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Marine Energy Installations and Coastal Ecosystems: A Critical Perspective on Environmental Impacts and Mitigation Strategies

Abstract

The transition to renewable energy encourages the acceleration of the development of marine energy such as waves, currents, and tides. Despite being categorized as low-carbon energy, marine energy infrastructure installations raise critical questions regarding their impact on vulnerable coastal ecosystems. This perspective article aims to critically analyze the environmental aspects of marine energy installations and offer a mitigation approach based on the principles of prudence and adaptive management. The perspective raised emphasizes that the success of marine energy is not only determined by technological efficiency, but also by the integration of ecological considerations in project planning, design, and operation.

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Keywords: Marine Energy, Coastal Ecosystems, Environmental Impact, Mitigation, Adaptive Management.

1. Introduction

Marine energy is getting increasing attention in the agenda to reduce carbon pollution as part of the transition strategy to a more sustainable and low-carbon energy system. Amid growing concerns about climate change, rising global temperatures, and environmental degradation due to fossil fuel exploitation, countries are working to expand renewable energy mixes that are not only reliable but also environmentally friendly. Marine energy which includes wave energy, ocean currents, tides, and the conversion of marine thermal energy is seen as one of the energy sources with great potential but relatively not yet optimally utilized. According to the International Renewable Energy Agency, the technical potential of marine energy globally is significant enough to contribute to supporting low-carbon energy systems, particularly in island countries and coastal areas with strong oceanographic dynamics (Khan et al., 2022).

In the geographical context of Indonesia as the largest archipelagic country in the world, the potential of marine energy is becoming increasingly strategically relevant. The length of the wide coastline, the existence of straits with strong currents, and the characteristics of tidal currents in various regions provide great opportunities for the development of marine and wave power plants. In addition to supporting national energy security, marine energy is also seen as able to answer the challenges of electrification in remote areas that have not been reached by conventional power grids. Thus, on a macro level, the development of marine energy not only has a global environmental dimension, but also an economic dimension and equitable development (Langer et al., 2021).

In addition to direct impacts, there are also potential indirect and cumulative impacts that often receive less attention in the project planning stage. The construction of more than one marine

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energy installation in a single region can gradually increase ecological pressures, especially if it is not accompanied by a comprehensive cumulative impact assessment. Underwater noise during the construction phase, for example, can interfere with the migratory behavior of marine mammals and pelagic fish, while changes in current patterns due to kinetic energy extraction have the potential to affect the distribution of nutrients and larvae of marine organisms. These impacts may not be immediately noticeable in the short term, but can emerge as changes in the structure of biota communities in the long term (Khan et al., 2022).

On the other hand, there is also an argument that some underwater infrastructure can create an artificial reef effect, which is to provide a new substrate for organisms to grow and develop. This perspective shows that the impact of ocean energy is not always absolutely negative. However, without long-term monitoring and empirical data-driven studies, it is difficult to be sure whether these benefits are actually able to offset the potential loss of natural habitat or actually lead to undesirable changes in species composition. Thus, an analytical approach is needed that is not dichotomous between "eco-friendly" and "destructive" but rather considers the spectrum of possible impacts (Li et al., 2023).

Within the framework of sustainability, the development of marine energy should be judged not only by its contribution to the reduction of global carbon emissions, but also by its ability to maintain the integrity of coastal ecosystems at the local level. An ecologically just energy transition requires integration between technological innovation, environmental governance, and the participation of coastal communities. Without a comprehensive approach, there is a risk of an environmental paradox, where solutions to the global climate crisis create new ecological pressures on a regional scale (Woodroffe, C., 2024).

Based on this background, this perspective article aims to critically analyze the environmental impact of marine energy installations on coastal ecosystems by focusing on physical, biological, chemical, and socio-ecological aspects. In addition, this article also discusses mitigation strategies that can be implemented through ecosystem-based approaches and adaptive management. Thus, the discussion was not only oriented towards the identification of potential impacts, but also on concrete efforts to ensure that the development of marine energy can run in harmony with the principles of sustainable development and protection of the coastal environment (Willsteed, E, 2025).

2. Environmental Aspects That Need to Be Criticized

The installation of current turbines and tidal generation systems has the potential to change the distribution of current and wave energy in coastal areas. The extraction of kinetic energy from water masses can modify the local current speed as well as the wave propagation pattern, which ultimately affects the sediment transport mechanism. These changes can impact erosion and accretion patterns and affect the stability of coastlines in the long term. In sensitive ecosystems such as seagrass beds and coral reefs, even small changes in current dynamics can affect nutrient distribution, sedimentation rates, and aquatic productivity. Therefore, hydrodynamic change cannot be seen solely as a technical problem of marine engineering, but as an ecological issue that is directly related to the sustainability of coastal landscapes and the balance of their natural systems.

In addition to physical changes in the waters, the construction phase of marine energy installations also has the potential to cause disturbances to habitats and biodiversity. The installation of structural foundations and subsea cables can cause direct disturbance to benthic habitats, while support vessel activity has the potential to increase turbidity and pressure on subsurface organisms. The existence of fixed structures in the sea can also change the configuration of aquatic spaces and affect the migration paths of fish and marine mammals. On the other hand, some studies suggest that underwater structures can serve as new substrates that trigger the artificial reef effect and attract organisms to colonize. However, a critical perspective demands a long-term data-driven evaluation to ascertain whether such local biodiversity increases are truly capable of compensating for the potential loss of natural habitats. Without comprehensive monitoring, these kinds of ecological benefit claims risk being premature.

Another impact that is no less important is the underwater noise generated during the construction and operational stages. Activities such as foundation laying and the movement of heavy vessels produce high-intensity acoustic waves that can affect marine mammals' behavior, communication patterns, and navigation systems. Fish and other organisms can also experience physiological stress or changes in distribution patterns due to such sound disturbances. Although noise in the operational phase is generally lower, the cumulative impact of multiple projects within a single area still needs to be taken into account. Fragmented development without considering cumulative impacts has the potential to gradually increase ecological pressures and ultimately reduce the carrying capacity of coastal ecosystems.

In addition to physical and biological aspects, marine energy installations also have the potential to affect the quality of the waters. Construction activities can increase turbidity which reduces the penetration of sunlight, thus impacting photosynthetic organisms such as seagrass and phytoplankton. The use of anti-corrosion materials in underwater structures also carries the risk of releasing certain chemical compounds that have the potential to have toxic impacts on marine life. Although most of these impacts are often considered transient and spatially limited, coastal ecosystems have a tolerance threshold for physical and chemical disturbances. In this context, the application of the precautionary principle is important so that the development of marine energy does not cause long-term ecological consequences that are difficult to recover.

3. Governance and Ecological Justice Challenges

One of the main challenges in marine energy development is how to ensure that the planning process is carried out in an inclusive and transparent manner. Without a meaningful participation mechanism, coastal communities risk only bearing the impact, while economic benefits are more enjoyed by actors outside the local community. This situation can trigger inequality and ecological injustice, where the groups that are most dependent on marine resources have the weakest bargaining position in the decision-making process. Within the framework of sustainability, ecological justice demands that the distribution of environmental benefits and burdens be proportionate and take into account the socio-economic vulnerability of coastal communities.

Integrated marine spatial planning is an important instrument to minimize conflicts in the use of space and integrate various sectoral interests. This approach allows the identification of suitable zones for marine energy installations by taking into account ecological sensitivity, biota migration pathways, conservation areas, as well as fishermen's fishing areas. However, the implementation of marine spatial planning often faces challenges of inter-agency coordination, overlapping regulations, and limited scientific data on the condition of marine ecosystems. Without adequate databases and strong institutional coordination, marine spatial planning risks becoming mere administrative documents that are ineffective in preventing conflict.

In addition, governance challenges also relate to the need to integrate cumulative impact analysis in marine energy development policies. In many cases, environmental impact evaluations are carried out separately for each project, without considering interactions between projects within a single area. This kind of sectoral approach can ignore the gradual accumulation of ecological stress. Therefore, sustainable marine energy governance requires a regulatory framework that is able to see ecosystems as a single system, rather than as a collection of individual projects.

From the perspective of ecological justice, it is also important to consider the intergenerational dimension. Today's decision-making regarding the placement and design of marine energy infrastructure will affect the condition of coastal ecosystems in the long term. If management is carried out without the principles of prudence and public participation, the risk of environmental degradation can be passed on to future generations. Thus, the challenge of marine energy governance is not only about administrative efficiency, but also about ensuring that the energy transition takes place in a fair, inclusive, and responsible manner for the sustainability of coastal ecosystems.

4. Mitigation Strategies: From Technical to Adaptive

Mitigation should not be understood as an additional step taken after the technical design of a project is completed, but rather as an integral part of the overall planning and decision-making process from the initial stage. In the context of marine energy development, reactive mitigation approaches tend to focus only on handling impacts after they have occurred, while proactive approaches place environmental aspects as key considerations in determining the location, design, and operational patterns of installations. Thus, mitigation is not just an instrument of impact control, but a framework to ensure that marine energy projects are designed in harmony with the ecological characteristics of coastal areas.

One of the key strategies that needs to be prioritized is an ecosystem-based approach. This approach requires a thorough understanding of environmental conditions before the project is implemented, including mapping sensitive habitats such as coral reefs, seagrass beds, mangroves, and marine life migration routes. The determination of the installation location should take into account the results of the study so that conservation areas and key ecological corridors can be avoided. In addition, a cumulative impact analysis across projects needs to be conducted to identify potential ecological pressures that may arise from the interaction of multiple installations within a single water area. By viewing ecosystems as a single interconnected system, an ecosystem-based approach helps minimize the risk of unexpected degradation.

In addition to careful spatial planning, technological innovation also plays an important role in mitigation strategies. The use of turbines with low rotational speeds, for example, can reduce the risk of collisions with marine life as well as minimize disturbances to organisms that are sensitive to changes in currents. Installation methods designed to produce lower noise, including more environmentally friendly foundation installation techniques, can help suppress acoustic impacts on marine mammals and fish. In addition, the selection of non-toxic and corrosion-resistant materials is important to prevent the potential release of harmful substances into the waters. This kind of technological innovation shows that engineering design and environmental protection do not have to be in a conflicting position, but can be developed synergistically.

Furthermore, effective mitigation requires a structured and sustainable long-term monitoring system. Monitoring hydrodynamic conditions, water quality, and biodiversity should not be positioned as a mere administrative obligation, but as an instrument of scientific evaluation of the project's environmental performance. The monitoring data should be analyzed periodically and used as a basis for adjusting installation operations if impacts that exceed ecological thresholds are identified. In this context, adaptive management approaches have become particularly relevant as they enable dynamic responses to the uncertainty and variability of coastal ecosystems. Instead of relying on static assumptions about environmental conditions, adaptive management recognizes that natural systems are complex and changing, so operational policies must be flexible and scientifically evidence-based.

By integrating ecosystem-based approaches, environmentally friendly technology innovations, and adaptive monitoring and management, mitigation strategies can evolve from mere technical actions to comprehensive governance frameworks. This approach not only seeks to reduce negative impacts, but also ensures that marine energy development takes place responsibly, transparently, and in line with the principles of coastal ecosystem sustainability.

5. Reflections and Future Directions

This Marine energy is an important part of the sustainable energy transition. However, sustainability is not only measured by low carbon emissions, but also by its ability to maintain the integrity of coastal ecosystems.

This article asserts that the success of marine energy development lies in the integration of environmental science, participatory governance, and the principles of prudence. Thus, marine energy is not only a symbol of technological innovation, but also an example of true sustainable development practices.

6. Conclusions

This The development of marine energy offers a great opportunity in supporting the transition to low-carbon energy systems, especially for countries with coastal and island characteristics.

However, this article asserts that the "clean energy" label should not be seen only from low carbon emissions during the operational phase. Marine energy installations still have potential impacts on coastal ecosystems, both through changes in hydrodynamics, habitat and biodiversity disturbances, underwater noise, and risks to water quality. These impacts can be direct or cumulative, and have implications not only ecologically, but also socially.

Therefore, the success of marine energy is not only determined by technological advancements, but by the extent to which environmental considerations are integrated from the planning stage. Ecosystem-based approaches, the application of precautionary principles, environmentally friendly technological innovations, and adaptive monitoring and management are key to minimizing ecological risks. In addition, inclusive and participatory governance is needed to ensure that the energy transition takes place in a just manner and does not come at the expense of coastal communities.

Thus, marine energy can truly be part of sustainable development if its development is carried out carefully, based on science, and responsive to ecosystem dynamics. A successful energy transition is not just about replacing energy sources, but about ensuring that solutions to the climate crisis do not create new environmental pressures in coastal regions.

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