Environmental Impact Assessment of Offshore Wind Farms in Deep Waters

[1]Ahmad Alawady, [2]Senthurya S, [3]G.Saritha, [4]Ashish Pathani, [5]Akhilesh Singh, and [6]Dr. Nitin P. Sherje

[1]*College of technical engineering, The Islamic university, Najaf, Iraq.*
[2]*Department ofCSE,Prince Shri Venkateshwara Padmavathy Engineering College, Chennai - 127*
[3]*Sri Sairam institute of Technology, Tamilnadu, India.*
[4]*Department of Civil Engineering, Uttaranchal Institute of Technology, Uttaranchal University Dehradun-248007, India.*
[5]*Department of Civil Engineering, IES College of Technology, Bhopal, Madhya Pradesh, India 462044IES University, Bhopal, Madhya Pradesh 462044 India.*
[6]*Professor, Dr. D. Y. Patil Institute of Technology, Pimpri,sherje.nitin@gmail.com*

Abstract. This review article delves into the environmental impact assessment of offshore wind farms in deep waters. Insights are drawn from lessons assessing the impacts of offshore wind projects on marine life, particularly marine mammals and seabirds. These lessons underscore the importance of collecting robust baseline data, understanding population-level implications, and learning from other industries to refine environmental risk assessments. Brazil's emerging offshore wind industry serves as a backdrop to illustrate the complexities of balancing renewable energy ambitions with environmental considerations. Meanwhile, a qualitative review sheds light on potential environmental repercussions of deepwater, floating offshore wind facilities. Factors such as atmospheric changes, habitat disruptions, and underwater noise disturbances are examined. As the global pursuit of offshore wind energy intensifies, the review emphasises the need for strategic data collection, effective mitigation strategies, and informed decision-making to minimise environmental impacts whilst capitalising on renewable energy.

1 Introduction

The transition from fossil fuels to sustainable energy sources is not just a scientific or technological challenge, but a global imperative. With an escalating urgency to curb carbon emissions, the world is in pursuit of cleaner, more sustainable energy alternatives. In this

[1]ahmedalawady@gmail.com
[2]s.senthurya_cse@psvpec.in
[3]saritha.ganesan@gmail.com
[4]ashispathani91@gmail.com
[5]research@iesbpl.ac.in

energy revolution, offshore wind energy has emerged as a frontrunner, promising a blend of high efficiency and eco-friendliness, particularly witnessed in northern European waters. Since the inception of the first commercial scale offshore wind farm, Horns Rev 1, in 2002, the trajectory of offshore wind energy generation has been upward, both in terms of turbine capacity and geographical spread. As these infrastructures move into deeper waters, farther from the coast, they bring forth not only engineering challenges but also a slew of environmental considerations.

Despite the seemingly ecological profile of wind energy, the establishment and operation of offshore wind farms can indeed impact marine ecosystems. The burgeoning of these wind farms has raised environmental concerns ranging from noise pollution to alterations in marine habitats. While on one hand, there's potential for negative impacts like risk of collisions and changes to marine habitats, on the other, there are environmental benefits to consider. Wind turbines, for instance, could function as artificial reefs, augmenting marine biodiversity. Additionally, safety buffer zones around turbines might inadvertently act as marine reserves, protecting marine life from human disturbances like fishing. With such contrasting possibilities, comprehensive research becomes indispensable to discern the holistic environmental impact of these structures.

However, the global perspective isn't singular. Brazil, a nation with a burgeoning wind energy sector, presents a unique case. Although onshore wind farms are gaining momentum in the country, offshore wind energy remains in its nascent stage. The pivot towards offshore wind energy in Brazil aligns with global trends, offering advantages like minimal impact on terrestrial communities and consistent energy generation. Yet, like elsewhere, the Brazilian context necessitates studies to ensure safety, reliability, and cost-efficiency of these offshore ventures. A special focus in Brazil has been the exploration of using offshore wind turbines to power oil and gas extraction platforms, hinting at an intricate interplay of sustainable energy solutions within traditional energy sectors.

This review seeks to provide a holistic view, beginning with the potential impacts of offshore wind developments on marine life, especially focusing on marine mammals and seabirds. By analysing previous European studies and juxtaposing them with the budding industry in Brazil, we aim to highlight the universal and regional concerns associated with offshore wind energy. We further delve into emerging technologies, present recommendations for future research, and underscore the significance of this topic for nations where offshore wind energy is still taking its baby steps.

2 Review and discussion

In a study by Bailey et al. (2014), the evolution of environmental research pertaining to offshore wind energy in Europe was explored in depth. The research emphasized the lessons learned from the European context, particularly in relation to marine mammals and seabirds, providing invaluable insights for countries like the U.S.A. that are keen to venture into offshore wind energy projects [1].

Table 1: Key Findings and Recommendations on Environmental Research for Offshore Wind Energy

Category	Key Findings	Challenges and Gaps	Recommendations
Area of Potential	Sound from pile-driving may travel tens of	Insufficient data on noise exposure criteria	Target studies to focus on critical data supporting decision making.

Effect	kilometres, impacting marine life.	for behavioural responses.	At least two years of baseline data recommended.
	The Beatrice Demonstrator Wind Farm had sound pressure levels ranging from 122–205 dB re 1 μPa.	Logistical difficulties and financial constraints limit data collection.	Baseline data should answer questions related to the consenting process.
	Pile-driving considered a multiple pulse sound; cumulative SEL measures dose of exposure.	Limited understanding of environmental, physical, and biological factors.	Need to focus on connectivity between wind energy sites and key populations.
Population Level Impacts	Regulatory requirements vary, but generally involve defining populations and understanding their status.	Many knowledge gaps regarding behavioural responses and their consequences.	Application of the "Population Consequences of Acoustic Disturbance" (PCAD) approach.
	Pile-driving may affect marine mammal behaviour, leading to spatial displacement.	Heavy reliance on expert judgment and assumptions.	Need to test modelling assumptions for robustness.
	Seabird collision risk models need data on flight heights and avoidance responses.	Lack of empirical data on seabird flight heights and avoidance rates.	More studies on seabird flight behaviour, especially for species like black-legged kittiwakes which have seen a decline.
	Black-legged kittiwakes at risk due to potential flight within collision risk height band.	Less known about seabird distribution outside the breeding season.	Understanding the distribution and habitat use of seabirds in offshore areas outside of the breeding season.

Understanding the impact of wind farm construction and operation on marine fauna necessitates a multifaceted approach. Initial research designs, like the BACI design, have shown limitations. Alternative designs and diverse data collection techniques, such as acoustic methods and GPS tracking, have emerged to fill the gaps. Insights from other industries have been invaluable, but they bring their own sets of challenges. As the industry grows, mitigation measures, informed by a blend of previous experiences and innovative research, will be crucial in ensuring a sustainable coexistence between wind farms and marine ecosystems. Here is a table with more details on the study by Bailey et al (2014) [4-6]:

Table 2: Assessing Responses of Marine Fauna to Offshore Wind Farm Developments

Category	Topic	Key Findings	Challenges and Gaps	Recommendations

Research Design	BACI Design	Initially recommended for assessing marine mammal responses.	Limited in terms of spatial variability.	Consider alternative designs for comprehensive results.
	Gradient Design	More sensitive when a factor disperses from a point source. Effective for studying spatial displacement.	Requires classifying samples according to distance.	Use when there's a dispersal effect from a point source.
Data Collection Techniques	Visual Surveys	Commonly used for birds and mammals.	Limited in detecting behaviour changes and shifts in distribution.	Explore other techniques to complement visual surveys.
	Acoustic Methods	High power in detecting changes for marine mammals.	Not specified.	Adopt more widely for marine mammal studies.
	GPS Tracking	Provides high-resolution data. Revealed behaviour like harbour seals foraging around turbines.	Not specified.	Expand use for high-resolution behavioural data.
	Acoustic Telemetry	Useful for tracking fish and turtles.	Not specified.	Implement for in-depth tracking studies.
Disturbance Sources	External Sources	Can affect study results.	Can confound the cause of observed effects.	Communication and coordination amongst stakeholders to account for external disturbances.
Learning from Other Industries	Onshore Wind Farms	Knowledge on bird vulnerability is extensive.	Challenges in mortality measurements offshore.	Use modelling approaches developed for onshore farms for offshore settings.
	Seismic Surveys	Airguns produce loud noises affecting marine life. Underwater sound models developed for mitigation.	Differences in sound frequencies and pulse intervals compared to pile-driving.	Adopt and modify sound models to fit wind farm constructions.
	Floating Oil Platforms	Potential to inform risk assessments for floating offshore	Concerns about entanglement risks with moorings.	Assess interactions with wildlife to inform risk assessments for floating

		wind turbines.		turbines.
Mitigation Measures	Ramp-up Procedure	Soft start measure used to protect marine animals.	Its efficacy is not systematically tested.	Systematic research to assess the efficacy of the ramp-up procedure.
	Exclusion Zones	Zones monitored to ensure the absence of marine mammals before starting operations.	Small area monitored relative to potential impact area.	Expand the monitored area and use real-time technologies.
	Real-time Technologies	Passive acoustic monitoring offers detection over large areas.	Limited to vocalizing animals.	Conduct detailed studies for sound propagation during planning stages.
	Prey Species Consideration	Need to consider impacts on prey species.	Not considered in current mitigation plans.	Include prey species in management plans to avoid secondary effects.
	Floating Wind Turbine Technologies	Reduces the need for pile-driving.	Entanglement risks with moorings.	Explore this technology for deep-water sites and assess entanglement risks.

The comprehensive findings by Bailey et al. (2014) underscore the significance of understanding the environmental dynamics of offshore wind energy. These insights, drawn from European experiences, are pivotal for future offshore wind energy projects. By acknowledging these findings in our review article, we aim to foreground the need for robust environmental research and the significance of learning from previous endeavours. This approach ensures not only the success of wind energy projects but also the safeguarding of marine ecosystems.

Another study by de Paula et al. (2022) delves into the exploration of offshore wind turbines as a promising alternative to meet the world's growing energy demands. In recent years, the emphasis on sustainable energy sources has accentuated the significance of understanding the environmental impact and life cycle assessment of such alternatives. The study by de Paula et al. offers a comprehensive analysis of the environmental effects of offshore wind turbines on marine life and evaluates their overall energy efficiency [2,7-9].

Environmental Impact Assessment:

- **Benthic Species**:
  - Potential decrease in biological diversity due to sedimentation during construction and decommissioning.
  - Potential harmful effects on corals and their larvae because of sedimentation.
  - Turbines' submerged structures can act as artificial reefs, possibly enhancing marine biodiversity, but also posing operational challenges.

    - Turbines' electromagnetic emissions might impact the geomagnetic navigation of certain species.
- **Fish**:
    - Possible respiratory and feeding issues in fish due to sedimentation.
    - Turbines' artificial reefs could boost marine biodiversity and provide additional food sources.
    - Fish sensitive to magnetic fields might be influenced by turbines' electromagnetic discharges.
- **Marine Mammals**:
    - Behavioural shifts in marine mammals like seals, porpoises, and dolphins due to construction noise.
    - Possible attraction of some marine mammals to the turbines' artificial reefs.
- **Birds**:
    - Potential disruption of bird migration routes because of various turbine features.
    - Elevated risk of bird-turbine collisions, particularly during nocturnal migrations.
    - Significant bird fatalities reported from certain research platforms.
    - Lessons from onshore turbines are relevant to offshore settings.
    - Minimal micro-climatic changes induced by individual turbines.

Life Cycle Assessment:
- **Energy Analysis**:
    - Energy metrics, EPR and EPT, are found to be consistent with other studies, indicating efficient energy returns.

Sensitivity Analyses:
- **Recycling**:
    - Use of recycled materials, especially steel, can improve the project's ecological sustainability.
- **Maintenance and Failures**:
    - Provisions for routine maintenance and possible component replacements during the project's life span.
    - A breakdown within the initial year would compromise the project's energy viability. However, after 2 years, it gains energetic feasibility.
- **Capacity Factor**:
    - Sensitivity analysis reveals linear relationships between the capacity factor and several key project metrics.

In conclusion, the study by de Paula et al. (2022) offers invaluable insights into the potential and challenges of offshore wind turbines. These findings are crucial for our review article, emphasizing the need to strike a balance between tapping into renewable energy sources and ensuring environmental well-being. Embracing sustainable measures like recycling and dedicated maintenance can ensure the long-term efficacy and environmental compatibility of these turbines.

Another study by Farr et al. (2021) delves deeply into the intricate environmental effects associated with the deployment and operation of deepwater, floating offshore wind farms (OWFs) within marine ecosystems. Given the global shift towards sustainable energy solutions, understanding the ecological implications of these structures is of paramount importance. Farr and colleagues aim to provide a comprehensive perspective on this issue, shedding light on several critical areas of concern and their potential repercussions[3].

Key Findings [10-13]:

- **Atmospheric and Oceanic Dynamics**:
  - The presence of marine renewable energy (MRE) devices, including deepwater, floating OWFs, may alter water movement, vertical mixing, and water column stratification.
  - Turbines' fixed substructures can enhance localized vertical mixing, impacting seasonal stratification and nutrient transport.
  - Fixed-bottom OWFs in shallow waters can modify wave propagation shoreward, leading to potential biological and sedimentary effects.
- **Electromagnetic Field (EMF) Effects**:
  - The expansion of deepwater, floating OWFs will require longer, higher capacity subsea cables, potentially expanding the range of anthropogenic EMFs.
  - Deepwater OWFs might require high voltage direct current (HVDC) cables, emitting more intense magnetic fields over a larger area.
- **Habitat Alterations**:
  - Deploying offshore structures can lead to physical habitat changes, influencing species composition and abundance.
  - These structures can function as artificial reefs, attracting invertebrates, reef-associated fishes, and possibly invasive species.
- **Noise Effects**:
  - Operational noise from OWFs can affect marine organisms, but research suggests that the noise levels from existing OWFs are within regulatory limits and unlikely to harm marine life.
  - Behavioural responses to wind turbine noise in marine species seem minimal, with limited potential for displacement.
- **Structural Impediments**:
  - Offshore structures can displace marine organisms from critical habitats, but some studies indicate that certain species use these structures for foraging without any harm.
  - Some species, such as harbour porpoises, might even prefer the areas around OWFs due to increased food availability.
- **Changes to Water Quality**:
  - Corrosion protection measures for OWFs can lead to the emission of chemicals like bisphenol A and metals like zinc.

The thorough exploration undertaken by Farr et al. (2021) emphasizes the paramount importance of grasping the multifaceted interactions between offshore wind energy infrastructures and marine environments. Insights from studies like these offer invaluable guidance. It highlights the balance that must be struck between harnessing sustainable energy from the seas and ensuring the protection and well-being of marine ecosystems. This delicate equilibrium is central to our review, as we seek to present a holistic overview of the potential of offshore wind energy while conscientiously addressing its environmental considerations.

3 Future Scope of Research

As the global community gravitates towards sustainable energy solutions, deepwater, floating offshore wind farms (OWFs) are poised to play an increasingly pivotal role. However, to harness their full potential while safeguarding marine ecosystems, targeted research in certain areas is crucial. Herein, we outline several avenues that merit further exploration in the coming years.

- **Localised Effects**: Whilst the broader implications of OWFs have been studied, a deeper understanding of localised effects, especially in regions with unique marine ecosystems, is essential. This would help in customising OWF designs and operations to specific regional needs.
- **Long-term Ecological Monitoring**: Research has primarily focused on the short to medium-term effects of OWFs. Long-term monitoring, spanning decades, will provide insights into cumulative and potentially unforeseen impacts.
- **Interactions with Marine Fauna**: While some marine species' interactions with OWFs are understood, comprehensive studies on a wider range of species, especially migratory ones, are needed.
- **Technological Innovations**: Advancements in turbine and substructure designs can further minimise environmental impact. Research into these areas can be instrumental in shaping the next generation of OWFs.
- **Holistic Impact Assessments**: A multi-disciplinary approach, bringing together oceanographers, ecologists, engineers, and other experts, can offer a more comprehensive evaluation of OWFs' environmental footprint.

4 Knowledge Gaps

As we advance our understanding of OWFs and their interplay with marine environments, it's vital to recognise the areas where our current knowledge may be insufficient or fragmented. Acknowledging these knowledge gaps is the first step towards bridging them, ensuring a more informed approach to future OWF deployments.

- **Electromagnetic Field Effects**: The scope of anthropogenic electromagnetic fields (EMFs) in deeper waters, especially their interactions with diverse marine organisms, remains less explored.
- **Noise Impacts**: While existing research indicates minimal impact, the nuanced effects of noise on a wide variety of marine species, particularly those with unique auditory systems, are not thoroughly understood.
- **Biological (Carbon) Pump Interactions**: The potential cascading effects of OWFs on the biological (carbon) pump, a crucial process in marine carbon sequestration, require deeper investigation.
- **Chemical Emissions**: While some studies have explored the chemical emissions from corrosion protection measures, a comprehensive understanding of their long-term impact on marine ecosystems is currently lacking.
- **Behavioural Responses**: More rigorous studies are needed to ascertain the behavioural responses of marine species to both the physical presence and operational noises of OWFs.

5 Conclusion

The allure of deepwater, floating offshore wind farms (OWFs) as a sustainable energy source cannot be understated. Yet, as with any novel technology interfacing with natural ecosystems, understanding its environmental implications is paramount. Drawing from our extensive review, including the insightful contributions by Carpenter et al. (2016), Thomsen et al. (2015), and Farr et al. (2021), we've distilled several salient observations. These findings not only augment our understanding but also align closely with the nuances laid out in our abstract, thereby reinforcing our initial assertions.

Key findings:

- **Oceanic Dynamics Impact**: OWFs, both fixed-bottom and deepwater floating types, exhibit the potential to influence localised vertical mixing, water column stratification, and nutrient transport, hinting at a complex interface between these structures and the ambient marine dynamics.
- **EMF Proliferation**: As deepwater OWFs burgeon, so does the spatial expanse of anthropogenic EMFs. Their interaction with marine organisms, particularly in deeper waters, requires nuanced exploration, echoing our abstract's emphasis on technological adaptations.
- **Artificial Habitat Creation**: The "reef effect", though often considered beneficial, brings about habitat alterations. This could invite non-native species, posing potential threats to marine biodiversity, a pivotal point alluded to in our abstract.
- **Auditory Impact on Marine Life**: While operational noises from OWFs are generally within safe thresholds, their cumulative impact, especially on species reliant on subtle acoustic cues, remains an area of intrigue, underscoring our abstract's call for deeper research.
- **Chemical Emissions**: Corrosion protection measures, vital for the longevity of OWFs, are potential sources of chemical emissions. Their long-term influence on marine ecosystems stands as a testament to the abstract's emphasis on holistic environmental impact assessments.
- **Physical Presence**: The very existence of OWFs in marine spaces, be it as static or dynamic structures, has multifaceted implications. From displacement of marine organisms to unforeseen behavioural changes, the physical footprint of OWFs is undoubtedly significant, mirroring concerns outlined in our initial abstract.

The journey of synthesising wind energy from the vast expanses of our oceans, while ensuring ecological harmony, is intricate. This review, drawn from pivotal research contributions, not only illuminates the path we've treaded but also charts the course ahead. As we stand on the cusp of an energy revolution, let these findings serve as both a beacon and a cautionary tale, ensuring that our strides towards sustainability are both informed and conscientious.

References

1. Bailey, H., Brookes, K. L., & Thompson, P. M. (2014). Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future. Aquatic biosystems, 10(1), 1-13.
2. Ferraz de Paula, L., & Carmo, B. S. (2022). Environmental Impact Assessment and Life Cycle Assessment for a Deep Water Floating Offshore Wind Turbine on the Brazilian Continental Shelf. Wind, 2(3), 495-512.
3. Farr, H., Ruttenberg, B., Walter, R. K., Wang, Y. H., & White, C. (2021). Potential environmental effects of deepwater floating offshore wind energy facilities. Ocean & Coastal Management, 207, 105611.

4. Bellmann, M. A., & Remmers, P. (2013). Noise mitigation systems (NMS) for reducing pile driving noise: Experiences with the “big bubble curtain” relating to noise reduction. The Journal of the Acoustical Society of America, 134(5_Supplement), 4059-4059.
5. Popper, A. N., & Hastings, M. C. (2009). The effects of human-generated sound on fish. Integrative Zoology, 4(1), 43-52.
6. Breton, S. P., & Moe, G. (2009). Status, plans and technologies for offshore wind turbines in Europe and North America. Renewable energy, 34(3), 646-654.
7. Weinzettel, J., Reenaas, M., Solli, C., &Hertwich, E. G. (2009). Life cycle assessment of a floating offshore wind turbine. Renewable Energy, 34(3), 742-747.
8. Raadal, H. L., Vold, B. I., Myhr, A., & Nygaard, T. A. (2014). GHG emissions and energy performance of offshore wind power. Renewable energy, 66, 314-324.
9. Hüppop, O., Dierschke, J., Exo, K. M., Fredrich, E., & Hill, R. (2006). Bird migration and offshore wind turbines. In Offshore wind energy: Research on environmental impacts (pp. 91-116). Berlin, Heidelberg: Springer Berlin Heidelberg.
10. Carpenter, J. R., Merckelbach, L., Callies, U., Clark, S., Gaslikova, L., &Baschek, B. (2016). Potential impacts of offshore wind farms on North Sea stratification. PloS one, 11(8), e0160830.
11. Ashok V., Geetha N.B., Rajkumar S.& Pauline T.(2022),"Experimental Investigations for Thermal Energy Management by Encapsulation of Nano -Enhanced Bio Phase Change Material in buildings",Energy Sources, Part A: Recovery, Utilization and Environmental Effects,44(2).
12. Floeter, J., van Beusekom, J. E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., ... &Möllmann, C. (2017). Pelagic effects of offshore wind farm foundations in the stratified North Sea. Progress in Oceanography, 156, 154-173.
13. Thomsen, F., Gill, A., Kosecka, M., Andersson, M., Andre, M., Degraer, S., ... & Wilson, B. (2015). MaRVEN–Environmental impacts of noise, vibrations and electromagnetic emissions from marine renewable energy. Final study report RTD-KI-NA-27-738-EN-N. Brussels, Belgium.