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Environmental impact of wind farms from a biodiversity perspective

A comparative study of terrestrial and marine wind farms

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Abstract

This thesis examines the environmental impacts of wind power, emphasizing its effects on biodiversity both on land and at sea. A comparative case study analysis of biodiversity impacts between wind farms within terrestrial and marine settings is carried out. The two case studies are: the Tarifa Wind Farm in Spain and the Hornsea Project One in the UK. The research investigates how wind farms disrupt local ecosystems and discusses mitigation measures currently implemented.

The findings highlight significant biodiversity impacts, including risks to birds, bats, marine mammals, and benthic organisms. For instance, the Tarifa Wind Farm shows high fatality rates among raptors and bats due to collisions with turbines. Meanwhile, the Hornsea Project One affects marine mammals through noise pollution and benthic organisms through habitat disturbances. However, positive impacts were also noted, such as the creation of artificial reefs at the Hornsea site, which can enhance local biodiversity by providing new habitats.

Despite these findings, challenges remain in fully addressing the negative impacts on local ecosystems. Effective mitigation measures, such as selective turbine stopping and noise reduction strategies, show promise but require continuous adaptation and monitoring.

The thesis offers targeted recommendations for policymakers and future studies to enhance the ecological sustainability of wind energy projects. Recommendations include implementing robust environmental guidelines, creating buffer zones around critical habitats, enforcing seasonal restrictions on construction activities, and investing in technology to minimize wildlife disturbances. Furthermore, ongoing post-installation monitoring is crucial to assess the long-term ecological impacts and effectiveness of these measures.

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1 Introduction

1.1 Background

An analysis of the crises of the modern world reveals a growing need for a global energy transition. Centralized energy systems rely heavily on fossil fuels. An increase in the price of the most important primary energy source has a decisive impact on the stability and efficiency of economic systems. The current war in Ukraine clearly illustrates this dependency. On the other hand, the effects of climate change related to human economic activity are becoming increasingly severe. According to the Intergovernmental Panel on Climate Change (IPCC), between 3.3 and 3.6 billion people already live in areas vulnerable to severe climate change (IPCC, 2022).

Implementing the international community`s plan to reduce temperatures relative to the pre-industrial period by 1.5°C (or even 2°C) by the middle of this century, depends on the intensity and scope of this energy transition. Its acceleration will also be important for long-term energy security, price stability and energy flexibility (Jasiński, Kacejko, Matuszczak, & Szulczyk, 2022).

Wind power, a form of renewable energy that uses wind turbines to generate electricity, has been increasingly adopted worldwide due to its sustainability and low carbon footprint. It's a clean and sustainable energy source that has seen a significant uptake across various countries (Galparsoro, Menchaca, Garmendia, & al., 2022). However, the development of wind power projects, both onshore and offshore, can have significant impacts on biodiversity (Galparsoro, Menchaca, Garmendia, & al., 2022).

In 2020, despite the pandemic, the world's wind power industry achieved record growth, adding 93 GW of capacity, an increase of nearly a third compared to the previous record in 2015 (Council, 2021). The majority of new installations (93%) were onshore farms, with a smaller portion (6.1 GW) installed offshore. China and the US led the way in adding new capacity, with 52 GW and 16 GW respectively. In Europe, the largest investments came from the Netherlands (2 GW) and Germany (1.6 GW) (Jasiński, Kacejko, Matuszczak, & Szulczyk, 2022). Global installed wind turbine capacity exceeded 750 GW, with China in the lead. In Europe, Germany, Spain and the UK have the largest installed capability. Wind power's share of electricity generation is increasing across Europe, with a 15% average share for the EU, with Denmark reaching 48%, and other countries also recording high rates (Jasiński, Kacejko, Matuszczak, & Szulczyk, 2022).

1.2 Historical Context of Wind Power

Humanity has harnessed wind energy for over 15 centuries, marking significant periods of technological and industrial development. Initially critical for industrialization, wind energy's usage declined with the advent of cheaper energy sources. Jos Beurskens categorizes the history of wind energy into four distinct periods: the Classical period (600-

1890), the development of electricity-generating wind turbines (1890-1930), the first innovation phase (1930-1960), and the second innovation phase starting in 1973 (Beurskens, 2014).

From 600-1890, the evolution of wind energy was characterized by the transition from simple mechanical devices powered by human or animal effort to more sophisticated windmills. Notably, vertical windmills emerged in Persia and China by the mid-7th century AD, highly regarded for their construction (Beurskens, 2014). This period also saw the development of windmills in Europe, where innovations such as the post windmill, which could be manually rotated to face the wind, improved energy efficiency (Beurskens, 2014).

The period from 1890-1930 witnessed significant advancements with the invention of the dynamo, allowing energy from wind to be used more widely. The development of wind turbines advanced with figures like James Blyth and Charles Brush, who pioneered early models of electricity-generating windmills (Beurskens, 2014). Aerodynamic research during this time led to more sophisticated designs, optimizing the efficiency of wind turbines (Beurskens, 2014).

The post-World War II era (1930-1960) saw a resurgence in wind turbine development, driven by a scarcity of fossil fuels. Innovations in rotor structures and the integration of wind turbines into power grids marked this period. Denmark and the US led these advancements, focusing on improving turbine efficiency and operational safety (Beurskens, 2014).

The oil crisis of 1973 revitalized interest in wind energy, highlighting its potential as a sustainable alternative to fossil fuels. This period marked a shift from experimental to commercial stages in wind turbine technology, with significant advancements in materials and design. The emphasis on diversifying energy sources led to the growth of both onshore and offshore wind farms, with the first commercial offshore wind farm established in Denmark in 1991 (Beurskens, 2014).

1.3 The role of Biodiversity in Ecosystem Resilience and the Impacts of Wind Energy Development

In this thesis, “biodiversity” is specifically defined as the variety of animal life, or fauna, within ecosystems affected by wind farms (Compendium 5.2: Ecological roles of animals, 2022). This focus is critical as fauna play key roles in maintaining ecological balance and are often directly impacted by wind energy developments (Compendium 5.2: Ecological roles of animals, 2022). Animals, ranging from birds and bats to marine mammals, are integral to the ecological dynamics and serve as indicators of the health of their ecosystems. Their well-being reflects the broader environmental impacts of wind farms, including changes in habitat, migration patterns, and food webs (Compendium 5.2: Ecological roles of animals, 2022).

The significance of biodiversity has been underscored by global crises like the COVID-19 pandemic, which highlighted the vulnerabilities of our interconnected global systems (Shroff & Cortés, 2020). This crisis has demonstrated how closely human health is linked to the environmental health of our planet, emphasizing the urgent need to address environmental degradation, species extinction, and climate change (Shroff & Cortés, 2020).

Nevertheless, human activities, including the construction and operation of wind farms, pose significant challenges to biodiversity. These include the risk of bird and bat collisions with turbine blades, habitat fragmentation, and disturbances from noise and vibrations (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021). It is crucial to mitigate these impacts to ensure that the development of wind energy is sustainable and harmonizes with efforts to conserve biodiversity (Scale Climate Action, 2023).

1.4 Environmental Impacts on Biodiversity

The deployment of wind farms is a critical component of the global strategy to mitigate climate change through renewable energy sources. However, the environmental impacts of these installations, particularly on biodiversity, pose significant challenges. This subchapter explores the complex interactions between wind farms and local ecosystems, focusing on both the direct and indirect effects on terrestrial and marine wildlife (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

Direct impacts on wildlife

One of the most immediate and visible impacts of wind turbines is the risk they pose to birds and bats through collisions (Schöll & Nopp-Mayr, 2021). These incidents primarily occur because birds and bats do not always perceive the turbine blades as obstacles, especially at high speeds or in poor visibility conditions.

Research indicates that the location of turbines, whether on migration routes or local flyways, greatly influences collision rates. The design and operation of turbines can exacerbate these risks, with taller turbines and those placed in high-density bird areas posing greater threats (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

Beyond collisions, wind farms significantly alter habitats where they are installed. The physical footprint of turbines, along with roads, power lines, and other infrastructure, leads to habitat loss and fragmentation (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021). This disruption affects not only the flora and fauna residing directly at the site but also those in surrounding areas, as changes in land use and habitat structure can alter local ecosystems (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021). Such fragmentation can impede the movement of species, reduce the availability of food resources, and alter predator-prey dynamics, potentially leading to a decline in biodiversity (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

Indirect Impacts on Ecosystems

The operational aspects of wind turbines, including noise and subaudible vibrations (infrasound), can also impact wildlife (Bergström, et al.). These auditory disturbances may interfere with the communication, feeding, and mating behaviors of various animal species. For marine installations, the noise can affect aquatic species, including fish and marine mammals, altering their behaviors and potentially affecting their survival and reproduction (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

Wind farms can create barrier effects, where the physical presence of turbines and associated infrastructure acts as a deterrent to wildlife movement. This can fragment populations, leading to decreased genetic diversity and even local extinctions. For flying species, turbines may alter aerial pathways, while for terrestrial wildlife, the infrastructure may limit access to feeding, breeding, or nesting areas (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

Cumulative and Long-term Effects

The long-term consequences of habitat fragmentation include the genetic isolation of populations, where groups of the same species become genetically segregated due to reduced mobility and interaction (Liu, et al., 2018). This isolation can lead to inbreeding and reduced genetic diversity, weakening population resilience against diseases or environmental changes, and diminishing their adaptive capabilities (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

Wind farms can also trigger trophic cascades within ecosystems. For example, a decline in predatory birds due to turbine collisions could lead to an increase in the population of certain prey species. This imbalance can result in overgrazing or other forms of habitat degradation, affecting the entire ecosystem's health and functionality (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

While wind farms are a vital component of renewable energy infrastructures, their environmental impacts, particularly on biodiversity, necessitate careful consideration and management. Balancing the benefits of renewable energy with the needs of biodiversity conservation requires integrated planning, innovative mitigation strategies, and adaptive management to minimize negative impacts while maximizing ecological and social benefits.

Environmental Impact Assessment (EIA) for Biodiversity

The Environmental Impact Assessment (EIA) plays a pivotal role in this context as a tool for systematically evaluating potential impacts on biodiversity, serving as a preventive mechanism that enables stakeholders to anticipate and address environmental effects (Cypress, 2023). This approach has been instrumental in projects like the Hornsea Project One in the UK, helping to identify and mitigate impacts on local bird populations and other biodiversity aspects (ENVIRONMENTAL IMPACT ASSESSMENT REPORT (EIAR) FOR THE PROPOSED CROAGHAUN WIND FARM, CO. CARLOW, 2020) (Cypress, 2023).

The proactive use of EIA in various contexts, such as the guidelines for offshore wind farms, underlines its capacity to shape project planning and implementation towards minimizing biodiversity impacts while enhancing ecological and community sustainability (Bojars, et al., 2016) (Santos, et al., 2018).

1.5 Statement of the Problem

The global energy transition towards renewable sources, such as wind power, is a critical response to the dual crises of climate change and fossil fuel dependency. However, the environmental impacts of wind power on biodiversity present a complex and multifaceted problem that warrants thorough investigation (IUCN, Offshore wind farms – green energy or biodiversity threat?, 2010).

Wind farms, both onshore and offshore, have been increasingly adopted worldwide due to their sustainability and low carbon footprint. However, their construction and operation can lead to habitat loss or degradation, which can adversely affect wildlife populations. Birds and bats are particularly vulnerable, with risks of collision with turbine blades and barotrauma from rapid air pressure changes near the turbines (Choi, Wittig, & Kluever, 2020). Noise and vibration disturbances from wind turbines can also impact wildlife behavior and stress levels (Choi, Wittig, & Kluever, 2020). Furthermore, offshore wind farms can affect marine life, including fish and marine mammals, through underwater noise and habitat changes (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021).

Despite the implementation of various mitigation measures, such as careful site selection, design, and operation of wind farms, and the use of radar systems to detect incoming flocks and adjust turbine blade rotation accordingly, these impacts persist (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021). The effectiveness of these measures varies and they may not fully address all the impacts. Therefore, there is a pressing need to understand these impacts more fully and to develop effective strategies for mitigation.

This thesis aims to investigate the environmental impacts of wind farms from a biodiversity perspective, with a focus on understanding the scale and nature of these impacts, the effectiveness of current mitigation measures, and the potential for new strategies to minimize these impacts. To do this a comparison of the implementation of two wind park project, one terrestrial (Tarifa Wind Farm, Spain) and one at sea (Hornsea Project One, UK) is conducted. These sites were chosen because of their scale, the ecosystems with which they interact, and the availability of data. This research will contribute to the ongoing efforts to ensure the sustainability of wind power and its compatibility with biodiversity conservation.

1.6 Research Questions

1.6.1 Overarching Research Question

The overarching research question is “What are the environmental impacts of wind power on land and at sea in relation to biodiversity?”. This research question is poised at the intersection of renewable energy development and ecological conservation, challenging the dichotomy between the drive for sustainable energy solutions and the imperative to conserve biodiversity. It reflects an acknowledgment that while wind power represents a formidable force in the fight against climate change, its deployment must be judiciously managed to mitigate adverse effects on ecosystems, whether terrestrial or marine.

1.6.2 Subsidiary Research Question

In order to delve deeper into the overarching research question, the following subsidiary research question was formulated:

- What are the current identified impacts of wind power on fauna in relation to e.g. land use changes?

This subsidiary question will allow for a more detailed and nuanced examination of the environmental impacts of wind power. The question will involve a comprehensive review of the existing literature on the environmental impacts of wind power, focusing on aspects such as climate change, land use change, biodiversity. This will provide a broad understanding of the range of potential impacts associated with wind power.

By addressing this subsidiary research question, a more comprehensive and nuanced understanding of the environmental impacts of wind power, both on land and at sea is provided. This will ultimately contribute to a more holistic understanding of the environmental implications of wind power, informing more sustainable practices in the deployment of wind power technologies.

This history of wind power underlines its role in global energy diversification and sustainability, reflecting a long tradition of technological innovation and adaptation to changing energy needs (Beurskens, 2014).

1.7 Case study areas descriptions

The Tarifa Wind Farm and the Hornsea Project One were selected based on:

- Geographical Representation: These sites provide two representative examples of terrestrial and marine wind power projects in Europe, because they are located in distinctly different ecological zones that exemplify the unique environmental challenges faced by each type (de Lucas, Janss, & Ferrer, The effects of a wind farm on birds in a migration point: the Strait of Gibraltar, 2003) (Horton, 2014). The Tarifa Wind Farm, situated at the southern tip of Spain, is an ideal representation of terrestrial wind energy development due to its positioning along a major migratory route for birds, which makes it a critical area for studying avian impacts (del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023).

On the other hand, the Hornsea Project One, located off the Yorkshire coast in the UK, serves as a prime example of offshore wind energy impacts, situated in a marine environment known for its high biodiversity, including significant populations of marine mammals and birds (Horton, 2014). This contrast allows for an in-depth exploration of how wind energy interacts with and influences terrestrial versus marine ecosystems, providing valuable insights into the varied ecological dynamics and enabling the development of tailored mitigation strategies that address the specific needs of each setting.

- Data Availability: Environmental impact assessment reports available for Hornsea Wind Farm and research data are available for both sites.
- Ecosystem Diversity: Each site interacts with distinctly different ecosystems, offering a broader perspective on biodiversity impacts.

1.7.1 Terrestrial Wind Park (Tarifa Wind Farm)

The Tarifa Wind Farm, situated near the southernmost point of mainland Spain, stands as a pioneering project in the use of wind energy in Europe. This region, known for its consistently high winds, particularly the Levante and Poniente, makes it an ideal location for wind power generation. The wind farm's proximity to the Strait of Gibraltar further enhances its wind-catching capabilities due to the natural wind funnel created by the geographical layout (The Wind Power, 2023).

Originally developed in the early 1990s, the Tarifa Wind Farm has undergone several upgrades to optimize its efficiency and environmental compatibility. One of the most significant upgrades was the replacement of 90 older turbines with 12 new, more powerful and technologically advanced models. This upgrade not only increased the farm's efficiency but also reduced its physical and environmental footprint, reflecting a commitment to sustainable practices in renewable energy development (La Vanguardia, 2019).

The new turbines installed at the Tarifa Wind Farm are state-of-the-art Alstom Ecotecnia models, known for their robust performance in high wind conditions. Each turbine boasts a capacity of 3 MW, significantly higher than the older models. This upgrade has allowed the wind farm to maintain a substantial output while decreasing the number of turbines, thereby reducing visual and environmental impacts (The Wind Power, 2023)

Tarifa's wind farm is not only a testament to technological advancement but also to environmental consciousness. The strategic placement of turbines takes into consideration migratory bird paths and local biodiversity, which are particularly sensitive due to the nearby Strait of Gibraltar, a crucial migratory route for many bird species. The wind farm operates under strict regulations to minimize its impact on these birds, particularly during migration seasons (Cordis , 2022).

As the locality with the highest concentration of wind installations in Andalucía, Tarifa has established itself as a leader in renewable energy within the region. The wind farm contributes significantly to the local economy, providing jobs and infrastructure development while also enhancing Tarifa's profile as a center for sustainable energy development.

This leadership in wind energy aligns with broader regional goals of increasing renewable energy contributions to the energy mix, reducing reliance on fossil fuels, and promoting environmental sustainability (Ciudad de Tarifa Al Minuto, 2023).

1.7.2 Offshore Wind Park (Hornsea Project One)

Hornsea Project One represents a monumental achievement in offshore wind energy, leveraging its scale and innovative technology to advance sustainable energy production. Located about 120 kilometers off the Yorkshire coast (figure 2), this offshore wind farm spans an area of approximately 407 square kilometers in the North Sea, strategically selected for its optimal wind speeds and suitable water depths for large-scale operations (Orsted). Hornsea One reached full operational status in 2019 and is managed from Ørsted's East Coast Hub located in Grimsby, England. Ownership of the offshore wind farm is split evenly between Ørsted and Jupiter Offshore Wind Limited, each holding a 50% stake (Tethys, n.d.). The initial development was carried out by Smart Wind Ltd, which is a collaborative venture between Mainstream Renewable Power and Siemens Project Ventures GmbH, following its selection by the Crown Estate under the Offshore Wind Round 3 Program (Tethys, n.d.).

Operated by Ørsted, Hornsea One includes 174 turbines, each with a 7 MW capacity provided by Siemens Gamesa Renewable Energy. These turbines are installed on monopile foundations, chosen for their compatibility with the seabed's composition, predominantly sand and clay (Hornsea Project One, North Sea, 2021). The farm connects to the grid through three offshore substations and includes a central reactive compensation substation to ensure the quality of energy transmitted over the long distances to shore (Horton, 2014).

The total installed capacity of 1.2 gigawatts (GW) enables Hornsea One to supply electricity to over one million homes, significantly contributing to the UK's renewable energy goals (Orsted). Each turbine, towering around 190 meters from sea level to blade tip, harnesses the consistent wind speeds of the North Sea to generate a substantial and reliable supply of electricity (Orsted).

The onshore facilities include a substation, underground cabling, essential buildings and structures, equipment for low-voltage electricity and communications, along with necessary roads, paths, drainage systems, and landscaping (Hornsea Project One, North Sea, 2021). Situated at North Killingholme in North Lincolnshire, the onshore substation plays a critical role in channelling electricity from the offshore wind farm directly to the nearby national grid substation. This substation is constructed from Powercrete, known for its high thermal conductivity (Hornsea Project One, North Sea, 2021). Spanning a 32,200m² area, the wind farm is equipped with essential components such as transformers, reactors, high-voltage gas-insulated switchgear systems, either a static VAR compensator (SVC) or a static synchronous compensator (STATCOM), and harmonic filters (Hornsea Project One, North Sea, 2021). Offshore cables reach the mainland at Horseshoe Point, located south of Grimsby, and connect to the underground onshore cables via transition joint bays. The cables extend underground for approximately 40 km from the point of landfall to the onshore substation at North Killingholme (Hornsea Project One, North Sea, 2021).

In March 2021, an agreement was finalized for the sale of Hornsea's transmission assets to Diamond Transmission Partners Hornsea One (DTP), a joint venture between Mitsubishi's fully owned subsidiary, Diamond Transmission Corporation, and Chubu Electric Power (Hornsea Project One, North Sea, 2021). This deal encompasses the transfer of the onshore substation, export cables, the offshore RCS, and three offshore substations. Additionally, Orsted will continue to provide operations and maintenance services under a long-term service agreement (Hornsea Project One, North Sea, 2021).

Hornsea One's operational base in Grimsby serves both logistical needs and as a catalyst for regional economic growth, providing over 350 operational jobs and supporting more than 3,000 roles during the construction phase (Orsted).This is part of Ørsted's broader strategy, investing more than £13 billion in the UK's offshore wind sector, emphasizing the project's role in stimulating long-term economic growth and job creation.

The logistics of constructing and maintaining such a large-scale project offshore are complex, involving the coordination of maritime and engineering activities to install and maintain turbines at this scale. The project utilizes some of the industry's largest installation vessels to manage the heavy components, a challenging task given the North Sea's variable weather conditions (Orsted).

Hornsea Project One not only validates the technical and economic feasibility of large-scale offshore wind farms but also sets new industry standards for innovation in renewable energy technologies. It serves as a model for future projects globally, pushing the boundaries of what is achievable in offshore wind energy generation (Orsted).

2 Methodology

2.1 Research Design

This study employs a qualitative approach to comprehensively assess the environmental impacts of wind power on biodiversity, both on land and at sea. The research is structured around a comparative case study analysis complemented by a systematic literature review. This design is chosen to provide a robust framework that supports the exploration of complex ecological interactions and the varied impacts of wind energy developments in different settings.

2.2 Data Collection

Comparative Case Study Analysis involves the systematic comparison of two or more cases to understand the differences and similarities between them. This approach is based on Robert K. Yin's (Yin, 2003) case study research methodology, which emphasizes the importance of context and depth in understanding complex phenomena.

Implementation:

- Case Selection: The Tarifa Wind Farm and Hornsea Project One were chosen due to their distinct settings (onshore vs. offshore) and their detailed environmental impact assessments.
- Data Collection: Data were gathered from multiple sources, including EIAs, government and NGO reports, and academic studies. This ensured a comprehensive understanding of each case.
- Data Extraction: Key data points related to biodiversity impacts were systematically extracted and categorized for each case.
- Comparison Framework: A structured framework was developed to compare the impacts on different species groups (e.g., birds, bats, marine mammals, benthic organisms) and types of impacts (e.g., collision, noise).

Uniqueness:

While comparative case study analysis is a well-established method in social sciences, its application in studying the environmental impacts of wind farms on biodiversity is relatively novel. This study is unique in its detailed comparative approach, which integrates multiple data sources and focuses on both terrestrial and marine ecosystems. This research provides a comprehensive and contextualized understanding of the impacts, which can inform future studies and policy decisions.

2.3 Data Analysis

Content analysis was applied to qualitative data from the case studies and literature review. This included:

- Comparing the differential impacts of terrestrial versus marine wind farms.

- Evaluating the effectiveness of existing mitigation measures based on empirical evidence.

This qualitative approach allowed for an in-depth understanding of the complex interactions between wind farms and biodiversity.

2.4 Literature review

Secondary data for this study were gathered through a comprehensive search across independent academic databases, including ScienceDirect and Google Scholar. The search strategy was meticulously designed, utilizing specific keywords to ensure thorough coverage of relevant topics. These keywords included wind farms, biodiversity impacts of wind energy, terrestrial and marine wind farm impacts, avian mortality at wind turbines, bat collisions at wind turbines, marine mammals and wind farms, benthic organisms at offshore wind farms, and environmental impact assessments of wind farms. Additionally, secondary data were also sourced from governmental agencies and reports prepared for governments, enriching the research with diverse perspectives and detailed analyses.

To ensure the integrity and rigor of this study, particularly given the politically sensitive nature of the environmental impacts of wind farms, careful consideration was given to the reliability and validity of the sources used. Primary data were derived from Environmental Impact Assessments (EIAs), journal articles, and reports from reputable governmental and non-governmental organizations.

Each source was selected based on its credibility and relevance to the research questions, with a preference for documents that had been published by authoritative bodies known for their expertise in environmental science and policy. This approach ensured that the data collected were both reliable—accurate and consistently reproducible—and valid—appropriately applied and interpreted within the context of this study.

Furthermore, the analysis incorporated a triangulation method to cross-verify information across multiple sources, enhancing the robustness of the findings (Hassan, 2024). This method is particularly effective in mitigating the influence of bias and ensuring that the conclusions drawn are reflective of a comprehensive understanding of the documented impacts and mitigation strategies associated with wind energy development.

3 Results

3.1 Biodiversity Impacts of Wind Energy: Offshore vs Onshore Wind farms

Table 1 Comparative Biodiversity Impact Results at Tarifa and Hornsea Wind Farms

Case Study	Species Group	Specific Concerns	Observed Impact	Impact type	Sources
Tarifa Wind Farm	Birds	Collision with turbines, habitat disruption	High fatality rates among raptors; altered flight paths	Direct	(de Lucas, Ferrer, Bechard, & Munoz, 2012) (de Lucas, Janss, & Ferrer, The effects of a wind farm on birds in a migration point: the Strait of Gibraltar, 2003)
Tarifa Wind Farm	Bats	Collision with turbines, noise disruption	High mortality rates, notably in Pipistrellus, Nyctalus and Eptesicus species	Direct and Indirect	(del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023)
Hornsea Project One	Birds	Collision with turbines, displacement	Mortality rates within acceptable limits; potential cumulative impacts from nearby projects	Direct and Indirect	(Horton, 2014) (Hornsea Project One, North Sea, 2021) (Wind, 2010)
Hornsea Project One	Marine Mammals	Noise from pile driving, habitat change	Behavioral changes and displacement; low physical injury risk due to mitigation measures	Indirect	(Horton, 2014) (Hornsea Project One, North Sea, 2021) (Wind, 2010)

Hornsea Project One	Benthic Organisms	Seabed disturbances from turbine installation	Changes in habitat structure; potential for artificial reef creation benefiting some species	Direct and Indirect	(Wind, 2010) (Liu, et al., 2018) (Bergström, et al.) (Horton, 2014)

The table above summarizes the biodiversity impacts observed at both the Tarifa Wind Farm and the Hornsea Project One. Each row of the table provides detailed information on the specific species groups affected, the nature of the concerns, the observed impacts, and the types of impacts. The sources for each entry are provided to ensure traceability and to allow further exploration of the underlying data.

- Birds at Tarifa Wind Farm: The high fatality rates among raptors are a significant concern, with altered flight paths observed as birds attempt to navigate around turbines. These impacts are primarily direct, resulting from collisions with turbine blades .
- Bats at Tarifa Wind Farm: Bat mortality is notably high, with Pipistrellus, Nyctalus, and Eptesicus species being most affected. The impacts include both direct collisions and indirect effects from noise disruption .
- Birds at Hornsea Project One: While mortality rates due to turbine collisions are within acceptable limits, there are concerns about cumulative impacts from nearby wind projects. Both direct and indirect impacts are considered, including potential displacement effects .
- Marine Mammals at Hornsea Project One: Noise from pile driving and habitat changes pose indirect risks, leading to behavioural changes and displacement. However, physical injury risks are mitigated by measures such as soft start procedures for pile driving .
- Benthic Organisms at Hornsea Project One: The installation of turbines causes seabed disturbances, altering habitat structures. This can lead to the creation of artificial reefs, which might benefit some species, although the long-term impacts require further research .

The comparative analysis of the biodiversity impacts at Tarifa and Hornsea wind farms reveals several key points:

- Terrestrial vs. Marine Impacts: The terrestrial wind farm at Tarifa primarily affects birds and bats through direct collisions with turbines and habitat disruption. In contrast, the offshore wind farm at Hornsea impacts a broader range of species, including birds, marine mammals, and benthic organisms, with a mix of direct and indirect effects.
- Mitigation Effectiveness: Mitigation measures at both sites show varying degrees of effectiveness. For example, selective turbine stopping at Tarifa has significantly reduced bird fatalities, while noise mitigation measures at Hornsea help to minimize impacts on marine mammals.
- Species-Specific Concerns: Each site presents unique challenges for biodiversity conservation, highlighting the need for site-specific mitigation strategies. The high mortality rates among raptors at Tarifa and the behavioural changes in marine mammals at Hornsea underscore the diverse impacts of wind energy developments.

4 Discussion

4.1 Case Study 1: Onshore Wind Park (Tarifa Wind Farm) - Biodiversity Impact Discussion

4.1.1 Specific Biodiversity Concerns: Birds at Tarifa Wind Farm

The Tarifa Wind Farm, located at a critical migratory point between Europe and Africa, poses considerable risks to avian species, especially raptors and soaring birds. The region is known for its dense raptor population, including Griffon Vultures (Gyps fulvus), which are particularly vulnerable to collisions with turbine blades. The interaction between wind turbines and birds at this location provides a unique perspective on the environmental impact of wind energy on avian biodiversity (de Lucas, Ferrer, Bechard, & Munoz, 2012).

The mortality rate of Griffon Vultures due to wind turbines has been a significant concern at the Tarifa Wind Farm. Studies have shown a notably high rate of fatalities, which sparked the implementation of selective turbine stopping programs as a mitigation measure. This strategy led to a reduction in vulture mortality by 50% during operational adjustments, underscoring the effectiveness of targeted interventions in reducing bird collisions at wind farms (de Lucas, Ferrer, Bechard, & Munoz, 2012).

Birds exhibit behavioral changes in response to the presence of turbines. Soaring birds, such as vultures and eagles, alter their flight paths to avoid turbines, which is evident in their adjusted flight altitude and direction near the wind farm. This behavioral adaptation helps reduce collision rates but also highlights the disruption to natural flight patterns caused by wind farm operations (de Lucas, Janss, & Ferrer, The effects of a wind farm on birds in a migration point: the Strait of Gibraltar, 2003).

The selective turbine stopping technique employed at the Tarifa site represents a proactive approach to mitigating the impact on birds. By halting turbines when high bird activity is detected, particularly during peak migration periods, the wind farm has effectively reduced the risk of avian fatalities. This method, while successful, calls for continuous monitoring and adaptation based on bird behavior and migration patterns to maintain its effectiveness (de Lucas, Ferrer, Bechard, & Munoz, 2012).

The Tarifa Wind Farm serves as a critical case study for understanding the complex interactions between wind energy development and avian conservation. The findings from Tarifa suggest that while wind energy is a promising renewable resource, it requires careful management to minimize its ecological impact, particularly on biodiversity hotspots like migratory pathways. Ongoing research and adaptive management strategies are essential to balance energy production with biodiversity conservation, ensuring that renewable energy developments do not undermine the ecological integrity of sensitive areas (de Lucas, Janss, & Ferrer, The effects of a wind farm on birds in a migration point: the Strait of Gibraltar, 2003).

This example shows a clear picture of the significant impact of wind farms on bird populations, particularly in areas crucial for migration and biodiversity. The Tarifa Wind Farm highlights the necessity for ongoing research and adaptive mitigation strategies to reduce environmental impacts while harnessing wind energy.

4.1.2 Specific Biodiversity Concerns: Bats at Tarifa Wind Farm

The Tarifa Wind Farm, located in a region crucial for bat activity in southern Spain, significantly impacts local bat populations. This impact raises substantial conservation concerns due to the interactions between the wind farm operations and bat behaviour, especially regarding mortality patterns and the environmental factors driving these interactions (del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023).

Analysis from the Tarifa Wind Farm area reveals that bat fatalities are notably high, primarily affecting the Genera Pipistrellus, Eptesicus, and Nyctalus, which together account for over 90% of the fatalities recorded (del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023). The temporal distribution of these fatalities highlights a seasonal pattern, with peak deaths occurring during the warmer months of summer and autumn, particularly in August when bat activity is highest due to optimal feeding and breeding conditions (del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023).

The study identifies temperature as a significant environmental factor influencing bat mortality rates. The increase in fatalities correlates with rising temperatures, which enhance bat activity levels. This relationship is particularly pronounced when daily temperatures exceed 30 °C, suggesting that bats are more active and thus more susceptible to turbine collisions during hotter conditions (del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023).

The implications for conservation are profound, as the high mortality rates could impact the population viability of these bat species, particularly those already vulnerable or with limited distribution. The research suggests that modifications to turbine operations, such as curtailing operations during peak bat activity periods identified in the study, could significantly reduce mortality rates (del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023).

This analysis underscores the complex challenge of balancing renewable energy development with biodiversity conservation, particularly in regions like Tarifa, where ecological contexts significantly influence the potential impacts of wind farms on local wildlife. The continuation of detailed monitoring and targeted mitigation strategies is essential to minimize adverse effects and ensure the sustainable integration of wind energy solutions into Spain's diverse ecological landscapes (del Mar Salguero, De la Cruz, Munoz, & Arroyo, 2023).

4.2 Case Study 2: Offshore Wind Park (Hornsea Project One) - Biodiversity Impact Results

4.2.1 Specific Biodiversity Concerns: Birds at Hornsea Project One

The Hornsea Project One offshore wind farm, due to its location and scale, has the potential to significantly affect avian populations, particularly species such as kittiwakes (Horton, 2014). The Flamborough and Filey Coast, designated as a site under the UK's Protected Sites system, is particularly sensitive due to its importance to the kittiwake population (Wind, 2010). Environmental assessments have considered both the direct impact of the project as well as cumulative effects in conjunction with other nearby projects (Horton, 2014).

The kittiwake populations at Flamborough and Filey Coasts have been the focus of particular scrutiny. The predicted mortality rate from Hornsea Project One, when considered alone, falls within acceptable limits established through the Population Biological Removal (PBR) thresholds (Horton, 2014). PBR is a rule used to determine a sustainable limit on fatalities for a specific population, ensuring that the number of deaths does not threaten the population's viability (Chambert, Duriez, & Besnard, 2023). These thresholds are designed to ensure that the population can sustain losses without long-term detrimental effects. Specifically, the mortality figures ranged between 357-472 birds per annum with a 98% avoidance rate, which is under the PBR threshold of 512 birds (Horton, 2014).

However, when the cumulative impact of Hornsea Project One is considered alongside other planned projects in the vicinity, the estimated mortality rates for kittiwakes increased to between 759-874. This figure notably exceeds the PBR threshold, raising significant concerns about potential adverse effects on the integrity of the Flamborough and Filey Coast protected site area (Horton, 2014). Such figures prompt critical discussions among stakeholders, including Natural England (Advisors for the UK Government regarding the environment (Gov.uk, n.d.)) and the project's environmental assessors. Despite these concerns, the Secretary of State, after considering all representations and assessments, concluded that using a 'building block' approach—which considers only the projects up to and including Hornsea—would not adversely affect the integrity of the protected area. This decision was based on the lower range of mortality estimates, which still fall within the PBR threshold when only including Hornsea and earlier projects (Horton, 2014).

The assessment process revealed disagreements among expert witnesses regarding the size and trend of the kittiwake population at the designated site. These disagreements underscore the complexities involved in accurately assessing environmental impacts and the necessity of adopting a precautionary approach (Horton, 2014). The decision by the Secretary of State to rely on the most conservative population estimates highlights this precautionary principle, ensuring that even potentially underestimated population trends do not lead to unsustainable mortality rates (Horton, 2014).

The case of Hornsea Project One illustrates the intricate balance required in offshore wind farm development, where the need for renewable energy sources must be weighed against potential biodiversity impacts. For kittiwakes and other sensitive bird populations, the careful evaluation of mortality thresholds, alongside robust and adaptive management strategies, is crucial. These strategies may include modifying turbine operations during key migration periods or adjusting turbine layouts to minimize disruption to flight paths and habitats (Horton, 2014).

The Hornsea Project One's impact on bird populations, particularly kittiwakes, represents a critical case study in environmental management within the offshore wind energy sector. The outcomes of these assessments not only influence the project's operational strategies but also contribute to broader discussions on sustainable practices in offshore wind development. The ongoing monitoring and research will be essential to refine impact assessments and mitigation strategies, ensuring the conservation of avian species while supporting the UK's renewable energy goals (Horton, 2014).

4.2.2 Specific Biodiversity Concerns: Marine Mammals at Hornsea Project One

Hornsea Project One poses unique challenges to marine biodiversity, particularly marine mammals like harbour porpoises, which are predominant in the area. The Hornsea site's environmental assessments reveal that the harbour porpoise (Phocoena phocoena) is the most abundant cetacean in UK waters, and the North Sea is notably important for this species due to its substantial population estimated at approximately more than 500 000 individuals (ASCOBANS, n.d.).

The geographical significance of the North Sea for harbor porpoises is primarily because these animals forage over vast areas, feeding on a variety of fish species that inhabit both demersal and pelagic zones (Wind, 2010). During the baseline survey work conducted over two years at the Hornsea site, a considerable number of harbour porpoise sightings were recorded, averaging a density of about 1.683 individuals per square kilometer (Horton, 2014). This high density underscores the critical nature of the area for this species and the potential impact of the wind farm.

The construction and operational phases of the Hornsea project introduce several risk factors for marine mammals, including physical injury, disturbance, displacement, and changes in prey availability due to the noise and vibrations from pile driving activities (Horton, 2014). However, the risk of direct injury from such activities is considered very low, provided the animals are not within close proximity (less than 600 meters) to the pile driving site. To mitigate potential risks, a series of measures have been proposed, including the employment of trained marine mammal observers and the adoption of a soft-start approach to pile driving, which gradually increases energy to allow marine mammals to vacate the area before reaching harmful energy levels (Horton, 2014).

While physical injuries might be rare due to the mitigative strategies employed, behavioral changes and displacement due to noise pollution remain significant concerns (Wind, 2010). The avoidance behavior seen in harbor porpoises can lead to significant displacement, with estimates suggesting that a worst-case scenario could affect an area of approximately 46.6 square kilometers surrounding the pile driving activities. This displacement not only affects the porpoises' immediate habitat use but could also have longer-term ecological impacts on their population dynamics and prey interactions (Horton, 2014).

Further complicating the assessment of impacts is the potential cumulative effect of concurrent or sequential offshore development projects in the North Sea. Such cumulative exposure can exacerbate the displacement effects and potentially reduce the availability of critical foraging habitats. The assessments estimate that, under worst-case scenarios, concurrent projects could lead to displacement scenarios affecting up to 4.28% of the North Sea harbour porpoise population (Wind, 2010). This figure highlights the need for comprehensive regional management strategies that consider both individual and cumulative impacts on marine mammals (Horton, 2014).

In conclusion, the Hornsea Project One represents a critical intersection between renewable energy development and marine conservation. The strategies employed and the findings from ongoing monitoring will significantly influence not only local conservation efforts but also future offshore wind developments, ensuring that they are conducted in an environmentally responsible manner that minimizes impacts on marine biodiversity (Wind, 2010).

4.2.3 Specific Biodiversity Concerns: Benthic Organisms at Hornsea Project One

The Hornsea Project One presents a significant concern for benthic organisms due to the extensive seabed disturbances caused by the installation of wind turbine foundations and cabling (Wind, 2010). The primary impact arises from the physical alteration of seabed habitats, which can lead to changes in benthic community structures and function. This includes the displacement or destruction of benthic fauna, changes in sediment composition, and potential smothering of organisms due to increased sedimentation during construction activities (Wind, 2010)

The installation of monopile foundations involves drilling into the seabed, which significantly disturbs the benthic habitats. This disturbance is characterized by the removal or displacement of sediments, which can bury benthic flora and fauna, thereby altering the original habitat conditions (Wind, 2010). The Hornsea Project has acknowledged this impact, noting that the sediment plumes generated by such activities can extend several meters from the installation site, affecting a wide area of the seabed (Wind, 2010).

Post-construction, the disturbed areas may be recolonized by benthic organisms. However, the nature of recolonization can vary, depending on the severity of the disturbance and the resilience of the species involved. Studies related to Hornsea Project One indicate a potential for a shift in community composition, where opportunistic species might dominate the recolonization process, potentially leading to a long-term change in benthic community structures (Wind, 2010).

Interestingly, while the initial impact of seabed disturbance is largely negative, there are instances where the structures associated with wind farms, such as turbine bases, can act as artificial reefs (Degraer, et al., 2020). These structures may enhance local biodiversity by providing new habitats for various marine species, including those not originally present in the area (Degraer, et al., 2020). This phenomenon has been observed at other offshore wind farm sites and could potentially occur at Hornsea, although this outcome is not guaranteed and requires further monitoring and research to confirm (Degraer, et al., 2020).

The cumulative impacts of multiple wind farms in the North Sea, including Hornsea, are a significant concern for benthic ecosystems. The combined effects of physical habitat alteration, increased sedimentation, and potential changes in hydrodynamic conditions could amplify the impacts on benthic communities (Wind, 2010). These cumulative impacts necessitate a comprehensive management approach to mitigate adverse effects on the seabed ecosystem over the long term (Wind, 2010).

In conclusion, while the Hornsea Project One presents several challenges for benthic organisms due to its construction and operational activities, there are also potential benefits in terms of habitat creation. The net impact on benthic biodiversity will depend on the balance between these adverse effects and any mitigative or enhancement measures implemented. Continued monitoring and research are essential to fully understand and manage the impacts on these crucial ecosystems (Wind, 2010).

4.3 Research Gap Identification: Comparative Impacts on Land vs Sea Ecosystems

The expansion of wind energy is a pivotal element of the global shift toward renewable energy sources, yet it presents differentiated environmental challenges across terrestrial and marine ecosystems (Bojars, et al., 2016). This section explores the distinct and overlapping impacts of wind farms on terrestrial and marine ecosystems, emphasizing the need for targeted mitigation strategies and pinpointing crucial research gaps that persist in the field.

Terrestrial wind farms predominantly affect avian and bat populations, with collision risks being particularly significant (Bojars, et al., 2016). These animals often fail to detect turbine blades in time, especially when turbines are positioned along migratory routes or in areas frequented by these species. The infrastructure associated with wind farms, including roads and power lines, also contributes to significant habitat fragmentation (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021). This not only disrupts the natural movements of terrestrial wildlife but may also alter local flora and lead to changes in predator-prey dynamics. Additionally, the noise and vibration produced by turbines can interfere with the natural behaviors of terrestrial wildlife, affecting their mating, feeding, and migratory patterns (IUCN, Mitigating biodiversity impacts associated with solar and wind energy development: guidelines for project developers, 2021)

In marine settings, the installation of turbines similarly disrupts local ecosystems but through different mechanisms (Bojars, et al., 2016). The construction of turbine foundations can lead to the formation of artificial reefs which, while beneficial to some marine species, may disrupt the existing ecological balance (Degraer, et al., 2020). The process of installing these turbines, particularly the pile-driving phase, generates substantial noise pollution that can have profound impacts on marine mammals and fish, disrupting their communication and navigation abilities (Horton, 2014). Furthermore, the electromagnetic fields generated by submarine power cables present another layer of potential impact, affecting species that are sensitive to electromagnetic variations, such as certain types of sharks and rays (Bojars, et al., 2016).

Despite these impacts being increasingly documented, both terrestrial and marine wind projects share common concerns such as the visual impacts and potential barrier effects created by turbines, which can alter the movement patterns of various species across both environments (Bojars, et al., 2016).

Significant research gaps remain, especially in understanding the cumulative impacts of wind farms as they become more prevalent worldwide (Jasiński, Kacejko, Matuszczak, & Szulczyk, 2022). The specific responses of different species to turbine presence are still under-documented, requiring more detailed studies to ascertain how individual species are affected. Moreover, while various mitigation measures have been proposed—from turbine shutdowns during critical migration periods to the installation of deterrent systems—their effectiveness remains variably proven and is a subject of ongoing research (Bojars, et al., 2016).

Addressing these research gaps is essential for achieving a better balance between the expansion of renewable energy and the conservation of biodiversity. A deeper understanding of these issues will help in crafting targeted mitigation strategies that reduce adverse impacts while contributing to global sustainability objectives. By concentrating on these areas of research, we can guide policy enhancements and practical adjustments that ensure wind energy projects harmoniously blend into our natural landscapes and marine environments.

4.4 Terrestrial and Marine Biodiversity Impacts: Mitigating and Adapting to Challenges in Wind Energy Development

The terrestrial and marine environments, represented respectively by the Tarifa and Hornsea wind farms, exhibit distinct challenges and impacts associated with wind energy development. On land, the Tarifa Wind Farm has shown significant implications for avian and chiropteran (bats) species, primarily through habitat disruption and collision risks. Birds and bats, due to their mobility and migratory patterns, are particularly vulnerable to physical structures such as wind turbines. The reduction in the number of turbines and strategic turbine placement has mitigated these impacts to some extent but highlights the need for ongoing monitoring and adaptive management strategies.

In marine settings, as demonstrated by Hornsea Project One, the primary concerns extend to marine mammals, fish, and benthic organisms. The construction phase, involving activities like seabed drilling and pile-driving, notably disrupts the marine habitat, leading to potential shifts in species composition and function. While mitigation measures such as soft start procedures for pile driving have been implemented, the effectiveness of these measures requires continuous evaluation against the backdrop of evolving marine activities.

Placing wind farms on landscapes or seascape causes the change of land use which is very significant. For terrestrial installations, this generally means converting forested, agricultural, or natural habitats into industrial areas. These changes may result in habitat fragmentation, decrease in land for traditional purposes, and alterations in local biodiversity patterns. In contrary to that, offshore wind farms usually implies a transition of the marine space usage with changes in the fishing routes as well as modifying the seabed. All of these operations have to be properly managed so that energy production is oscillating with ecological and community sustainability.

This interpretation of biodiversity impacts is also crucial for aligning with global sustainability goals, particularly those aimed at preserving and restoring terrestrial and marine ecosystems (SDGs 14 and 15) (UNDP, n.d.). The reduction of biodiversity due to wind farms can counteract efforts to combat climate change with renewable energy solutions (SDG 13), showcasing the intricate balance required between different environmental objectives (UNDP, n.d.).

Environmental Impact Assessments (EIAs) have been instrumental in identifying and quantifying these impacts, offering a framework to incorporate ecological considerations into project planning stages. EIAs facilitate the identification of significant impacts, prediction of cumulative effects, and the development of mitigation or enhancement measures. For wind energy projects, this means assessing not just the direct impacts of construction and operation, but also the broader ecological changes brought about by land use shifts and new infrastructure.

The findings from the analysis hold significant implications for conservation and policy-making, particularly in the realm of renewable energy development and biodiversity preservation. Policymakers and conservationists must work together to devise policies that not only encourage the expansion of renewable energy but also safeguard the habitats and species affected by such developments. This requires the creation of robust environmental guidelines and the implementation of strategic conservation plans that are specifically tailored to the ecological characteristics of each site.

Effective policy measures could include for example creating buffer zones around critical habitats, enforcing seasonal restrictions on construction activities to avoid peak breeding or migration periods, and investing in technology that minimizes wildlife disturbances. Additionally, there should be a stronger emphasis on post-installation monitoring to assess long-term ecological impacts and the effectiveness of mitigation strategies. This ongoing evaluation can inform adaptive management approaches that adjust policies and practices in response to observed environmental changes and scientific advancements.

Furthermore, conservation strategies should be integrated into national and international sustainability agendas to ensure that biodiversity considerations are upheld in the pursuit of climate goals. By aligning wind energy development with biodiversity conservation, policies can create a synergistic effect that promotes ecological health while advancing towards energy sustainability. This dual approach not only addresses the direct impacts of wind farms but also contributes to a broader environmental resilience that supports both human and ecological well-being.

Looking forward, it is crucial that research continues to improve the methodologies for assessing and interpreting the impacts of wind farms on biodiversity. This includes developing better models for predicting cumulative impacts, enhancing the effectiveness of mitigation measures, and exploring new ways to achieve co-benefits for biodiversity and renewable energy production. Such efforts should aim to not only reduce the negative impacts of wind farms but also enhance their role in supporting ecological networks and functions.

5 Conclusions

5.1 Summary of Findings

This thesis explored the environmental impacts of wind power on biodiversity through a comparative analysis of terrestrial (Tarifa Wind Farm, Spain) and marine (Hornsea Project One, UK) wind farms. The findings indicate that both types of wind farms have substantial impacts on biodiversity, particularly on birds, bats, marine mammals, and benthic organisms. Key impacts include habitat disruption, collision risks, and noise and vibration disturbances. Despite mitigation efforts like turbine management and construction modifications, challenges persist in fully alleviating the negative effects on local ecosystems.

The study brought into light the necessity of adopting biodiversity considerations to the planning and operation of wind farms in order to achieve the balance between renewable energy development and ecological continuum. This is important for meeting the global sustainability goals, particularly, those that are devoted to the maintenance and restoration of terrestrial and marine ecosystems.

While wind farms are a vital component of renewable energy infrastructures, their environmental impacts necessitate careful consideration and management. Balancing the benefits of renewable energy with the needs of biodiversity conservation requires integrated planning, innovative mitigation strategies, and adaptive management to minimize negative impacts while maximizing ecological and social benefits.

One notable positive impact observed at the Hornsea Project One is the potential creation of artificial reefs from the turbine foundations, which can provide new habitats for marine species and enhance local biodiversity. This finding underscores the complexity of wind farm impacts, presenting both challenges and opportunities for biodiversity.

5.2 Study Limitations

A primary limitation encountered in this study was the restricted availability of detailed data on the specific impacts of the wind farms. This lack of data, limited the depth of analysis that could be conducted on local biodiversity.

For the Hornsea Wind Farm, the main challenge was the scarcity of peer-reviewed scientific articles, necessitating a reliance primarily on environmental assessment reports. In contrast, the situation for the Tarifa Wind Farm was the opposite; while scientific literature were available, comprehensive environmental assessment reports were lacking. This disparity in data types available for the two sites introduced challenges in conducting a balanced and uniformly detailed comparative analysis.

5.3 Recommendations for Future Research

Considering the difficulties and site-specific character of biodiversity impacts of wind farms, further studies should undertake the long-term ecological studies on the existing wind farms to contribute to emerging knowledge. This would offer a more detailed dataset to assess the effectiveness of mitigation measures and re-evaluate the impacts of new projects. Research must also find out new technologies and methods to lessen animal accidents and habitat disruptions.

Perhaps one more area of study can be the socio-economic effects of wind farms on local communities by focusing on how transformation of land use and marine resources affect the local community's standard of living, employment, and other local activities. This will enable a perspective that incorporates both ecological and social impacts of wind energy development in order to develop strategies that help both human and ecological communities.

Lastly, as wind energy develops, integrating systematic Environmental Impact Assessments (EIAs) that comprises climate change projections will also be vital. This will be useful for the planning of future wind energy projects which are robust to changing conditions of climate and which have a low environmental footprint.

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