Environment Impacts of Nearshore Marine Renewable Energy

Yizhou Chen

The Experimental High School Attached to Beijing Norma University, Beijing, China

chenyizhou2027@163.com

Abstract. At this time, the number of nearshore Marine renewable energy projects is increasing, and the review of the ecological footprint they may bring in coastal and shallow water systems is also on the rise. Building these projects close to the demand area can reduce the loss during transmission. However, most of the time, these facilities occupy some relatively sensitive habitats. The ecological responses of these habitats have not been well understood up to now. This article investigates the relevant literature on the environmental impact of nearshore MRE, and compiles the evidence in aspects such as underwater noise, electromagnetic fields, collision risks, habitat changes, and hydrodynamic alterations. By comprehensively reviewing these studies, it can be found that the responses of organisms are related to the type of technology, species characteristics, and local environment. There has been no such widespread situation that would cause serious or irreversible damage. However, most of the relevant records cover a relatively short period of time, involve a small area, and adopt different methods. This results in a relatively weak knowledge reserve in this regard. This article, by comparing the results obtained from different devices and different locations, determines where consensus has been reached and where uncertainties still exist. In terms of cumulative impact and long-term impact. This article also emphasizes the value of expanding the monitoring scope and conducting a comprehensive assessment to provide some guidance for future nearshore MRE projects.

Keywords: Nearshore marine renewable energy, Environmental impacts, Ecological risk assessment.

1. Introduction

1.1. Background and Context

As the global urgency in mitigating climate change grows, Marine renewable energy is gradually becoming a key focus in low-carbon strategies. Nearshore options, which include placing wave devices, tidal devices, and coastal current devices in shallow water, have aroused particular interest because these devices are relatively close to demand centers. The cost required for installation is lower, and the power loss during transmission is also less than that of offshore equipment. It is precisely these advantages that have enabled planners to incorporate nearshore Marine renewable energy into the regional energy roadmap.

In recent years, nearshore energy infrastructure has become increasingly common, which has raised concerns among ecologists that it may have some impact on coastal habitats. Seagrass beds can buffer coastlines, tidal flats can recycle nutrients, and wetlands and coral reefs can protect biodiversity. However, these coastal ecological environments are particularly vulnerable to damage from human activities. When people install and operate Marine renewable equipment, it will cause changes in the local physical environment and increase sound waves and electromagnetic stress. These effects may trigger a series of chain reactions in organisms and the broader ecosystem.

Against this backdrop, research on the environmental impacts of nearshore Marine renewable energy is currently booming. Recent studies have not provided a comprehensive summary but have focused on individual stressors associated with coastal facilities. This review, by collating evidence related to the main impact pathways, And it is helpful to measure to what extent the literature can support strict environmental assessment for achieving such a transformation.

1.2. Research Problem or Question

Although the development of nearshore Marine renewable energy technology has been quite rapid in recent years, its impact on the environment remains uncertain. There is some evidence suggesting that it can bring local benefits, such as new substrates that can function like small coral reefs, attracting fish and invertebrates to gather. However, The same structures may also cause changes to the seabed habitat, increase chronic underwater noise, emit electromagnetic fields, and alter environmental currents. These different observations highlight how the ecology of a specific location will react, and also explain why it is rather difficult to conduct a broad summary of it.

There is a particularly crucial obstacle now, which is that the current literature still presents a fragmented state. To elaborate, most studies isolate a single technology, a single stressor, or a narrow area. The methods they adopt, spatial scopes, and time frames are also different. As a result, It is particularly difficult to determine which environmental impacts are consistently recorded, which ones depend on local actual conditions, and which ones remain merely speculative. This review article raises three specific questions. The first one is: What exactly are the main environmental stress factors related to nearshore Marine renewable energy systems? The second question is whether the evidence is concentrated or dispersed among devices and regions, and where exactly does the concentration or dispersion occur? The third question is which uncertainties impose the greatest restrictions on reliable risk assessment?

1.3. Objectives of the Study

This study aims to integrate all existing work on the environmental impact of nearshore Marine renewable energy systems. It does not add new data but combines the relationships between different nearshore MRE technologies and Marine ecosystems that are already known, considering the ecological benefits and losses that have been recorded. And identify the deficiencies in the main concepts and methods that have always existed in the literature. This study, by concentrating and integrating evidence, depicts the current understanding of these aspects and marks the topics that most require research, so that there will be a more solid foundation for future environmental assessments.

1.4. Significance of the Study

This review in the article has significant academic value. It integrates those scattered and often incompatible studies into an analytical framework, thus providing a clearer picture of the environmental risks that arise along with nearshore Marine renewable energy projects. However, it does not directly offer management solutions. On the contrary, it has gathered the evidence needed by researchers and regulatory agencies to shape future research, establish a sound and reasonable risk framework, and conduct policy discussions based on data. By listing known situations and existing gaps, it has promoted the transparency and scientific rigor of offshore energy decision-making.

1.5. Overview of the Paper Structure

The remaining part of this article is arranged as follows: In the literature review and methodology sections, it will detail which studies were included and how this evidence was synthesized. Then, in the results section, it will provide a structured description of the identified environmental stressors, the assessment methods used, and the governance issues raised. In the following discussion session, these findings will be considered within a broader scientific and policy context. In the final conclusion section, the key insights of this review will be distilled and the significance of these insights for future research and environmental assessment of nearshore Marine renewable energy systems will be expounded.

2. Literature Review

Over the past two decades, research on the environmental impact of nearshore Marine renewable energy, or MRE systems, has been increasing along with the steady growth of coastal and shallow water energy installations. Early comments mentioned that although these technologies are generally regarded as relatively environmentally friendly, the ecological effects they produce The ecological effects in the coastal areas still lack relevant literature for detailed documentation and solid experience to support them. Subsequent research has highlighted that the nearshore area is ecologically different from deeper waters. The nearshore area can support more intensive biological production, has a closer connection between the bottom and upper layers, and also has more intense human activities. All these situations mentioned above can enhance the environmental response brought about by the energy structure.

Among all the literature, the authors have unanimously pointed out some environmental stress factors related to nearshore Marine renewable energy devices. Studies have repeatedly indicated that underwater noise, electromagnetic fields, collisions with moving parts, habitat changes, and local hydrodynamic changes are the main ways to produce ecological effects [1,2,3]. Some review papers have mentioned that these pressures can alter the behavior and physiology of Marine organisms. However, there are significant differences in the criticality and reliability of the evidence between stressors and species groups. Copping et al. emphasized that these factors should not be evaluated in isolation. Their criticality will vary with changes in equipment design, site characteristics and project scale. It is very necessary to conduct a specific environmental assessment for nearshore development projects.

Some studies have highlighted that the impact of nearshore Marine renewable energy systems on the ecosystem is not all negative. Although the construction and operation of nearshore MRE systems may cause interference to the habitats of benthic organisms or introduce acoustic and electromagnetic disturbances, the actual presence of energy devices there will also increase the complexity of the habitats. And it can also serve as an artificial reef. Under certain specific conditions, this situation may lead to an increase in local biodiversity [2,4]. However, these potential benefits are generally related to specific locations. Compared with the potential risks, less research has been conducted on this system, as researchers such as Adams proposed. The structure of Marine renewable energy may serve as a "stepping stone", facilitating the movement of species among fragmented Marine landscapes and enhancing their connectivity. Although the ecological consequences that this connectivity will bring are still unclear at present, there may be different situations among different taxonomic groups.

In the paper, methodological limitations are repeatedly presented. Most empirical data are obtained from brief monitoring activities, laboratory analyses, or single-device tests. Long-term and cumulative ecological consequences have largely not been tested [1,3], that is, there is still much room for improvement in the ability to assess long-term or cumulative ecological effects [1,3]. Given the fundamental differences in fluid dynamics, species composition and ecosystem sensitivity, some comments have cautioned against directly applying the discoveries of offshore or deepwater energy systems to nearshore environments. Several authors have pointed out that uncertainty is particularly evident in nearshore environments, where natural variability is relatively high. It will blur the project-related signals, making impact attribution and trend detection more complicated [5-7].

Numerical simulation has now become an indispensable part of environmental impact assessment. It plays a significant role in evaluating collision risks and hydrodynamic changes. However, most simulations still rely on rough estimates of animal behavior and environmental changes, and there are few long-term field data that can be collected to test these hypotheses. This point is also reflected in references [1,3]. It is precisely for this reason that when predicting the entire array or region, the confidence is only mediocre. Hydrodynamic studies have always shown that extracting energy near the coast can change water flow velocity, wave paths, and sediment movement. However, at the scale that affects the ecosystem, it is still very difficult to find on-site evidence that can confirm such changes.

Among these four studies, there is a recurring issue, which is the lack of cumulative and large-scale impact assessment. Most assessments focus on individual stressors in isolation, rarely considering how they interact with each other or paying attention to the consequences of increased deployment density. Regulatory and governance reviews have found that There are extensive regional differences in environmental assessment frameworks, making it difficult to compare or integrate the investigation results from different locations. Both ecological research and governance research have highlighted the lack of standardized methods for assessing the cumulative effects of nearshore Marine renewable energy development when multiple projects span multiple management jurisdictions.

Based on the content mentioned above, these literatures have actually provided some hints about what kind of impact nearshore Marine renewable energy devices might have on the environment. However, these research findings are scattered across various disciplines and different types of equipment, and are also distributed at different spatial scales. The authors of the article repeatedly put forward opinions, hoping for a comprehensive study, also hoping to extend the time of observation records, and also hoping for a unified evaluation method. This review, by concentrating the relevant evidence of nearshore technology in one place and pointing out which aspects the researchers have a relatively solid understanding of. And there is still considerable uncertainty in which aspects up to now, which responds to the calls made by the authors.

3. Results

In this section, this paper synthesizes some published evidence regarding the impact of nearshore Marine renewable energy systems on the environment. From the results, no new data is presented, but rather the recurring patterns, some agreed viewpoints, and unresolved issues in the literature are extracted [1,2]. For these pieces of evidence, this article groups and organizes them according to the main stressors, the methods for studying these stressors, and the governance issues that constitute their management.

Repeated studies have clearly pointed out that underwater noise, electromagnetic fields, collision risks, habitat changes, and near-field oceanographic alterations are the main environmental stressor sources of nearshore MRE facilities, which have been mentioned in relevant literature [1,2]. The sounds generated during operation generally fall within the auditory bandwidth range of fish and Marine mammals. Short-term behavioral changes were also recorded in their responses, which are also documented in references [1,3]. However, most of the records are actually from short observation Windows. As a result, it becomes rather difficult to quantify the impact at the population level. Retrospective studies with a longer time span emphasize that monitoring work rarely continues after the initial operation period. Currently, confidence in the impact of chronic exposure is still relatively low. This is reflected in references [1,4,5,8].

This article holds that the electromagnetic fields generated by submarine power cables are generally regarded by people as a possible source of stress for species that rely on electrical or magnetic cues. Although laboratory analyses and numerical models have shown that there may be behavioral changes, the data directly collected at nearshore operation sites is relatively scarce. This leads to the situation that under the current conditions, The ecological relevance issues of these exposure situations cannot be resolved. After a comparative review of nearshore facilities and offshore facilities, it was found that the electromagnetic field level in coastal waters is generally not very high. However, the lack of on-site observation and the absence of standardized monitoring plans still have a negative impact on the assessment work.

So far, the assessment of the collision risk between Marine organisms and the moving parts of MRE devices has mainly relied on modeling and theoretical work [1,3]. These studies all consistently indicate that in low-probability impact situations, fish and Marine mammals can actively avoid the rotor. However, the actual evidence obtained in the field is still relatively scarce. This is largely because observing animals in the vibrant nearshore waters is a challenging task. Through comparative evaluation, it can be seen that the estimated risk can change sharply with the assumptions made about species behavior and the way turbines are built, which emphasizes the necessity of caution when dealing with the output results of the model [1,3,6,8].

Habitat alteration is a spatially clear impact pathway, which includes physical disturbances generated during installation and long-term consequences brought about by the existence of structures. The reported results obtained from different locations have very significant differences. Some studies have recorded the improvement effect of artificial reef on habitats However, some studies have also pointed out that the sensitive benthic biological environment has undergone degradation. Overall, these changes mediated by habitats can enhance local biodiversity, but their overall ecological significance is determined by site selection, the type of original habitat, and the cumulative pressure brought about by other coastal activities.

This paper finds that local hydrodynamic changes may occur, such as potential variations in water flow, wave state, and sediment transport, which are mainly verified by numerical models [1,3]. The results of these simulations indicate that the deployment on an array scale may amplify the impact, but the current on-site evidence is still relatively scarce. Many comprehensive studies on the impact of nearshore Marine renewable energy have repeatedly pointed out that hydrodynamic changes are one of the least confirmed pathways through measurement. In terms of sediment dynamics and downstream ecological responses [1,3,5,8], among all stressor categories, it can be seen from the literature that the quality of the evidence is inconsistent and there is a great deal of uncertainty. When making explanations, one should maintain a cautious attitude [1,2].

This article mentions that numerical simulation and environmental monitoring are the key foundations for the impact assessment of Marine renewable energy in nearshore areas [1,2]. Generally, models are used to test those processes that cannot be directly observed. However, most models are based on simplified assumptions and have not been verified through long-term measurements [1,3]. Although field campaigns are necessary, they are generally restricted by some factors, such as relatively short duration, high cost, and inconsistent protocols. Recent comments have all agreed that the coupling between modeling and monitoring is still not very good at present. Such a gap leads to the persistence of uncertainty. When estimating the impact of cumulative or array scale [1,2,5,7].

In addition to evaluating the technology, this paper also tracks the progress in risk management and regulation. There is a risk-based adaptive framework, which also includes the idea of risk retirement. This framework has been incorporated into the selected governance Settings [2,5]. Through comparative work, it can be found that there is now an increasing amount of evidence to show that The observed environmental impacts are generally relatively low, which enables these tools to be disseminated. However, there are still significant differences in the rules among different regions [2,5,7]. This heterogeneity of rules in different regions highlights how the governance environment guides the reading and use of scientific evidence in the nearshore MRE project [9-10].

4. Conclusion

This article provides a review of the latest evidence on the environmental impact of nearshore Marine renewable energy systems, focusing on the main stressors, the methods adopted for assessment, and the governance measures that have been taken. From these circumstances, it can be seen that although many impact pathways have been recorded one by one, the experience records in this regard are not complete. It has a very strong geographical particularity. So far, no serious or irreversible ecological damage has been clearly recorded. However, due to the limited scope of existing research in terms of space and time, there is still considerable uncertainty.

The main contribution of this review lies in its distinction between areas where scientific understanding is already relatively solid and those where the gap remains the greatest. By integrating scattered evidence from different technologies and regions, it has managed to control the fragmentation of concepts and addressed the environmental risks brought about by nearshore Marine renewable energy projects. It has provided a clearer and more unified understanding.

Looking ahead, the results of the research particularly emphasize the need to shift towards a cumulative long-term assessment framework based on empirical evidence. As the scale of nearshore Marine renewable energy deployment continues to expand, it is crucial to closely integrate validation models with ongoing environmental monitoring. This approach is conducive to gradually reducing uncertainties. And it plays a crucial role in providing guidance for reasonable decision-making.

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