

Harnessing Ocean Wave Energy through Wave Energy Converters for Sustainable Marine Power Generation

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Abstract: The increasing global demand for energy and the need to reduce dependence on fossil fuels have encouraged the development of renewable energy sources, including marine energy. Ocean waves have considerable energy potential due to their continuous movement and availability in coastal areas. This article discusses the utilization of ocean wave energy through Wave Energy Converters (WECs) for sustainable marine power generation. The discussion covers the basic principles of wave energy, WEC working mechanisms, and common technologies such as oscillating water columns, point absorbers, and overtopping devices. Factors affecting system performance, including wave height, wave period, efficiency, and environmental conditions, are also examined. Although WEC technology offers potential for cleaner and sustainable electricity generation, challenges related to efficiency, durability, cost, and environmental compatibility remain. Further technological development is therefore needed to support wider implementation of wave energy systems.

Keywords: Ocean Wave Energy; Wave Energy Converter (WEC); Marine Renewable Energy; Sustainable Power Generation; Wave Energy Conversion

1. Introduction

The increasing global demand for electricity, combined with concerns over fossil fuel depletion and environmental degradation, has accelerated the development of renewable energy technologies. Renewable energy sources such as solar, wind, hydropower, and marine energy offer opportunities to reduce dependence on conventional fossil fuels and support the transition toward a more sustainable energy system. Among these resources, ocean energy has attracted considerable attention because of the vast and relatively continuous energy available in marine environments. Ocean waves are generated primarily by the interaction between wind and the sea surface and contain both kinetic and potential energy. The amount of energy available in waves is influenced by several physical parameters, particularly wave height, wave period, and water density. With relatively high energy density and predictable characteristics in suitable locations, ocean waves have significant potential for electricity generation, particularly for coastal and island communities [1].

The conversion of wave energy into useful electrical power is commonly achieved through Wave Energy Converters (WECs), which capture wave motion and convert it into mechanical energy before transforming it into electrical energy. Various WEC concepts have been developed, including oscillating water columns, point absorbers, attenuators, and overtopping devices. Each technology has different operating principles and performance characteristics depending on wave conditions, water depth, and deployment location. Despite its potential, wave energy technology still faces several challenges, including strong waves, corrosion, biofouling, extreme weather conditions, high installation costs, limited technological maturity, and variations in wave conditions. These factors can affect the reliability, efficiency, maintenance, and economic feasibility of WEC systems [2].

This article aims to discuss the potential of ocean wave energy and its conversion into electrical power through Wave Energy Converters. The discussion focuses on the fundamental principles of wave energy, the working mechanisms and types of WEC technologies, factors affecting conversion efficiency, and the opportunities and challenges associated with their implementation. Through this discussion, ocean wave energy can be examined as a potential marine renewable energy resource for supporting sustainable electricity

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generation and reducing dependence on fossil based energy systems [3].

2. Materials and Methods

This study uses a qualitative descriptive approach based on a literature review to examine the utilization of ocean wave energy through Wave Energy Converters (WECs) for sustainable marine power generation. This approach was selected to provide a comprehensive understanding of ocean wave energy, WEC technologies, energy conversion processes, system performance, and the challenges associated with their implementation. The study relies on secondary data obtained from scientific journals, conference proceedings, academic books, technical reports, and publications from recognized institutions related to marine renewable energy and wave energy conversion. The literature search was conducted using academic databases and search engines with keywords such as *ocean wave energy*, *wave energy conversion*, *Wave Energy Converter*, *marine renewable energy*, *wave power*, and *sustainable marine power generation*. The collected literature was screened based on its relevance to the research topic, with priority given to studies discussing ocean wave characteristics, WEC operating mechanisms, energy conversion efficiency, environmental conditions, and technological development. The selected references were subsequently reviewed and compared to identify important concepts, technological characteristics, and factors influencing wave energy conversion [4].

The analysis focuses on the fundamental characteristics of ocean waves, including wave height, wave period, wavelength, water depth, and seawater density. These parameters are examined to understand the energy potential of ocean waves and their influence on the performance of WEC systems. The study also examines the process of converting wave motion into mechanical energy and subsequently into electrical energy. Several WEC technologies, including oscillating water columns, point absorbers, attenuators, and overtopping devices, are compared based on their operating principles, energy capture mechanisms, deployment conditions, advantages, limitations, and potential applications [5].

The performance of WEC systems is analyzed by considering physical and environmental factors such as wave height, wave period, water depth, wave direction, device configuration, and power take off efficiency. Marine environmental conditions, including corrosion, biofouling, storms, and extreme wave conditions, are also considered because they can influence the durability, reliability, maintenance requirements, and long-term performance of WEC systems. The relationship between wave characteristics and system performance is evaluated by comparing findings reported in previous studies [6].

Finally, the collected information is analyzed using a comparative descriptive method. The results from different references are compared based on wave energy characteristics, WEC technology, energy conversion mechanisms, system performance, environmental impacts, and implementation challenges. The findings are synthesized to provide an overview of the potential and limitations of wave energy conversion technology as a sustainable source of marine power. This methodology provides a basis for assessing the feasibility of WEC systems in coastal and island regions and their potential contribution to sustainable electricity generation [7].

3. Results

The literature review indicates that ocean waves represent a promising source of renewable energy for sustainable marine power generation. The energy potential of ocean waves is mainly influenced by wave height, wave period, water depth, and seawater characteristics. Higher wave heights and longer wave periods generally provide greater energy potential, making areas with consistent and energetic wave conditions more suitable for wave energy conversion. However, wave characteristics vary depending on geographical location and environmental conditions, so the selection of an appropriate wave energy system must consider the characteristics of the target site. The reviewed studies also indicate that wave energy has potential applications in coastal and island regions, particularly in areas where access to conventional electricity infrastructure is limited [8].

The analysis of Wave Energy Converter (WEC) technologies shows that different devices use different mechanisms to capture wave energy. Oscillating Water Column (OWC) systems utilize water movement inside a chamber to produce airflow that drives a turbine, while point absorbers capture the relative motion between floating components and the surrounding water. Attenuators extract energy from the relative motion of long structures aligned with the direction of wave propagation, whereas overtopping devices collect seawater in an elevated reservoir and release it through turbines. The results demonstrate that WEC performance is strongly related to wave conditions, device configuration, water depth, and energy conversion efficiency [9].

The results further demonstrate that the efficiency and reliability of WEC systems are affected by both technical and environmental factors. Wave height, wave period, wave direction, and device characteristics influence the amount of energy that can be captured and converted into electricity. Marine conditions such as

corrosion, biofouling, storms, and extreme waves can also affect system durability and operational reliability. In addition, high installation and maintenance costs, variable wave conditions, technological limitations, and environmental considerations remain important challenges. Overall, the findings indicate that suitable wave conditions, appropriate WEC technology, efficient energy conversion, and adequate structural durability are essential for improving the long term viability of wave energy systems [10].

4. Discussion

The results indicate that ocean wave energy has significant potential to contribute to sustainable marine power generation. The amount of energy available is strongly influenced by wave characteristics, particularly wave height and wave period, while variations in wave conditions between locations and seasons can affect system performance. Therefore, local wave assessment is essential for determining the feasibility of a wave energy project. The comparison of WEC technologies also shows that each system has specific advantages and limitations. Oscillating Water Column systems can be applied in coastal areas, point absorbers can capture wave motion from different directions, attenuators extract energy along elongated structures, and overtopping devices use wave run up to generate electricity. These differences demonstrate that WEC selection should be based on wave characteristics, water depth, site conditions, and intended application rather than relying on a single configuration [11].

The performance of WEC systems depends on the efficiency of each stage of the energy conversion process, from wave energy capture to mechanical and electrical energy generation. Energy losses during these stages can reduce the overall electrical output, making improvements in hydrodynamic design, power take-off systems, and control strategies important for increasing energy capture. In addition, WEC structures are continuously exposed to seawater, waves, currents, and changing weather conditions. Corrosion, biofouling, storms, and extreme waves can reduce equipment performance and increase maintenance requirements. Therefore, WEC systems require adequate structural strength, corrosion protection, and reliable mooring and anchoring systems to ensure long-term durability and operational safety [12].

From environmental and economic perspectives, wave energy offers an opportunity to generate electricity without directly relying on fossil fuels during operation, but WEC deployment may interact with marine ecosystems, coastal processes, navigation, and other ocean activities. Environmental assessment and monitoring are therefore necessary before large scale implementation. Economic feasibility also remains a challenge because installation, maintenance, and component replacement in offshore environments can require substantial investment. For coastal and island regions such as Indonesia, WEC systems could complement other renewable energy sources and provide electricity for remote communities and marine facilities. Overall, successful wave energy utilization requires the integration of suitable wave resources, appropriate WEC technology, efficient energy conversion, structural durability, environmental compatibility, and economic feasibility. Further research and technological development are needed to improve WEC efficiency, reliability, affordability, and environmental performance [13].

5. Conclusion

Ocean wave energy represents a promising marine renewable energy resource that can contribute to sustainable electricity generation. The utilization of this energy through Wave Energy Converters (WECs) enables the conversion of wave motion into mechanical and electrical energy. Different WEC technologies, including oscillating water columns, point absorbers, attenuators, and overtopping devices, provide different approaches to capturing wave energy and can be selected according to local wave characteristics and deployment conditions.

The effectiveness of wave energy conversion is influenced by wave height, wave period, water depth, device configuration, energy conversion efficiency, and marine environmental conditions. Although WEC technology offers significant potential, challenges related to system efficiency, structural durability, corrosion, maintenance, installation costs, environmental impacts, and variable wave conditions still need to be addressed. Therefore, appropriate site assessment and technology selection are essential for achieving reliable and sustainable operation.

Overall, the development of WEC technology can support the transition toward cleaner marine power generation, particularly in coastal and island regions with suitable wave resources. Further research and technological development are needed to improve energy conversion efficiency, system reliability, economic feasibility, and environmental compatibility. With continued innovation and appropriate implementation strategies, ocean wave energy can become an important component of a sustainable marine renewable energy system.

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