DIGEST

BIODIVERSITY AND OFFSHORE WIND POWER

Mitigating the impact of offshore wind energy on flying fauna: synthesis of recommendations in the absence of effectiveness evaluations

In response to current climate crisis, the rapid reduction of greenhouse gas emissions is essential. Since electricity production from fossil fuels is one of the main sources of CO_2 emissions, the energy transition to renewable energies is a major issue for achieving carbon neutrality by 2050. Offshore wind energy appears to be a strategic solution to meeting the need for decarbonized electricity, diversifying the energy mix and strengthening energy sovereignty. Nevertheless, despite its climate benefits, it requires substantial infrastructure that disrupts the environment in which it is installed. This poses major environmental challenges, particularly in terms of biodiversity: disturbance in the water column and on benthic habitats (seabed), sound emissions that likely harm marine mammals, collision risks for birds and bats, etc.

This "Key for Understanding" is based on a review of scientific literature dealing with offshore wind and flying fauna (birds, bats, insects). Due to the lack of studies directly evaluating the effectiveness of mitigation measures, it focuses on the recommendations issued by scientists concerning these measures, intended for the scientific community, developers and operators of offshore wind farms, and government agencies.

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Offshore wind impacts: what are we talking about ?

In face of the current climate emergency, the energy transition towards renewable sources is essential to limit greenhouse gas emissions. **Offshore wind power appears as a strategic solution** to enable this transition and meet the growing need for decarbonized electricity, diversifying the energy mix and strengthening energy sovereignty. It is in this context that in 2022, the national offshore wind industry concluded a "marine wind pact" with the French State, setting the objective of awarding 2 GW (Gigawatt) of new projects per year from 2025, as well as an installed capacity of 18 GW by 2035 and 40 GW by 2050.

The **mitigation hierarchy framework** and associated regulatory tools (strategic environmental assessment, impact studies) frame the development of projects at sea and constitute a central approach to **reduce the effects of offshore wind on ecosystems**. The real challenge now is **to align the necessary acceleration of offshore wind deployment with effective mitigation measures for biodiversity.**

KEY ELEMENTS OF THIS SYNTHESIS

The study sites from which the recommendations originate are mainly concentrated in **Europe and the United States, in the North Sea, in the North Atlantic Ocean, in the Baltic Sea and in the Celtic Sea.**

The most numerous recommendations concern **birds**, particularly marine and migratory species, then **bats**. No study specifically deals with recommendations for insects.

The recommendations focus on :

- planning and impact assessment tools;
- park and wind turbine siting and positioning;
- operational modifications, technological or technical measures;
- research and development.

Micro-siting and macro-siting

The micro-siting measure, or spatial optimization of turbines at the park scale, aims to reduce the impacts of offshore wind farms on birdlife and bats by **adjusting the internal arrangement of turbines**. Unlike large-scale planning, which **determines the general location of projects** (macro-siting), micro-siting refines these choices at the local scale and focuses on the architecture of the wind farm itself: layout, orientation, spacing of turbines and preservation of flight corridors.

EXPERT PERSPECTIVES

Within a collaborative knowledge-building process focused on measures to mitigate the impacts of offshore wind on flying fauna, the **Foundation for Research on Biodiversity** (FRB) gave voice to **representatives of the wind industry** (developers, consulting firms), **public institutions** such as ADEME, **international conservation organizations** such as IUCN (International Union for Conservation of Nature), and **research institutes**. The experts thus discussed the results of this synthesis and shared their feedback rooted in the operational reality of offshore projects conducted in France.

Their feedback reveals **growing mobilization around the issues of mitigating the impacts of offshore wind on flying fauna.** While practices still differ according to institutional profiles, technical contexts and regulatory frameworks, several strong lines emerge clearly :

- shared recognition of the importance of acting both on **upstream planning** and on **the quantified effectiveness of measures applied to parks**.
- a common observation on the need to **structure the scientific governance of data**, harmonize methodologies and open facilities to supervised ecological experimentation.

These exchanges show that tools exist, knowledge is accumulating, but their mobilization remains hindered by institutional, cultural and organizational barriers. To overcome them, it is essential to **move from a logic of individual compliance to a collective dynamic**, based on knowledge sharing, data openness and cooperation between research, industry and public authorities.

This synthesis of "expert perspectives" calls for a change in the sector's environmental governance model: a model capable of **making energy ambitions and ecological imperatives coexist**, in a logic of continuous progress, transparency and mutual trust.

MEASURES TO MITIGATE THE IMPACT OF WIND TURBINES ON FLYING BIODIVERSITY

In accordance with Target 15 of the Kunming-Montreal Global Biodiversity Framework, all economic actors must reduce negative impacts on biodiversity, including the impacts of solutions to mitigate climate change. Thus, energy production, like other human activities, must transition towards more sustainable actions, while preserving biodiversity. To promote this transition and reduce the impacts of offshore wind, recommendations from scientific literature are proposed to the scientific community, developers and operators of offshore wind turbines and states in order to reduce impacts.

SPATIAL PLANNING

Spatial planning of offshore wind farms is a major lever for preventing ecological impacts on seabirds and migratory bats. All the works examined converge towards an approach that is both precautionary and collaborative, based on data.

This planning rests on several complementary pillars :

- First, **the acquisition and sharing of robust data** are essential to inform location decisions. They rely on targeted studies, standardized monitoring protocols and open collaborative platforms.
- Next, **impact assessment tools**, whether **mapping, statistical or modeled**, allow projecting risks prospectively and identifying areas of highest vulnerability for flying fauna. The strategic location of projects, including exclusion of sensitive areas, creation of buffer zones and respect for migratory corridors, reinforces this prevention logic
- Finally, at a finer scale, **micro-siting** allows adjusting the internal configuration of parks to improve their ecological permeability while optimizing their energy efficiency.

This spatial framework cannot be effective without **transnational coordination**, **multi-stakeholder commitment** and **continuous adaptation based on feedback and evolving knowledge**. Faced with the rapid rise of offshore wind and the complexity of marine ecological dynamics, spatial planning appears not as a simple technical step, but as an integrated approach, at the crossroads of science, environmental governance and sustainable development of maritime territory.

TEMPORAL PLANNING

Temporal planning is a pragmatic mitigation measure, complementary to spatial planning. Based on the seasonal and life-cycle patterns of sensitive species, it allows adjusting the schedule of the most intrusive project phases to limit their impact.

Available data show that disturbances during critical periods can cause significant ecological effects, such as a decrease in reproductive success or a modification of foraging behaviors. In response, reasoned timing of interventions appears as a promising prevention lever. It requires fine knowledge of local species and rigorous ecological monitoring.

EXPERIENCE FEEDBACK

In the United Kingdom, at the Kentish Flats offshore wind farm, a reduction measure targeting birdlife was implemented. It consisted of planning construction phases outside the period of high concentration of diving aquatic birds. Pile driving and turbine installation operations were thus carried out outside the wintering period, which avoided any significant interference with these species.

TURBINE CURTAILMENT

Whether general or targeted, **adaptive or predictive, different curtailment strategies** appear as essential tools to effectively reduce the effects of offshore wind farms on flying biodiversity. However, their operational success requires in-depth knowledge of the behaviors of targeted species, as well as rigorous and continuous evaluation of their effectiveness in real context with minimal loss of energy efficiency.

For this, three conditions are necessary :

- deploy latest-generation detection technologies;
- generalize behavioral and environmental monitoring specific to installation sites;
- establish integrated and collaborative management at regional and international scale.

Ultimately, these approaches will allow not only a significant reduction of ecological threats associated with offshore wind, but also better social and economic acceptability of these projects in a long-term sustainability perspective.

TURBINE VISIBILITY

Measures aimed at improving the **visibility of wind turbines** rely on a precautionary and proactive logic : it involves designing infrastructures that are more perceptible to sensitive species, based on a fine understanding of their sensory ecology and flight behaviors.

Identified actions include notably **lighting management, introduction of marked visual contrasts, choice of less attractive colors, or adaptation of the physical dimensions of turbines,** such as ground clearance or rotor diameter.

These measures, largely from interdisciplinary work crossing sensory ecology, engineering and flight biomechanics, must still be empirically validated in the marine context.

What are the advantages?

- For **operators**, these elements offer technical innovation paths compatible with safety requirements and regulatory constraints.
- For **scientists**, they open an essential applied research field for evaluating species-infrastructure interactions.
- For **decision-makers**, they reinforce the idea that designing wind farms respectful of biodiversity requires fine integration of ecological knowledge into technical choices.

In this perspective, turbine visibility emerges as a complementary lever for risk reduction, to be considered in parallel with other more structural measures such as micro-siting, curtailment or spatial planning.

DETERRENCE MEASURES

Deterrence measures aimed at limiting collisions between flying fauna and offshore wind turbines are still in their infancy. Most identified devices – acoustic, luminous, textured or electromagnetic – come from land-based trials and remain undocumented in marine context. Their effectiveness varies by species, with a risk of rapid habituation.

Some solutions, such as ultrasound or anti-perching systems, seem promising but still require testing at sea, while others, such as lasers, coatings or UV lighting, are at the experimental prototype stage.

In this context, deterrence devices must be considered as potential complements to other more proven measures (spatial planning, micro-siting, curtailment). Their future development will depend on investment in applied research, in close connection with ecological knowledge of the species concerned and offshore operating constraints. For developers and decision-makers, this is an area to actively monitor, by supporting pilot projects and scientific validation programs, to determine whether certain solutions can be operationally integrated into the next generations of offshore wind farms.

WIND FARM RENEWAL OR "REPOWERING"

The **renewal of wind farms** represents an emerging opportunity to more effectively integrate biodiversity issues into the long-term management of offshore infrastructures. By allowing spatial and technological redevelopment of the park, this phase offers the possibility of applying targeted mitigation measures, such as micro-siting or removal of high-impact turbines, based on better knowledge accumulated over time.

However, for this strategy to become a real lever for reducing impacts on birds and bats, it requires the implementation of robust and continuous ecological monitoring protocols, capable of identifying the most problematic turbines. Yet, the availability of fine data at sea remains a major challenge today. The success of renewal as a mitigation tool will therefore depend on increased investment in offshore environmental monitoring and a governance framework encouraging active exploitation of this data in project reconfiguration phases.

COMPENSATORY MEASURES

Compensatory measures constitute a last-resort tool in the hierarchy of mitigation strategies, intended to counterbalance the residual impacts of offshore wind farms on birds and bats, when avoidance and reduction options have been fully mobilized.

Their implementation relies on a diversity of complementary approaches: habitat restoration, targeted conservation actions and strategic planning.

These measures must be carefully planned, adapted to the species concerned and evaluated over time to ensure they effectively compensate for the ecological losses generated by wind farm construction.

Initiatives such as removal of invasive predators, creation of secure colonies, or funding alternative conservation programs, offer concrete avenues to strengthen the resilience of affected populations.

However, their success comes with uncertainty and relies on strict conditions: rigorous monitoring, inter-regional coordination and integration into a global environmental strategy. **It is therefore essential that compensatory measures are not perceived as a substitute for avoidance efforts, but rather as a targeted complement, mobilized with caution, transparency and with a long-term conservation framework.**

RECOMMENDATIONS TO REDUCE BIODIVERSITY RISKS

ANIMALS CONCERNED BY THE RECOMMENDATIONS :

Birds Bats Insects

FOR DEVELOPERS AND PROJECT OPERATORS

Like the rest of the private sector, developers and wind turbine operators must control, evaluate and regularly and transparently communicate their risks, dependencies and impacts on biodiversity, across their entire supply and value chains and provide the necessary information to consumers to promote sustainable consumption patterns. The following recommendations, from the review of scientific literature, allow progress towards these objectives.

Recommendations		Specific Actions	Impacted Animals
Spatial planning and site selection	Select priority areas with low ecological risk	• Implement minimum buffer zones around colonies and identified Natura 2000 sites • Use remote sensing (weather radar, satellite imagery) to identify migratory routes	Birds
		• Prioritize state-led spatial planning, based on consolidated ecological data, to avoid areas with high biodiversity stakes • Use faunal sensitivity maps andfield-based biological surveys to exclude major migration corridors • Apply a multi-criteria risk index (bird density, flight height, bat concentration, light attractiveness) from the environmental impact assessment (EIA) • Conduct a cumulative impact analysis integrating future projects planned in the long term	Birds, Bats
Deterrence technologies	Experiment with complementary deterrence devices	• Install anti-perching combs on nacelles and maintenance platforms	Birds
		• Deploy directional ultrasonic emitters automatically activated when wind speed is below 6 m/s	Bats

Temporal planning of works	Schedule intrusive activities outside sensitive periods	• Establish a local faunal calendar detailing reproduction, migration, and wintering periods.	Birds, Bats
		• Use low-noise equipment or install mobile sound barriers when work cannot be postponed	Bats
		• Implement a weather-migration alert system to suspend activities during massive passages • Shift pile driving, cabling and lifting outside species sensitivity peaks	Birds
Design and general park layout (macro-siting)	Optimize park location	• Exclude critical migratory corridors • Exclude areas with high individual density or essential habitats (colonies, gathering areas, feeding sites, ...) • Define safety buffer zones around sensitive habitats, with distances adapted to critical species	Birds, Bats
Fine park design and layout (micro-siting)	Optimize turbine placement and design	• Adjust row orientation to minimize barriers perpendicular to flight corridors • Increase air gap under blades to reduce collision risk with low-flying birds	Birds
		• Integrate wind flow and flight altitude models to set optimal air gap under blades • Plan internal unequipped corridors serving as movement corridors for species • Adjust the layout plan after one year of mobile radar monitoring and flight corridor modeling • Reduce the number of turbines in ecologically sensitive areas identified during preliminary studies	Birds, Bats
Facility renewal	Take advantage of renewal to reduce impacts	• Integrate the latest certified high-visibility blades	Birds
		• Conduct a fauna cost-benefit analysis before any replacement decision • Prioritize dismantling of high-risk turbines identified by long-term monitoring	Birds, Bats

Infrastructure adaptation and visibility	Make turbines more detectable and less attractive	• Paint a single blade black to improve perception during rotation • Apply zebra patterns at mast bases to contrast with marine horizon • Replace fixed lighting with synchronized flashing lights at reduced intensity certified for aviation	
		• Adapt nighttime lighting management, respecting maritime and aviation safety constraints, to limit light attraction	
		• Test matte coatings limiting ultraviolet reflection attractive to insects	
Ecological compensatory measures	Compensate residual impacts when avoidance is not possible	• Precisely plan any compensatory measure: define objectives, indicators and schedule before deployment • Adapt each action to the species and habitats concerned to maximize ecological relevance • Conduct rigorous and long-term monitoring to quantify, using precise metrics, losses and gains, and verify actual compensation effectiveness • Ensure inter-regional coordination to create synergies between different compensation zones	
Adaptive turbine shutdown	Implement dynamic shutdown based on detection	• Apply a predictive algorithm (wind, temperature, pressure) to anticipate high-risk nights for bats • Raise the turbine startup speed threshold to approximately 5 m/s during bat migrations, modulated by nighttime temperature	
		• Couple scanning radars, acoustic sensors and thermal cameras to identify approaching fauna • Program seasonal nighttime shutdown during spring and autumn migration peaks • Continuously optimize curtailment parameters from new monitoring data and feedback • Implement a standardized international curtailment protocol, regularly revised and adaptable to regional contexts	
		• Set an increased cut-off speed on warm, humid nights favorable to insects	

Environmental monitoring and model validation (collision risk, distribution/ habitat)	Ensure continuous monitoring and improve risk models	• Install a three-dimensional radar system covering the air column up to 1,000m • Combine observations from boats, aerial surveys and radars to obtain multi-scale coverage of bird movements	
		• Deploy passive acoustic sensors on masts to measure bat activity • Install sensors on lighthouses and other marine infrastructures to monitor migratory bats	
		• Update risk models regularly • Publish raw data on an open platform under free license • Implement robust Before-After-Control-Impact (BACI) protocols to scientifically evaluate measure effectiveness	
Data sharing and governance	Implement structured regional cooperation	• Create a common metadata protocol validated by authorities • Sign an inter-company agreement for exchange of experiences and pilot devices • Organize regular operator-researcher workshops to collectively update knowledge on mitigation measures and share feedback • Maintain a regional database with mortality and shutdown dashboard • Create a single interoperable portal to centralize environmental data from wind projects, managed by a third-party organization • Establish an inter-institutional scientific consortium to coordinate research and harmonize protocols • Authorize and support experimental approaches (dynamic lighting, innovative curtailment)	
	Establish incentives for biodiversity	• Reintroduce environmental weighting in calls for tenders to encourage innovation in favor of biodiversity.	

FOR THE SCIENTIFIC COMMUNITY

The scientific community working on the impacts of offshore wind on flying biodiversity can provide support for the development or improvement of risk reduction technologies. The following recommendations help improve knowledge and therefore the effectiveness of implemented measures.

Recommendations		Specific Research Actions	Impacted Animals
Research protocol design	Define robust methods to anticipate impacts	• Standardize multi-sensor protocols (visual – aerial – radar) to produce a baseline comparable between projects • Systematically apply Before-After-Control-Impact (BACI) schemes adapted to marine context	
Pre-implementation knowledge management	Target priority knowledge gaps	• Map areas where ecological knowledge is most lacking • Update a roadmap of priority research questions, shared with the industry • Conduct Before-After-Control-Impact (BACI) experiments on multiple sites to quantify cumulative impacts and test key hypotheses	
Feedback and prospective	Capitalize on decommissioning and renewal	• Monitor changes in fauna space use after dismantling • Measure effects of new high-visibility designs installed during renewal • Conduct meta-analyses on multiple decommissioned or repowered parks to identify long-term trends in impacts and potential benefits for biodiversity	
Mitigation measure validation	Test and quantify device effectiveness	• Design robust Before-After-Control-Impact (BACI) experimental protocols to test curtailment, light/sound deterrence, increased airgap, etc. • Publish raw results, methods and costs in an international database to enable effectiveness meta-analyses • Develop standardized metrics (collision rate/MWh, energy effort) to compare devices	
Analysis and modeling	Refine risk and movement models	• Integrate micro-weather conditions and insect density into bat activity models	
		• Continuously recalibrate collision risk models by coupling new multi-species telemetric data • Update sensitivity maps and cumulative analyses annually at regional scale to guide measure adaptation • Publish each model update with its source code and associated datasets • Develop a single, interoperable portal, managed by an independent organization, to centralize environmental data	
Data collection and monitoring	Harmonize and optimize faunal monitoring at sea	• Co-develop a harmonized international protocol (visual, acoustic, 3D radar, telemetry) with mandatory inter-calibration of methods • Equip parks with latest-generation detection devices (vertical/scanning radars, LIDARs, AI cameras) coupled with real-time environmental monitoring • Synchronize data collection windows between projects on the same maritime facade	

FOR STATE AUTHORITIES AND GOVERNMENT AGENCIES

Governmental agencies, and public authorities more broadly, must ensure that operators and developers respect their biodiversity obligations, to protect species and ecosystems on which our quality of life depends. The following recommendations contribute to this objective.

Recommendations		Specific Actions	Impacted Animals
Project selection criteria	Reintroduce environmental weighting in calls for tenders	• Define a minimum percentage of points allocated to biodiversity commitments • Publish a national scale of bonuses for ambitious mitigation measures (airgap, curtailment, BACI monitoring)	
National planning framework	Lead spatial planning at state level to avoid sensitive areas	• Develop national mapping of migratory corridors and integrate it into calls for tenders • Publish exclusion or vigilance zones before any competitive process • Update ecological data regularly and make it accessible to candidates	
Experimental regulatory flexibility	Facilitate testing of innovative solutions	• Implement temporary authorizations for dynamic lighting or adaptive curtailment	
Monitoring and control	Strengthen the capacity of instructing services to control measure implementation	• Recruit and train agents specialized in marine ecology	
Protocol standardization	Harmonize monitoring methods imposed on project developers	• Publish national methodological guides (radar, acoustic, data collection) • Impose standardized protocols and procedures at national (even international) scale, and ideally Before-After-Control-Impact (BACI) schemes to evaluate measure effectiveness	
Data governance	Centralize and open environmental data	• Require deposit of raw datasets in standard format • Create a single interoperable portal managed by a public organization for free data access	
Research-State-Industry coordination	Structure applied research via a national consortium	• Fund a multi-year program dedicated to mitigation measure effectiveness • Launch an inter-institutional consortium responsible for first identifying priority research questions, then developing for each a harmonized monitoring protocol and sharing obtained results	
Coordination and scientific governance	Strengthen research structure	• Sustain and support the Offshore Wind Observatory as an inter-institutional scientific consortium to coordinate projects, funding and knowledge capitalization • Advocate for environmental weighting reintroduced in calls for tenders to finance applied research • Establish a support fund for open-access publications from wind projects • Sustain and support the annual Conference on Wind Energy and Wildlife Impacts (CWW) bringing together academics, institutions and industrialists to align protocols and priorities	
Support for environmental innovation	Financially incentivize ambitious measures	• Use subsidies and tax incentives to stimulate research and development of mitigation technologies	

Given the challenges of climate change, offshore wind represents an important lever for limiting greenhouse gas emissions. Nevertheless, the development of this sector relies on infrastructure that can have harmful effects on biodiversity. This booklet highlights scientists' recommendations regarding measures to reduce these impacts, intended for the scientific community, developers and operators of offshore wind farms, and government agencies.

No single measure can address all issues related to the impacts of offshore wind sites on flying species. From the planning phase, the **mitigation hierarchy framework** is essential. The use of intelligent curtailment, acoustic or visual detection technologies, as well as deterrence devices from project design, would enhance species protection. Moreover, it is essential to develop **standardized impact assessment tools,** integrating specific criteria such as cumulative effect analyses and species resilience.

Finally, close collaboration between researchers, developers and public authorities is essential to **ensure the ecologically responsible and harmonious development of offshore wind farms**.

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See the full summary :

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