

From Waves to Electricity: An Overview of Wave Energy Converter Systems and Technologies for Sustainable Ocean Energy

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Abstract: Ocean waves are one of the renewable energy sources that have great potential because they are available naturally and have relatively consistent energy characteristics in certain marine areas. The utilization of wave energy is carried out through Wave Energy Converter (WEC) technology, which is a system that converts wave mechanical energy into electrical energy through hydrodynamic and Power Take-Off (PTO) mechanisms. Various types of WEC have been developed, including point absorbers, attenuators, oscillating water column (OWC), oscillating wave surge converters, and overtopping systems. This study aims to review the development of wave energy conversion systems and technologies by focusing on the working principle, type of device, PTO system, control strategy, and challenges of its application in the marine environment. The study method was carried out through a review of a number of studies and scientific articles on the development of WEC and wave energy conversion technology. The results of the study show that the development of WEC is not only focused on improving the ability to capture wave energy, but also on the development of hydrodynamic designs, PTO systems, control strategies, array configurations, and integration with offshore energy infrastructure. However, investment costs, resistance to extreme marine conditions, conversion efficiency, maintenance, and technological readiness remain challenges in moving towards commercial-scale implementation. The development of adaptive control systems, more efficient PTO technology, and the integration of WEC with other marine energy systems are important directions to improve the reliability and competitiveness of wave energy in the future.

Keywords: Wave Energy; Wave Energy Converter; Power Take-Off; Oscillating Water Column; Marine Renewable Energy

1. Introduction

The ever-increasing global energy demand is driving the development of renewable energy sources that can reduce dependence on fossil fuels. In addition to solar and wind energy, the ocean has great energy potential through waves, currents, tides, as well as differences in temperature and salinity. Wave energy is one of the attractive sources of marine energy because the mechanical energy carried by the waves can be converted into electrical energy using a special device known as a Wave Energy Converter (WEC).

WEC is a system designed to capture wave movements and convert them into usable energy. This technology has various forms and working principles. Some concepts use the up and down movement of buoys, while others take advantage of changes in air pressure due to rising water levels or utilizing wave water runoff to reservoirs. This diversity shows that there is no one WEC configuration that can be used universally for all marine conditions [1], [2].

2. Materials and Methods

This study uses a literature review method on research and scientific articles that discuss wave energy conversion systems and the development of Wave Energy Converter technology. The literature used includes research on the types of WEC, Power Take-Off systems, control strategies, design optimization, and developments in WEC technology in recent years.

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The analysis was carried out by grouping technologies based on the principle of energy conversion, the characteristics of the device's movement, and the PTO mechanism used. The types of technologies that are the focus include point absorbers, attenuators, oscillating water columns, overtopping devices, and wave-motion-based conversion systems.

In addition to the device aspect, the study also considers technical factors that affect WEC performance, such as wave height and period, hydrodynamic design, PTO efficiency, control strategy, marine environmental conditions, and maintenance needs. This approach is used to obtain an overview of WEC technology developments and the challenges that still need to be solved before its application can be expanded.

3. Results

The results of the study show that WEC can be grouped based on the way the device captures wave movement. One of the main groups is the point absorber, which is a device that generally has relatively small dimensions compared to the wavelength and utilizes vertical or relative movement between components. The movement is then forwarded to the PTO system to generate electrical energy.

The next group is the attenuator, which is a device that has an elongated structure and is placed in the direction or almost in the direction of the wave's coming. The relative motion of some parts of the device is used to drive the PTO system. This technology allows the capture of energy in several parts of the structure.

Oscillating water column (OWC) technology has a different principle. In this system, waves cause the water surface in the enclosed space to move up and down. This movement causes the air in the room to undergo compression and expansion so that the airflow can move the turbine. OWC can be developed in both fixed and floating configurations [3].

In addition to these three technologies, there are overtopping devices that utilize wave energy by directing water to reservoirs at a certain elevation. The water is then flowed back to the sea through turbines so that the potential energy of water is converted into electrical energy. These different types of WECs show that the conversion of wave energy can be done through different hydrodynamic mechanisms [1]

Another important development is the Power Take-Off (PTO) system. PTO is a part that takes mechanical energy from the WEC movement and converts it into energy that can be passed to the generator. Research on PTO includes hydraulic, mechanical, electrical, and various other configurations. The choice of PTO greatly affects the output power, efficiency, stability, and complexity of the WEC system [4].

4. Discussion

The development of WEC technology shows that the main challenge lies not only in the ability of the device to capture energy, but also in how that energy can be converted stably and economically. Ocean waves have a dynamic nature so the device must be able to work under different wave conditions. Changes in the height, period, and direction of the waves can cause changes in the WEC's hydrodynamic response and affect the power generated.

PTO systems are one of the important components in this problem. PTO that has high efficiency can increase the amount of energy that is successfully converted, but increasingly complex systems can also increase costs and maintenance needs. Therefore, PTO design needs to consider the balance between efficiency, reliability, cost, and durability in the marine environment.

Control strategies are also an important part of improving WEC performance. Control systems can regulate the device's response to incoming waves so that the device's movement can be adjusted to wave conditions. Recent studies on WEC technology show that design optimization, control strategies, array configuration, and integration with other energy systems are some of the main focuses of research [2].

The development of WECs in the form of arrays also provides an opportunity to increase the utilization of marine space. Multiple devices can be placed regularly so that wave energy can be captured by a number of WECs simultaneously. However, the interaction of hydrodynamics between devices needs to be considered because the presence of one device can affect the waves received by other devices. Therefore, the configuration and distance between WECs are important aspects in system design [5].

In addition to standing alone, WEC is also beginning to be studied to be combined with other marine energy technologies. Combined wave and offshore wind systems can use the same infrastructure so that the use of marine space and supporting facilities can be carried out together. Studies on combined wind and wave systems

show that integration is one of the directions for the development of marine energy technology [6].

Despite its potential, the implementation of WEC still faces technical and economic challenges. Extreme marine conditions can place a heavy load on structures, mooring systems, PTOs, and electrical components. In addition, the device must have the ability to withstand corrosion, material fatigue, and storm-induced loads. Construction and maintenance costs are also factors that need to be taken into account in development towards commercial scale.

Recent studies on WEC show that technology development is still directed at improving energy capture efficiency, operational reliability, design optimization, control systems, and performance validation.

5. Conclusion

Based on the results of the review, the Wave Energy Converter is one of the technologies that can be used to utilize the mechanical energy of ocean waves into electrical energy. Various technologies have been developed, including point absorbers, attenuators, oscillating water columns, overtopping devices, and various other wave movement-based systems.

The current development of WEC focuses not only on device design, but also on improving Power Take-Off performance, control strategies, array configurations, mooring systems, as well as integration with other offshore energy technologies. More efficient adaptive control systems and PTO technology are an important part of improving WEC's ability to cope with dynamic wave characteristics.

However, the widespread implementation of WEC still faces a number of challenges, especially cost, conversion efficiency, structural resilience to extreme marine environments, maintenance needs, and technological readiness. Therefore, further research needs to be directed at the development of WEC systems that are simpler, resistant to marine conditions, efficient, and able to adapt to changes in wave conditions.

Further development through the integration of WEC with offshore wind energy, array systems, artificial intelligence-based control technologies, as well as hydrodynamic design optimization has the potential to improve the reliability and utilization of wave energy as part of future marine renewable energy systems.

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