Advanced Data-Driven Modeling for Marine Biodiversity Risk in Offshore Wind

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SUMMARY

The expansion of offshore wind energy in the Mediterranean area necessitates a robust biodiversity impact assessment framework tailored to the region's unique ecological characteristics. This study introduces a methodology that integrates site-specific monitoring campaigns (carried out with various monitoring techniques) and advanced modeling to evaluate the potential impacts of offshore wind farms on birds and marine mammals. By refining the Band Collision Risk Model with high-resolution data on avian flight altitudes, seasonal behaviors, and avoidance patterns, and coupling it with acoustic propagation modeling to predict underwater noise effects on cetaceans, this framework offers a comprehensive approach to impact assessment. Site-specific surveys provide localized and site-specific data to enhance model accuracy; furthermore, the results that can be obtained through the methodology described represent an effective instrument to inform targeted mitigation strategies for offshore wind projects.

INTRODUCTION

The growing demand for renewable energy has positioned offshore wind power as a decisive component of energy transition in the Mediterranean area. However, this development presents environmental risks to the seabed and biodiversity, due to the unique ecological and socio-economic characteristics of the Mediterranean (Josep Lloret, 2022).
The Mediterranean area is characterised by an increasing interest in offshore wind energy development due to the large potential of the floating offshore wind technology (Konstantin Staschus, 2020); despite this growing interest, integrated biodiversity impact assessment approaches are still under development in the Mediterranean area, as methodologies used in the North Sea cannot simply be applied without proper evaluation.
This study presents an integrated framework combining different monitoring techniques and advanced modeling to assess the biodiversity impact of offshore wind projects.

1. METHOLOGICAL FRAMEWORK

To address the aforementioned challenges, the proposed framework outlines a possible science-based approach, consisting of the following phases (Figure 1):

- Phase I - Bibliographic data collection.
- Phase II - Data collection through marine fauna monitoring.
- Phase III - Data process through advanced modelling.

By integrating these elements, this study contributes to the development of site-specific, data-driven mitigation strategies that account for the distinct ecological conditions of the Mediterranean. The findings will help inform regulatory frameworks and industry best practices for sustainable offshore wind energy expansion in the Mediterranean Sea.

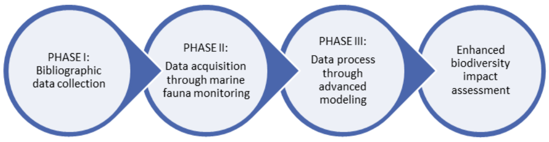

Figure 1: Outline of the proposed model to improve the analysis of biodiversity impacts through an integrated monitoring and advanced modelling approach

It is specified that, although it will not be further detailed, the methodology described is also effectively applicable to marine reptiles, fish and to chiropter fauna.

1.1 BIBLIOGRAPHIC DATA COLLECTION

The analysis requires a preliminary phase of bibliographic data collection regarding the potentially present species.
At this stage, valuable bibliographic data include the conservation status of species according to the IUCN Red List, as well as information on flight altitudes and modes (e.g. soaring, flapping, flocking or solitary flight), where available. Additionally, data from bird ringing[1], an internationally recognized method for studying migratory routes, can provide key insights into migration patterns.
For marine mammals, relevant bibliographic information should include the results of large-scale monitoring initiatives in the Mediterranean, such as the ACCOBAMS Survey Initiative (ASI), as well as long-term monitoring data from non-governmental organizations. Additionally, the Intercet GIS platform[2] should be consulted, as it serves as a networking tool at the Mediterranean level.

1.2 DATA COLLECTION THROUGH MARINE FAUNA MONITORING

Avifauna and marine fauna monitoring in the context of offshore wind development requires a multi-faceted approach that integrates traditional observation methods with aerial remote sensing. This combined methodology effectively captures species diversity, behavior, and spatial distribution, ensuring a comprehensive understanding that supports robust impact assessments and informed mitigation strategies.

1.2.1 AVIFAUNA MONITORING

Traditional monitoring techniques include radar-based tracking and transect visual surveys, both of which contribute valuable insights with distinct methodological strengths.
Radar monitoring offers continuous, weather-independent data acquisition, enabling the detection of nocturnal and high-altitude movements, as well as migratory patterns and avoidance behaviors.
However, radar systems often face limitations in species-level identification and require extensive post-processing to eliminate non-avian signals. Complementarily, transect visual surveys conducted

[1] e.g. The Online Migration Atlas (Spina, Baillie, Bairlein, Fiedler, & Thorup, 2022) and the European Union for Bird Ringing (EURING Databank, 2023)

[2] https://www.intercet.it/Public/PresentationMap

from boats or coastal vantage points provide high-resolution taxonomic data, direct behavioral observations, and context on habitat use and flock formations.

These surveys should be planned across different seasons to capture temporal variability in species presence, and conducted along standardized transects, recording key parameters such as species, abundance, flight height and direction, behavior, and environmental conditions.

Applying indices such as the Kilometric Abundance Index (KAI)—the number of individuals observed per kilometer (F., 1958)—can offer useful measures of relative abundance and population trends over time. Examples of individuals observed in monitoring using the described method are reported in Figure 2.

Figure 2: Examples of sightings made on sites where this approach has been applied: on the left, a Cory's shearwater (Calonectris diomedea), and on the right, a flock of glossy ibises (Plegadis falcinellus)

The monitoring plan should be structured and organized in compliance with national and international guidelines, as for example the BACI (Before After Control Impact) design, which is widely recognized for its effectiveness in environmental impact assessments. This approach involves collecting data both before and after the implementation of a project, as well as in control areas unaffected by the development. By comparing temporal and spatial datasets, the BACI design allows for the detection of changes directly attributable to the infrastructure, distinguishing them from natural variability.

To overcome the spatial and logistical constraints of traditional methods, aerial monitoring should be included as a complementary approach. Aerial surveys, carried out using aircrafts or UAVs equipped with high-resolution cameras, thermal sensors, and AI-assisted image analysis, allow for rapid coverage of large areas with minimal disturbance to wildlife. Aerial systems are integrated with flight planning software and geo-referencing tools to ensure accurate positioning and reproducibility of survey paths. Species or taxonomic groups can be observed and recorded in high resolution images, and spatial distribution maps can then be produced.

1.2.2 MARINE MAMMALS MONITORING TECHNIQUES

Key traditional methods include visual line transect surveys, photo-identification, and passive acoustic monitoring (PAM).

Visual line transects surveys, typically conducted from research vessels, provide direct observations of species presence and group size and behavior. These surveys should follow standardized protocols, and the collected data contribute for the abundance and behavioral analyses.

Photo-identification is a widely adopted technique for studying population structure and patterns. This method can support long-term monitoring of specific populations and life histories. Examples of individuals observed in monitoring using the described method are reported in Figure 3.

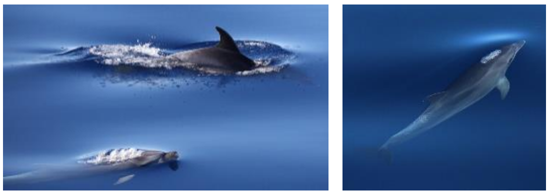

Figure 3: Examples of sightings made on sites where this approach has been applied: specimens of bottlenose dolphins (Tursiops truncatus)

Passive acoustic monitoring (PAM) complements visual methods by detecting and recording the vocalizations of marine mammals, particularly effective for species that are difficult to observe or active during low-visibility conditions. PAM systems may be deployed on moorings, buoys (see Figure 4), or autonomous platforms and can operate continuously over extended periods, providing insights into species presence, vocal activity patterns, and possible changes in acoustic behavior due to noise exposure. Hydrophones can be used via bottom arrangement or drifting recorder.

Figure 4: Example of positioning at sea of a hydrophone connected to a buoy

To expand spatial coverage and reduce logistical constraints, aerial surveys are increasingly used in marine mammal monitoring. High-resolution digital aerial surveys, conducted with fixed-wing aircraft or drones equipped with automated imaging systems,

offer a non-invasive, efficient approach for surveying large and remote offshore areas. These surveys can detect specimens from altitude with minimal disturbance.
Combining aerial data with acoustic and visual information provides a comprehensive picture of marine mammals' occurrence, seasonal trends, and spatial usage of the area.

2. ADVANCED MODELING IN BIODIVERSITY IMPACT ASSESSMENT

According to the described methodology, both the Band Collision Risk Model and acoustic propagation modeling rely on high-resolution datasets to enhance predictive accuracy and ecological relevance. Using both models together allows for a comprehensive evaluation of the potential impacts of offshore wind farms on marine wildlife.

2.1 THE BAND COLLISION RISK MODELING

Of all the potential impacts of offshore wind farms, collision deaths have attracted the most attention as the primary impact on bird populations. Birds can die by striking stationary superstructures, stationary or moving rotor blades, or they can be caught and fatally injured in vortices created by the rotor blades' airflow (Fox, 2006). Many birds, especially nocturnal migratory passerines, collide with stationary objects (Kerlinger, 2000), especially when these are illuminated, due to disorientation and attraction to the lights.
The Band Collision Risk Model is employed to estimate bird collision probabilities with offshore wind turbines; the model is refined with high-resolution data on:

- Flight altitude distributions.
- Seasonal migration patterns.
- Species-specific avoidance behavior at different turbine heights.

The output generated by the model indicates the probability (expressed in %) that an object of a certain size and moving at a certain speed crossing the circular area swept by the blades, will collide with them. The output value must be corrected taking into account the behavioral responses of birds to the presence of new obstacles along their path.
The effective use of the model envisages the following steps:

1. Flight activity data collection.
2. Seasonal migration patterns identification.
3. Avoidance behavior definition.
4. Calculation of collision probability.
5. Risk classification.

The model can be used to simulate different avoidance scenarios (where the worst-case scenario is represented by no avoidance).
Incorporating data from the monitoring activities enhances the accuracy of the risk assessments. These data can be used to refine the collision probabilities and adjust the model's predictions.
By following these steps and integrating relevant monitoring data, the Band Collision Risk Model provides a robust framework for estimating collision risks and guiding mitigation efforts.

2.2 ACOUSTIC PROPAGATION MODELING

Marine mammals are highly sensitive to underwater noise, making acoustic disturbance a critical factor in offshore wind impact assessments.
Research shows that underwater noise from wind turbine operations can impact cetacean communication and behaviour, with potential long-term consequences on their populations (Southall, 2007). The following methodology outlines how to apply acoustic propagation modeling for impact assessments:

1. Noise source identification.
2. Environmental factors modeling.
3. Species-specific hearing sensitivities definition.
4. Calculation of sound propagation.
5. Disturbance zones definition (see Figure 5).

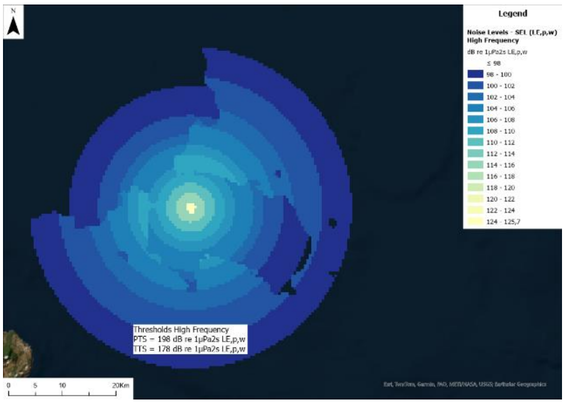

Figure 5: Example of the output of the acoustic propagation modeling

The disturbance zones (defined by distance from the noise source) are typically used to implement mitigation measures.
Different scenarios include seasonal changes in species presence, varying construction schedules, and operational noise levels.

The integration of site-specific environmental and biological data—collected through both acoustic monitoring and visual observations—proved essential in enhancing the predictive accuracy of the propagation model. Moreover, empirical data on marine mammal presence and behaviour within the study area allows for refined calibration of disturbance thresholds and a more reliable identification of risk zones.

3. DISCUSSION AND CONCLUSION

The study highlights the critical role of integrating advanced modelling techniques with site-specific monitoring for robust biodiversity impact assessments in offshore wind energy projects. Quantitative models—such as the Band Collision Risk Model for birds and acoustic propagation models for marine mammals—allow the incorporation of complex ecological variables into a structured, repeatable framework. When informed by high-resolution field data, these models achieve greater predictive accuracy and reduce uncertainty, supporting more ecologically valid assessments.

Empirical studies show that digital aerial surveys, compared to visual methods, improve detection rates and sample sizes, reducing type II errors and supporting more refined species distribution models (Ramūnas Žydelis, 2019).

Achieving similar accuracy with visual surveys would require greater effort and coverage.

Overall, the combination of modelling and high-quality monitoring enhances the precision of risk assessments and supports the development of effective, targeted mitigation strategies—an approach especially vital in complex and biodiverse regions such as the Mediterranean.

This integration represents a best-practice approach, enabling evidence-based decision-making for conservation and impact mitigation.