaborative frameworks all seem crucial elements for overcoming these structural barriers.

Thus, obstacles to the implementation of mitigation measures are numerous, systemic, and often interconnected. They call for a coordinated response combining regulatory simplification, a framework for applied research, economic incentives for environmental innovation, and more public investment in monitoring and analysis.

Establishing a framework for research and valorizing existing knowledge

Experts agree on one point: applied research on the impacts of offshore wind farms on aerofauna, and specifically on the effectiveness of mitigation measures, suffers from structural delays. These delays are attributed to a lack of coordination at the national level, and a lack of long-term funding, but also to the lack of recognition of industry-led research in academia. In addition, respondents noted an under-exploitation of existing environmental data, which are abundant but are often walled within institutions or inaccessible.

Research is still fragmented and disorganized nationally

A lack of coordination of the research on mitigation measures was pointed out by several respondents, both from academia and industry. From the point of view of researchers, effectiveness assessments require robust experimental approaches (ideally BACI-type), which are costly and difficult to carry out in marine environments, and lack long-term funding. In the absence of an institutional framework to coordinate these cooperations, partnerships are sometimes perceived as risky, exposing researchers to tensions or a lack of recognition, and making collaborations with industry unattractive to those wanting a traditional academic career. This leads to low involvement from research groups, which slows down the development of expertise in this area, even though it is of strategic importance.

On the developers' side, this fragmentation manifests itself through scientific guidelines that lack clarity and in the difficulties in finding long term research partners. Several have expressed their frustration at the lack of a national structure able to steer, capitalize, and disseminate results in a coherent manner. The planned closure of the National Observatory of Offshore Wind Energy in favour of separate administrations for each maritime region, is perceived as a negative sign for developing a unified national research strategy.

Concrete suggestions were made, including the creation of a cross-institutional scientific consortium, and the use of existing organizations such as the FRB's CESAB (Centre for the Synthesis and Analysis of Biodiversity) to act as a centre for data management and knowledge dissemination. The aim would be to combine research, public expertise, and wind farm operator contributions in common projects with shared governance tools.

Under-exploited and poorly accessible data

In addition to the need to acquire new knowledge, respondents agreed on another key element: the valorisation of collected environmental data. For several years now, developers have been required to deposit their data in official platforms such as DEPOBIO, but exploiting these data remains difficult. Several problems have been identified: format heterogeneity, lack of standard methods, lack of metadata, access to portals is complicated, and manpower for data treatment is insufficient.

To deal with these issues, it was repeatedly suggested that a single, easy to use, interoperable portal under third party management be created to centralize, organize, and analyse data, in a perspective of progressive open science. However, some respondents pointed out that the DEPOBIO platform already performs this function, at least in theory. The main problem at present is linked to the patchy and heterogeneous nature of user submissions.

Moreover, certain experts are doubtful: even if such a portal would improve transparency and facilitate cumulative analyses, the potential of these data for research remains limited, as their resolution is often insufficient to assess, for example, the precise effectiveness of impact mitigation measures.

The Belgian governance model (where the Royal Institute of Natural Sciences centralizes all data and publishes annual analysis reports) was mentioned as a source of inspiration. The aim would be not only to have a depository, but also to harmonize protocols, guarantee the quality of the metadata, and impose quality control: conditions that are a prerequisite for effective capitalization from experiences and reliable knowledge sharing across the sector.

Finally, several speakers stressed the need for supporting the publication of scientific research based on these data. However, they indicate that monitoring data cannot be published by themselves: data must be derived from protocols designed to investigate explicit research questions. When methodological conditions allow it, the publication of monitoring results in peer-reviewed journals can increase the international visibility of efforts made in France in relation to biodiversity and offshore wind farms, as well as make these results more accessible to the scientific community.

Reinforce the role of the State to supervise the coherent integration of biodiversity

Finally, several avenues for action were identified regarding the possible role of the State in the implementation of these proposals. First, there is a need to improve the coherence of public policies from different sectors (energy, biodiversity, fishing, marine planning), which are still too often designed and implemented in isolation. The State is also called upon to play a more active role as a facilitator of environmental innovation, by authorizing and accompanying field trials, and by making biodiversity-compatible wind sector development a clear political objective.
In parallel, experts stress the need to reinforce the State's technical and human resources, so that it can effectively ensure compliance with environmental obligations, interpret results, and actively contribute to the evolution of standards and practices.

Conclusion: towards a collective and integrated wind power-biodiversity approach

Contributions from the workshop and the questionnaire revealed that there is a growing awareness of the need to mitigate the impact of offshore wind farms on aerofauna. Although, actions vary depending on the type of institution, the technical context, and the regulatory framework, several key elements stand out. First, the importance of the planning phase and of assessing the effectiveness of implemented measures is recognized by all parties. Then, respondents agreed on the need to structure the scientific governance of data, harmonize methods, and allow regulated field trials.

The energy transition cannot succeed in the long term without fully integrating biodiversity conservation. These discussions showed that the tools exist, knowledge is accumulating, but exploiting these is hampered by institutional, cultural, and organizational barriers. To overcome these barriers, it is essential to shift from a perspective of individual compliance to one of collective endeavour based on data sharing, open access, and cooperation between research institutes, industry, and public bodies.

More than an inventory, this synthesis of "expert opinions" calls for the evolution of the model of environmental governance in this sector: a model that should be able to reconcile energy targets with environmental sustainability, in a manner that is forward-looking, transparent, and mutually trusting.

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APPENDIX I: METHODS

Bibliographic reference search strategy

Key words and search equations

To meet our objectives, we combined all terms related to aerofauna, mitigation measures, and their results. The final search equation was constructed as follows in the Web of Science Core Collection (WOSCC) search engine:

TS=((insect$ OR invertebrate$ OR butterfly OR lepidoptera OR avifauna OR aves OR avian OR bird$ OR bat$ OR chiroptera OR passerine$ OR raptor$ OR passeriforme$ OR seabird* OR shorebird* OR waterbird* OR "migratory bird*» OR gull* OR tern* OR petrel* OR shearwater* OR puffin*) AND ("wind energ*" OR "wind farm$" OR "wind power" OR "wind turbine$" OR "wind technolog*" OR " wind park$" OR "wind power station$" OR "wind power plant$" OR "wind facilit*" OR "wind installation$") AND (evaluat* OR solution$ OR mitigat* OR assessment* OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimize OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR curtail* OR "flight divert*" OR "attract* remov*" OR "nest* management" OR "m?cro-siting" OR deterr* OR "habitat restoration*" OR "habitat enhancement*" OR "habitat creation*" OR "ecological engineering" et "conservation strateg*» OR "site selection*» OR "displacement*» OR "buffer zone*») AND (impact* OR effect* OR collision$ OR behavio*r OR aversion OR repulsion OR disturb* OR mortalit* OR fatalit* OR carcass* OR "population size" OR "population density" OR abundance OR occurrence OR habitat loss* OR fragmentation* OR degradation* OR response OR disruption* OR success* OR breeding OR nesting OR reproduct* OR fidelit* OR site OR richness* OR composition* OR lifespan OR surviv* OR rate) AND (offshore OR sea OR marine OR ocean OR coastal OR "continental shelf» OR tidal OR pelagic OR intertidal OR estuar*))

All search equations used for each query of search engines, bibliographic databases, and specialized websites are given in Appendix II.

Shortcuts and limitations

Only terms in English were included in the search queries. However, selected publications were either in English or in French, in accordance with the team's language skills. No restrictions on the date or geographic area were applied to database searches. As for specialized websites, the search for documentation in English was prioritized, with the addition of one specialized website in French.

Literature sources

Only one bibliographic database was queried using the search equation given above: the Web of Science Core Collection database, which was available to the authors of this review via the French National Research Institute for Sustainable Development (IRD). Searches were carried out in the following citation indexes: SCIEXPANDED, SSCI, AHCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, and IC.

Two additional searches were carried out in:

- Google Scholar (https://scholar.google.com/). We used the Publish or Perish (v6) software to retrieve citations. Because of restrictions on the number of characters, the search equation was simplified. Moreover, we prioritized academic publications, limiting each sub-search to the first 50 results, as it has been shown document relevance decreases rapidly after that (Haddaway et al., 2015).

- Bielefeld Academic Search Engine (BASE) (http://www.base-search.net). As with Google Scholar, because of restrictions on the maximum number of characters, the search equation was simplified.

We manually searched the following nine websites for relevant technical documentation:

- The International Renewable Energy Agency (IRENA): https://www.irena.org/
- The Wind Technology Office: https://www.energy.gov/eere/wind/wind-energy-technologiesoffice
- The U.S. Wind Turbine Database: https://eerscmap.usgs.gov/uswtdb/
- The Bats and Wind Energy Cooperative (BWEC): https://www.batsandwind.org
- The 'Publication Library' of The Scotland Centre of Expertise Connecting Climate Change Research and Policy: https://www.climatexchange.org.uk/research/publications-library/
- Tethys: https://tethys.pnnl.gov/
- La Libraire "Energies renouvelables, réseaux et stockage", Agence de la Transition Ecologique (ADEME) https://librairie.ademe.fr/2889-energies-renouvelables-reseaux-et- stockage
- La page « Documentation et rapports », France Renouvelables : https://www.france-renouvelables.fr/documentation-et-rapports/
- The Mitigation Practices Database (MDP) Tool: https://www.nyetwg.com/mpd-tool

Estimate of search exhaustivity

To ensure the relevance of the search and a certain level of exhaustivity, an iterative process was carried out to "calibrate" the search equation to a predetermined list of 10 reference articles (hereafter, the "test list"). This "test list" comprised articles from relevant scientific journals previously identified by the team. We tested different keyword combinations and checked that the reference articles were retrieved. If articles from the "test list" were missing, keywords were added to improve search sensitivity until all articles were retrieved.

Criteria for article eligibility and study selection

Screening was carried out over two stages: 1) from "titles and abstracts", and 2) from "full texts". We assessed the relevance of retrieved articles using a set of inclusion and exclusion criteria (Table 2). When selecting from titles and abstracts, if the presence of an inclusion criterion was in doubt (or if the information was missing), the article in question would automatically be included in the next stage of the selection process. The technical reports retrieved from specialized websites were only assessed from the full text. To ensure the consistency and reproducibility of these decisions, the reliability of agreement between the different raters was compared using a Fleiss' Kappa test at hte start of each selection stage (APPENDIX III).

Given the high number of review papers that met our selection criteria, notably criteria related to the impact of offshore wind farms on biodiversity, and given that extracting metadata from this type of document is time-consuming, it was necessary to limit our selection. As literature reviews generally include the conclusions of previous work, it was decided to only retain review papers published from 2021 onwards. Discarding older review papers simplified our analysis without leading to any significant loss of information. However, reviews published before 2021 were read to make sure no essential information was left out. Moreover, the recommendations in the selected review papers were compared to those from primary research articles, to check whether recommendations are consistent over time, identify any evolution in the measures suggested, and ensure that no relevant measure from primary studies was omitted from these reviews.

Table 2. List of eligibility criteria used for the selection of documents from "titles/abstracts" and "full texts".

PICO Criteria		Description	Definition(s)
Inclusion criteria	Eligible populations	All flying vertebrates or invertebrates (i.e. all species of birds, bats and flying insects) affected by offshore wind farms	Wild species – i.e. species freely occurring in natural environments (*in situ*) or used in laboratories (*ex situ*). All non domesticated species.
	Eligible interventions	Mitigation measures to avoid, minimize and compensate the impacts of offshore wind farms on aerofauna	Mitigation measures for minimizing the negative impacts of offshore wind farms on aerofauna.
	Eligible comparators	The presence of a comparator is not required	Formal assessment of the effectiveness of measures is not required. Recommendations of measures to be adopted are acceptable.
	Eligible effects and measures	The presence of effects is not required	Studies are considered even if no effect was studied.
Exclusion criteria	Ineligible populations	All non-flying fauna	Subaquatic species are not considered in this review.
	Ineligible interventions	Measures not centred on the avoidance or reduction of negative impacts	Any intervention that does not aim to minimize the negative impacts of offshore wind farms on species' populations, either through actions put in place directly at the wind farm, or by measures taken before, after, or in parallel of their operation.
	Ineligible results	No significant mention of recommendations	Studies without clear or detailed recommendations of measures to be adopted.

"Critical appraisal": assessing study validity

Critical appraisable of study validity usually involves the examination of the methods used, the data collected, and potential study biases. Here, however, the information extracted was restricted to recommendations of mitigation measures and good practice. These recommendations were not based on the results of specific studies, but rather on the identification of problems and impacts, and the suggestions made for avoiding, reducing, or compensating these impacts. In the absence of detailed methods and results, it was therefore not possible to carry out a critical appraisable of the validity of the underlying research.

Narrative synthesis

Recommendations were analysed using an Excel spreadsheet where each mode of action or piece of information mentioned in an article was entered using the terms used by the authors. In addition, we answered a series of questions that allowed us to synthesize these recommendations and spot possible bias in the current literature.

Recommended measures were classified into broad categories, and more explicit subcategories (for instance, "turbine size" for the "turbine visibility" category).

Recommendations were also classified according to the mode of action suggested to limit the impact on biodiversity:

- *Planning and impact assessment tools* – spatial analysis, sensitivity maps, and other methods for guiding the development of wind energy projects, taking environmental risks into consideration.
- *Location and positioning of turbines* – site selection based on environmental criteria, in order to avoid critical habitats and migration corridors.
- *Policy and regulation* – the development of a legislative and regulatory framework, defining the restrictions or specific conditions for offshore wind project development.
- *Infrastructure adaptation* – modifications brought to the technical characteristics and design of wind turbines to limit their impact on wildlife (e.g. choice of materials, structural adjustments)
- *Technical or technological measures* – the integration of technological innovations to reduce the negative interactions between wind turbines and wildlife (e.g. installing radars, automatic shutdown of turbines in the presence of certain species).
- *Operational modifications* – adjustments made to wind turbine operation, including changing the timing of operation (e.g. temporary shutdown during migration periods) or slowing down blade rotation speed.
- *Environmental compensation* – the implementation of measures for offsetting the impact of wind farms, such as the creation of new habitats or funding conservation projects.
- *Collaboration and integrated management* – the development of cooperation between different actors (public authorities, academia, operators, NGOs) to share knowledge, harmonize practices, and optimize the management of affected ecosystems.
- *Research and development (R&D)* – encourage scientific research and technological innovation to better understand the effects of offshore wind farms and improve mitigation solutions.
- *Training and awareness raising* – actions for providing information and training to stakeholders (operators, public authorities, local communities) on the environmental issues and good practice.

Once the dataset was compiled, we harmonized the output to ensure that categories were coherent, and entries were in the right category. Similar records were combined into a single entry.

Subsequently, a table listing the most frequent recommendations ranked by overall occurrence was produced.
The figures and tables in this review, obtained by crossing key variables of the metadata (e.g. taxonomic group x solutions x results), were produced to identify knowledge gaps (i.e. subthemes that require additional primary research) and knowledge clusters (i.e. subthemes that have been sufficiently researched to allow a quantitative synthesis to be carried out).
After extracting the different recommendations, we produced a written report of our findings. This step allowed us to coherently present the solutions identified and to highlight similarities and differences between different sources. It also helped the integration of recommendations, allowing us to make clear operational suggestions, by order of importance.

APPENDIX II: SEARCH EQUATIONS USED IN THE LITERATURE SEARCHES

Full search equation, used with the Web of Science Core Collection (WOSCC):

• TS=((insect$ OR invertebrate$ OR butterfly OR lepidoptera OR avifauna OR aves OR avian OR bird$ OR bat$ OR chiroptera OR passerine$ OR raptor$ OR passeriforme$ OR seabird* OR shorebird* OR waterbird* OR “migratory bird*» OR gull* OR tern* OR petrel* OR shearwater* OR puffin*) AND ("wind energ*" OR "wind farm$" OR "wind power" OR "wind turbine$" OR "wind technolog*" OR " wind park$" OR "wind power station$" OR "wind power plant$" OR "wind facilit*" OR "wind installation$") AND (evaluat* OR solution$ OR mitigat* OR assessment* OR option$ OR measur* OR priorit* OR reduc* OR avoid* OR compensat* OR minimize OR adapt* OR interven* OR action$ OR manag* OR protect* OR manipulat* OR counteract* OR removal OR engineer* OR plan* OR strateg* OR offset* OR curtail* OR "flight divert*" OR "attract* remov*" OR "nest* management" OR "m?cro-siting" OR deterr* OR "habitat restoration*" OR "habitat enhancement*" OR "habitat creation*" OR "ecological engineering" et "conservation strateg*» OR “site selection*» OR “displacement*» OR “buffer zone*») AND (impact* OR effect* OR collision$ OR behavio*r OR aversion OR repulsion OR disturb* OR mortalit* OR fatalit* OR carcass* OR "population size" OR "population density" OR abundance OR occurrence OR habitat loss* OR fragmentation* OR degradation* OR response OR disruption* OR success* OR breeding OR nesting OR reproduct* OR fidelit* OR site OR richness* OR composition* OR lifespan OR surviv* OR rate) AND (offshore OR sea OR marine OR ocean OR coastal OR “continental shelf» OR tidal OR pelagic OR intertidal OR estuar*))

Simplified search equation derived from the initial full search equation, used with the Bielefeld Academic Search Engine (BASE):

• (insect invertebrate butterfly lepidoptera avifauna aves avian bird bat chiroptera passerine raptor passeriforme seabird shorebird waterbird "migratory bird" gull tern petrel shearwater puffin duck swan sandpiper coot guillemot plover cormorant grebe skua) AND (offshore sea marine ocean coastal "continental shelf" tidal pelagic intertidal estuary) AND ("wind energy" "wind farm" "wind power" "wind turbine" "wind technology" "wind park" "wind facility" "wind installation") AND (evaluation solution mitigation assess option measure priority reduce avoid compensate minimize adapt intervention action management protect manipulate counteract removal engineer plan strategy offset curtailment displacement buffer siting deterrent habitat)

Simplified search equation derived from the initial full search equation, used with Google Scholar:

• (insect OR bat OR chiroptera) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (evaluat* OR mitigat* OR assessment OR measur* OR reduc* OR avoid* OR compensat*) AND (impact OR effect OR collision OR behavior OR mortality OR fatality OR density)

• (insect OR bat OR chiroptera) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (evaluat* OR mitigat* OR assessment OR measur* OR reduc* OR avoid* OR compensat*) AND (abundance OR success OR breeding OR richness OR composition OR surviv* OR rate)

• (insect OR bat OR chiroptera) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (minimize OR manag* OR plan* OR offset OR siting OR restoration OR creation OR “buffer zone”) AND (impact OR effect OR collision OR behavior OR mortality OR fatality OR density)

• (insect OR bat OR chiroptera) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (minimize OR manag* OR plan* OR offset OR siting OR restoration OR creation OR “buffer zone”) AND (abundance OR success OR breeding OR richness OR composition OR surviv* OR rate)

• (bird OR seabird OR shorebird OR “migratory bird”) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (evaluat* OR mitigat* OR assessment OR measur* OR reduc* OR avoid* OR compensat*) AND (impact OR effect OR collision OR behavior OR mortality OR fatality OR density)

• (bird OR seabird OR shorebird OR “migratory bird”) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (evaluat* OR mitigat* OR assessment OR measur* OR reduc* OR avoid* OR compensat*) AND (abundance OR success OR breeding OR richness OR composition OR surviv* OR rate)

• (bird OR seabird OR shorebird OR “migratory bird”) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (minimize OR manag* OR plan* OR offset OR siting OR restoration OR creation OR “buffer zone”) AND (impact OR effect OR collision OR behavior OR mortality OR fatality OR density)

• (bird OR seabird OR shorebird OR “migratory bird”) AND ((offshore OR marine) AND (wind AND (energy OR farm OR turbine OR park))) AND (minimize OR manag* OR plan* OR offset OR siting OR restoration OR creation OR “buffer zone”) AND (abundance OR success OR breeding OR richness OR composition OR surviv* OR rate)

APPENDIX III: ASSESSING THE CONFORMITY TO ELIGIBILITY CRITERA WITH FLEISS' KAPPA TEST

Fleiss' Kappa test on title + abstract ratings:

- This test was conducted by three independent raters on a list of 10 bibliographic references, after initial calibration also using 10 references to harmonize the selection decisions.

- Results: *Kappa = 0,72*
  z = 3,22
  p-value = 0,0013

The Kappa value (0.72) indicates a high level of agreement between raters. Indeed, this value close is to the 0.75 threshold that is generally considered as an indication of high interrater reliability. Moreover, this agreement is highly statistically significantly (p = 0.0013).

Randolph's Kappa test on full text ratings:

- This test was carried out by two independent raters on a list of 10 bibliographic references. Randolph's Kappa test was chosen here as it is more adapted to analyses with two raters than Fleiss' Kappa test, which is designed for more than two raters.

- Results: *Kappa = 0,8*
  z = 4,22
  p-value < 0,001

The Kappa value (0.80) of this test indicates a very high level of agreement between raters with agreement being highly significant (p < 0.001).

Results of both tests show high agreement between raters at each stage of the bibliographic reference selection process. Whether selection was carried out on titles + abstracts (Kappa = 0.72) or full texts (Kappa = 0.80), the Kappa values indicate that rater decisions were highly congruent and reproducible. This congruence guarantees the reliability and robustness of the assessment of eligibility criteria during the entire selection process.