Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future

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Abstract: The worldwide shift towards sustainable energy resources has spurred a notable uptick in the establishment of deep-sea offshore wind farms. Offshore wind power emerges as a hopeful remedy to combat climate change and decrease the reliance on fossil fuels. Nevertheless, the establishment, functioning, and decommissioning of these offshore wind farms carry the possibility of causing adverse environmental consequences. This research undertakes a thorough evaluation of the environmental consequences of offshore wind farms located in deep waters, intending to assess their potential impacts on marine ecosystems, wildlife, seafloor habitats, and coastal communities through an extensive Environmental Impact Assessment (EIA). The findings from this assessment provide valuable insights for sustainable offshore wind farm development, emphasizing responsible planning and environmental stewardship to achieve a balance between renewable energy generation and environmental conservation.

Keywords: Offshore, EIA, Wind Farm, Environmental Impacts, Deep Water

1.Introduction

Wind energy usage has been steadily and quickly expanding. Onshore wind farms are widely spread around the nation, and many more are currently being built. Nevertheless, in alignment with worldwide patterns, there is a growing interest in offshore wind energy production due to its benefits, including reduced impacts on communities and the environment due to their remote location from human populations. Nonetheless, there is a need for research to reduce the expenses of new initiatives while simultaneously improving their quality, reliability, and safety. The pollution brought on by gas emissions and the effects of development on the area surrounding it are the two most known examples of environmental harm brought on by energy sources. Since oil and gas production and

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consumption produce significant amounts of greenhouse gas emissions, it is always interesting from an environmental standpoint to substitute renewable energy sources whenever feasible. Despite their polluting nature, oil and gas serve as crucial raw materials in the chemical industry, given their importance to the global economy [1]. Nevertheless, the world relies heavily on these energy sources, and a full transition to alternative sources will require a substantial amount of time. It is essential to highlight that the oil and gas industry is actively engaged in researching and promoting sustainable development, with numerous initiatives in place to reduce the environmental impact associated with energy production.

Wind energy has emerged as a less harmful energy source in recent years due to its renewable nature, reliance exclusively on the wind's natural flow, minimal influence on the environment, and lack of gas emissions. Therefore, it is in theory an excellent energy source substitute for oil and gas exploration and production units. Nonetheless, wind farm development and operation come with environmental and social consequences. Moreover, there are repercussions associated with these wind farms, considering the production of steel and concrete necessary for erecting wind turbines. Consequently, when evaluating the sustainability of a wind turbine's entire life cycle, it becomes imperative to identify and quantify its impacts and emissions.
To address the challenge of reducing the energy consumption of a floating oil and gas extraction platform currently relying on gas turbines, this study concentrates on assessing the environmental ramifications of an offshore wind turbine. Within this analysis, we focus on a turbine situated in regions earmarked as primary locations for offshore oil and gas production. Access is granted to areas with substantial water depths ranging from 650 to 1050 meters [2]. As a result, this study centres on a deep-water offshore wind turbine equipped with an appropriate mooring system. The greater depth values are designated for future wind turbine installations due to their reduced impact on human activities and higher wind speeds. This application is gradually gaining traction worldwide.

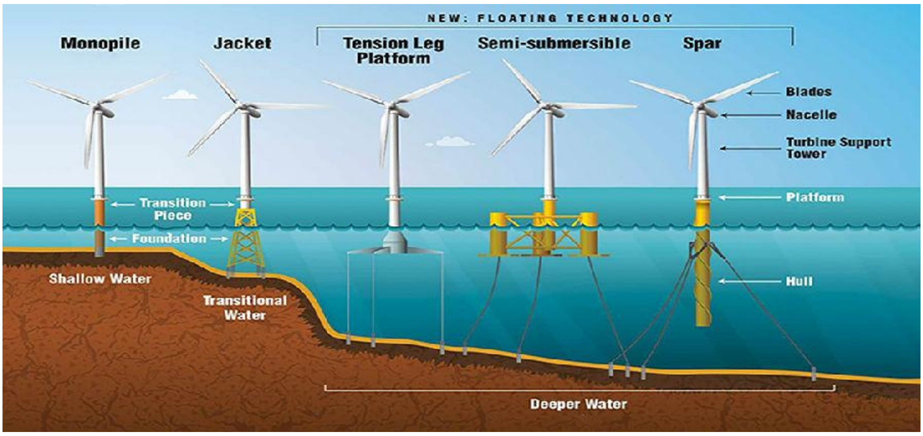

Figure 1. Offshore Wind Turbines
In this paper, we provide an evaluation of the turbine's potential environmental effects based on an EIA. Therefore, it is crucial to give a brief overview of the significance and applications of this technique. As stipulated in Article 9 of Law 6.938/81, the Environmental Impact Assessment (EIA) forms an integral part of Brazil's National Environmental Policy [3]. This policy is oriented towards safeguarding the preservation, enhancement, and restoration of an environmental quality conducive to life, with the

ultimate aim of securing socioeconomic progress, national security concerns, and the well-being of human beings. EIA is crucial for any task or project that has a small impact on the environment's natural order and must be carried out in accordance with legal requirements in order to avoid adverse environmental effects and emphasize advantageous ones.

2.Related Works

Several studies have delved into this area, addressing diverse aspects such as the ecological impact on marine life, seabed alterations, underwater noise pollution, and effects on local ecosystems. Studies have highlighted the importance of considering cumulative impacts and evaluating synergies with other marine activities. The goal is to find a middle ground between advancing renewable energy through offshore wind technology and safeguarding the environment by encouraging sustainable approaches. However, given that the technology is still in its early stages, with only a limited number of prototype turbines and floating systems currently operating in relatively shallow waters (such as Hywind in Scotland at a depth of 120 meters, as reported by 4C Offshore in 2018), it is not unexpected that none of the articles have specifically examined the environmental impacts of deepwater, floating offshore wind farms. Table 1 gives the summaries of some of the articles thatfocus on environmental objects.

Reference	**Object**	**Methodology**	**Findings**
Carpenter et al. (2016) [4]	Oceanic dynamics	Idealized models and field measurements were employed to evaluate the impact of offshore wind farms on the broader-scale stratification.	The foundations of Offshore Wind Farms significantly influence the overall stratification on a large scale due to the mixing they generate.
Copping et al. (2016) [5]	EMF-sensitive marine animals	Literature review and synthesis.	Different taxonomic categories of organisms possess the ability to perceive and respond to the electric and magnetic fields generated by Marine Renewable Energy (MRE) devices.
Claisse et al. (2014) [6]	Fish communities	Information obtained from yearly visual surveys was employed to compute and contrast secondary fish production, overall fish abundance, and total fish biomass between oil and gas	The results suggested that in the waters off the southern California coast, oil and gas platforms generate the highest secondary fish production per seafloor area when compared to all other marine habitats that were examined. This is primarily attributed to the extensive hard

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		platforms and their counterparts in natural reefs and various other marine environments.	structure they provide, which in turn fosters fish recruitment.
Brandt et al. (2011) [7]	Harbor porpoises (*Phocoena phocoena*)	Passive acoustic monitoring was employed to study how harbour porpoises reacted to the construction of offshore wind farms and the noise generated by pile-driving activities.	The acoustic activity of harbour porpoises experienced a notable decrease during the construction period. The duration of this impact diminished as the distance from the construction site increased, and no adverse effects were detected at an average distance of 22 kilometres.
Adams et al. (2016) [8]	81 marine bird species	A vulnerability assessment was conducted to evaluate the potential for avian species to experience collisions and displacement on a population-wide scale.	The findings indicated that pelicans, terns, gulls, and cormorants face the highest likelihood of collision, while alcids, terns, and loons are most susceptible to displacement.
Bejarano et al. (2013) [9]	Chemical releases	In addition to conducting a literature review and synthesis, we also assessed consequences to assess the potential environmental repercussions resulting from chemical releases at Offshore Wind Farms (OWFs).	Regular upkeep of offshore wind farms and the infrequent but severe instances of facility failures, such as the collapse of a turbine or electrical service platform, may have the potential to cause minor to moderate harm to marine ecosystems as a result of oil and chemical spills.

			The potential impacts on marine mammals and birds from thick oils like biodiesel and dielectric insulating fluids can differ based on the amount of the release, potentially leading to moderate risks of fouling.

3.Materials and Methods

In order to perform an environmental impact assessment on an offshore wind turbine and evaluate its potential impact on local biodiversity, it is essential to have a comprehensive understanding of several key factors. These factors include the turbine's specifications and size, the materials utilized in its construction, its location in terms of both geographical coordinates and water depth, its operational methods, and the biological characteristics of the areas under investigation. Based on a qualitative systematic review of the literature, we shall conduct this assessment in this study. The goal of this work is to demonstrate how a balance between energy use and CO_2 emissions may have a significant influence on the environment.
This analysis utilized databases containing data about utilized materials and sources describing the processes involved. Subsequent sections will delve deeper into these aspects. Additionally, it includes information about the location and processes, CO_2 emissions produced by turbine components (sourced from manufacturer catalogues), and their respective locations. Figure 2 illustrates the system's boundaries, inputs, and outputs.

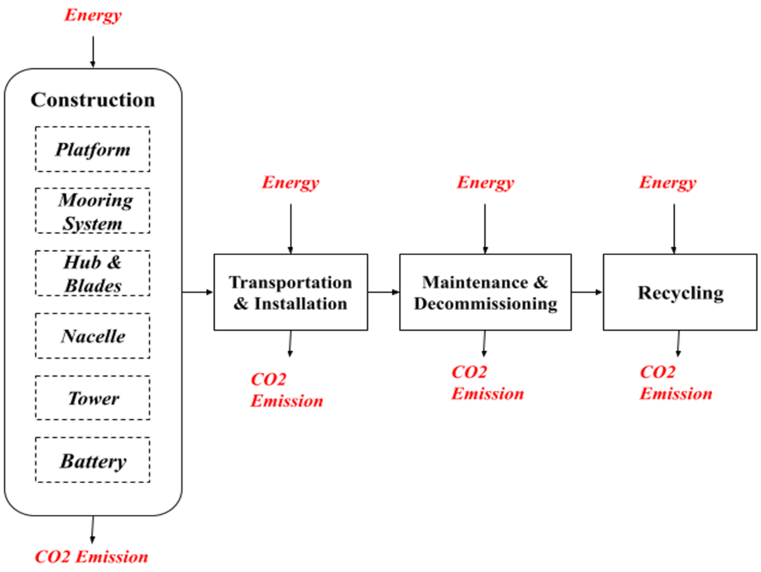

Figure2.Scheme of the system boundaries considered for the EIA.

George W. Boehlert and Andrew B. Gill [10] deliberated on the potential impacts that could manifest across different technology categories throughout their lifecycle stages, encompassing development, utilization, and retirement, while considering diverse spatial and temporal dimensions. They classified the consequences of marine renewable energy development using a framework and classification system that was adapted from those used by McMurray (2008) [11] for wave energy, taking stressors and receptors into account. Stressors are environmental characteristics that could change as a result of the installation, use, or decommissioning of renewable energy plants, while Receptors are ecosystem components that could react in some way to the stressor. Boehlert and Gill identified six environmental stressors, which include the following: Physical Presence of Devices, Dynamic Effects of Devices, Chemical Factors, Electromagnetic Fields, Energy Removal Effects, and Acoustics.

In an extensive study conducted by Copping et al. in 2016 [12], the researchers investigated various stressors concerning their potential risks and outcomes linked to changes in physical ecosystems resulting from energy extraction and alterations in the flow of energy, the impact of Electromagnetic Fields (EMFs) on marine creatures due to underwater cables, changes to benthic habitats and reef fish communities caused by energy devices, potential dangers to wildlife arising from underwater sound, and the likelihood of collisions near turbines.

4.Results and Discussion

4.1 Results

We analyzed how the system's elements might affect all the species that are found in the different locations by taking into account all of their characteristics. In light of a WWF report [13] which assesses the impacts of offshore wind turbines, we will classify and describe these effects across different categories and classifications. In this study, it is established that impacts are brought on by a variety of factors, including noise, electromagnetic fields, habitat changes, structural obstructions, and others. A more recent study [14] also found that these factors fall into several categories. The suspension and dispersion of particles during building and decommissioning in benthic species can lead to sedimentation, which can reduce ecological diversity. High levels of sedimentation have been linked to the death of larvae as well as a reduction in coral fertilization [13].

Depending on the components' grain sizes, sedimentation can have a variety of impacts. Furthermore, the submerged elements within an offshore wind turbine floating system, including the mooring system and the platform, can create a thriving ecological hub, functioning as artificial reefs with positive ecological implications. These structures are discovered to be inhabited by benthic species like mussels, which boost marine biodiversity by feeding and protecting crustaceans and molluscs, which in turn feed fish [14]. They can provide many species with a new home by revitalizing damaged natural environments. The inclusion of reefs in wind turbine constructions can pose a significant operational challenge due to the increased pressure on the structure caused by the weight of marine organisms, which in turn promotes corrosion. Additionally, the electromagnetic fields generated by electricity cables may negatively impact crustaceans' sensitivity to these fields and interfere with the geomagnetic navigation of vertebrate species. These effects can disrupt their ability to locate food and elicit evasion or attraction responses.

The primary detriment to fish is sedimentation, as it has the potential to obstruct their gills, leading to respiratory problems and hindering their ability to forage. Moreover, it is responsible for inducing avoidance behaviour in certain fish species due to increased water cloudiness and reduced predation. Artificial reefs produce effects akin to natural reefs by enhancing the diversity of organisms that serve as food sources for fish and fostering greater marine biodiversity. Some fish species with magnetic sensitivity may be impacted by electromagnetic fields. Cables have the potential to attract sharks and stingrays. Additionally, certain fish species may congregate on the platforms and mooring lines, changing their habitat [14].Construction noise is the most significant problem when it comes to marine creatures since it can affect how seals, porpoises, and dolphins behave. The majority of the time, it makes these creatures avoid the construction site, altering their habitats. Artificial reefs near wind farms could attract certain animal species in search of food, potentially causing shifts in their habitats. It's worth noting that mammals are not immediately affected by electromagnetic waves or sedimentation [14]

Wind turbines can have a variety of effects on birds. One of these is the fact that big buildings, with their strong magnetic fields, loud noises, and tall towers, provide significant barriers to migration paths.
Another consequence to consider is the elevated mortality rate among certain species, particularly exacerbated during nighttime flights due to reduced visibility [15]. Hüppop et al. [16] documented the discovery of 442 deceased birds from 21 different species between October 2003 and December 2004 in a research project conducted at the FINO 1 platform. This platform was situated approximately 45 km from the German island of Borkum, at a water depth of approximately 30 m, and was monitoring a wind farm. Importantly, hunger did not appear to be a contributing factor to the birds' deaths, as they were generally in good physical condition. Another aspect highlighted in the literature suggests that we may be able to impact the environmental conditions in large wind farm installations by altering atmospheric dynamics [14]. It is widely recognized that the wake generated by wind turbines downstream, characterized by a reduction in wind speed immediately after the rotor and the creation of turbulent flow, has the potential to modify the local microclimate conditions in the vicinity. Since we are just looking at one turbine, this issue does not significantly affect our study [19].
In addition to the effects on local biodiversity brought about by the system's normal operation, it's important to consider the likelihood of extreme events. It is essential to emphasize that LFP batteries carry a substantial risk of toxic and thermal consequences in the event of an explosion, as highlighted in the findings of Peng et al. [17] when considering the aforementioned battery system. The toxicological concerns connected to this issue are caused by the system's chemical components, which cause the release of CO, HF, SO_2, NO_2, and HCl gases. The batteries typically go through a calm initial burning stage when these things happen, which is in some ways advantageous because it can be noticed and handled with emergency measures before additional harm [20][21].Therefore, it is crucial to maintain ongoing vigilance over this system to avoid potential thermal damage, which could have adverse effects on both the turbine's functionality and the nearby marine ecosystem. Exposure to toxins and their toxicological consequences may pose significant risks to the local marine habitat, underscoring the importance of our continued diligence.

5.Discussion

With the Environmental Impact Assessment, we can infer that the majority of aquatic species would experience minimal disturbance from turbine operation, except in the event of a toxic discharge due to a battery explosion or other catastrophic failure resulting in complete system submersion. In cases of uninterrupted turbine operation, marine mammals, fish, crustaceans, and benthic organisms may encounter disruptions to their daily routines, potentially affecting their food foraging, migratory patterns, or reproductive behaviour.

Nonetheless, these disturbances are unlikely to pose a significant risk to the survival of any species. The primary concern lies with avian species, which could face the greatest negative consequences, including documented mortality from collisions. This is especially relevant given that both basins serve as migratory routes for various bird species.

It is evident that the risk of adverse impacts on local ecosystems would only become substantial with the installation of a larger number of turbines. This would increase the likelihood of extreme events and intensify the effects of construction, sedimentation, noise pollution, and electromagnetic radiation, presenting a notable risk that cannot be ignored. Concerning avian species, the risk of collisions would be significantly higher in the presence of a wind farm, given the numerous obstacles it would present. Given our analysis was based on a single turbine, we can broadly categorize the impacts as inconsequential. There are potential mitigation strategies to address bird mortality concerns, including implementing straightforward measures during system operation, like deactivating turbines during nights with adverse weather and heavy migratory activity and orienting the wind turbines parallel to the primary migratory route at the specific installation location [18].

6.Conclusion

The evaluations carried out for this project aimed to assess the environmental impacts of deep-water offshore wind farms in both quantitative and qualitative terms. We emphasize how much more sustainable and low-impact this energy source is compared to conventional energy sources that burn fossil fuels, despite some negative environmental repercussions. With this investigation, we discovered that the effects on marine fauna varied depending on the types of animals and the stage of the project.We have determined that in the scenario involving a single turbine, the system's operation is generally free from significant issues, such as battery explosions. This suggests a minimal risk of bird fatalities, and any potential concerns can be effectively addressed with simple mitigation measures.
We have identified that the construction of the platform designed to support the floating turbine in the project has the most significant negative impacts in terms of CO_2 emissions and energy costs, primarily due to its substantial steel content. It's essential to bear in mind that the use of semi-submersible platforms is a prevalent choice for deploying turbines in deep waters, aligning with our project goals. It's crucial to note that research in the field of offshore wind farms is an ongoing endeavour, and there are inherent limitations and information gaps, occasionally leading to conflicting findings. Ultimately, our research affirms the feasibility of implementing offshore floating wind turbines in deep waters, making a substantial contribution to decarbonizing the oil and gas industry. Nevertheless, it's undeniable that there are still economic, technological, and regulatory challenges to address, although these fall outside the scope of our current study.

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