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Ocean Wave Energy Converter

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Abstract: This research paper presents a comparative analysis of power extraction from an Oscillating Water Column (OWC) and a Point Absorber using mathematical modeling. Both systems are modeled under the same wave input conditions, with the OWC utilizing airflow dynamics to drive a turbine, and the Point Absorber modeled through heave motion equations. Linear wave theory and hydrodynamic interactions are applied to calculate power output. Results indicate that the OWC performs optimally in nearshore environments with consistent waves, while the Point Absorber is more efficient in offshore conditions. The comparison highlights how different wave characteristics influence energy capture efficiency.

Keywords: Oscillating water Column, Point absorber, Mathematical modeling, Ocean energy, Wave energy

1. Introduction

Ocean wave energy converters (OWECs) are innovative devices designed to capture the vast, renewable energy potential of ocean waves. As global demand for clean energy rises, wave power has gained significant attention due to its predictability and immense capacity. Waves, created by wind interacting with the ocean surface, carry kinetic and potential energy that can be converted into electricity. Among the various OWEC designs, two of the most prominent are the Oscillating Water Column (OWC) and the Point Absorber. The OWC harnesses wave energy by creating pressure variations in an air chamber, causing air to flow through a turbine, generating power [1]. It is especially suited for nearshore installations, where wave patterns are more predictable.

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In contrast, the Point Absorber is a floating device that captures energy through vertical motion, driven by wave oscillations. It is highly efficient in deeper waters and uses hydraulic or mechanical systems to convert this motion into electrical energy. These converters offer significant potential for sustainable energy generation [2]. However, the challenge lies in optimizing efficiency across varying sea conditions. Continued research into hybrid systems, combining technologies like OWC and Point Absorbers, could lead to enhanced energy output, offering a robust solution to meet future energy needs.

The future of wave energy in India holds significant promise as the country seeks to diversify its renewable energy portfolio. With an extensive coastline of over 7,500 km, India is well-positioned to harness wave energy, which could provide a reliable and sustainable power source. The Government of India, under its renewable energy mission, has already begun exploring the potential of ocean energy, including waves, tides, and ocean thermal energy conversion [3].

The article is structured as Section 2 with wave energy, Section 3 about proposed work, Section 4 about mathematical modelling in MATLAB, Section 5 about the results and conclusions in Section 6.

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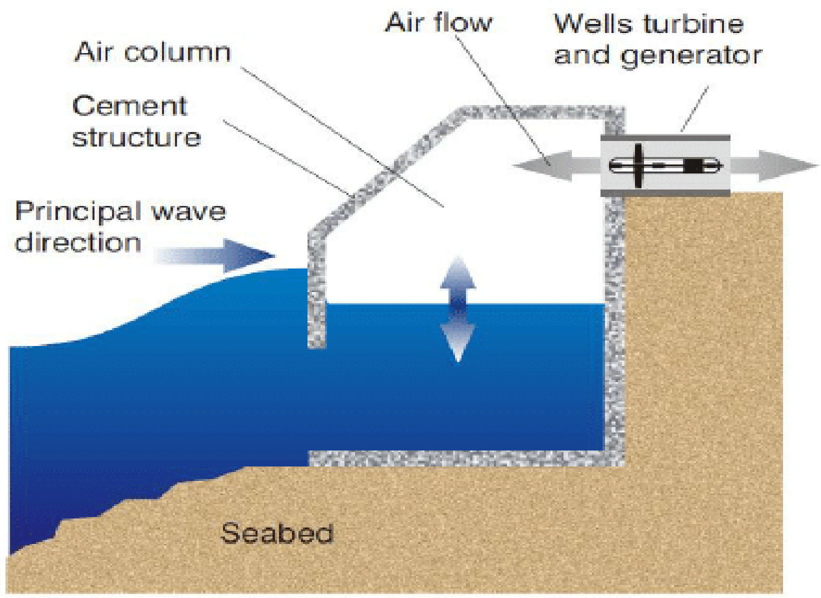

Fig. 1: Oscillating water column

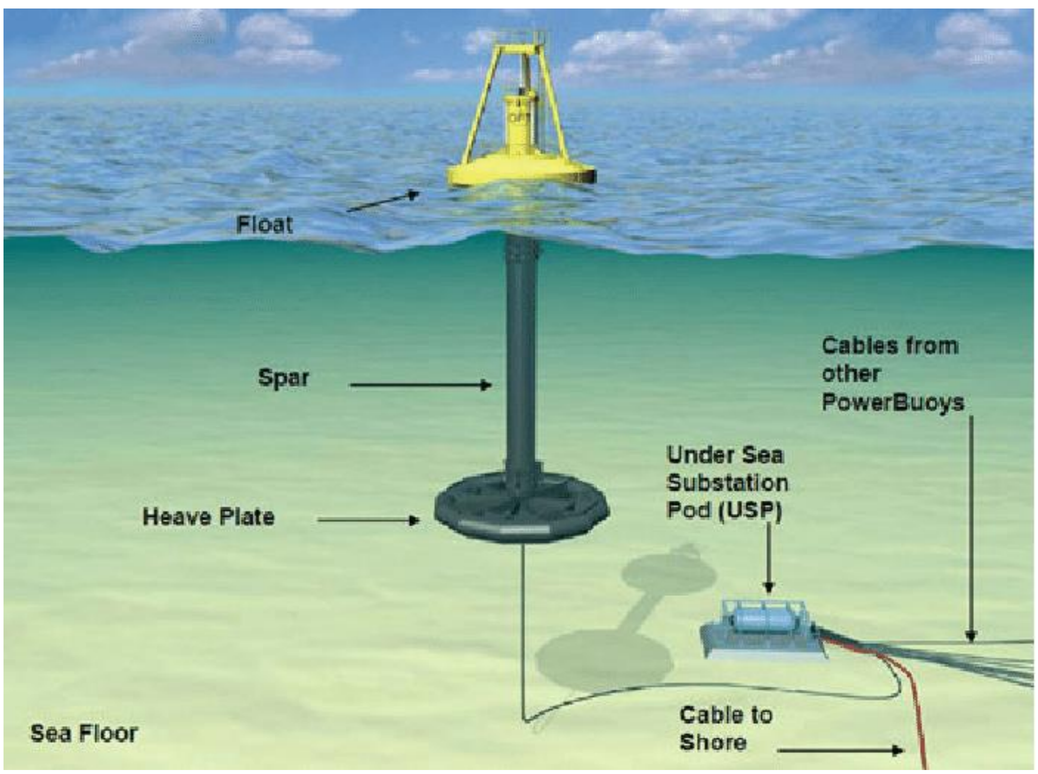

Fig. 2: Point absorbers

2. Wave energy conversion

2.1 Oscillating Water Columns (OWCs)

Fig. 1, shows the OWCs utilize the rise and fall of water within a chamber to generate airflow, which in turn drives a turbine connected to a generator [4-5].

2.2 Point absorber

Point absorbers depicted in Fig. 2, are the floating structures that move with the waves. These devices are typically small relative to the wavelength and can absorb energy from waves coming from any direction [6-7].

3. Proposed work

An ocean wave energy converter utilizing an Oscillating Water Column (OWC) and a point absorber can efficiently harness wave energy through innovative mathematical modeling and state-space analysis. The OWC captures air pressure changes caused by wave motion, driving a turbine for energy conversion. Meanwhile, the point absorber, a buoy-like structure, oscillates with waves, maximizing energy extraction through its unique design. By employing state-space analysis, we can create a dynamic model that represents the system's behavior under varying conditions, optimizing performance and ensuring robust energy output. This integrated approach offers a promising pathway for sustainable wave energy solutions [8].

3.1 Mathematical modelling

Mathematical modeling is the process of representing real-world systems using mathematical concepts and equations to analyze and predict behavior. It helps in understanding complex systems by simplifying their dynamics. In the context of point absorbers and OWCs, mathematical models describe their interactions with wave patterns, energy conversion processes, and efficiency. For point absorbers, models focus on oscillation dynamics and optimal buoy design. For OWCs, models analyze air pressure variations and turbine performance, enabling the optimization of energy capture and conversion under different wave conditions [4-5].

3.2 State space analysis

State space analysis is a mathematical framework used to model and analyze dynamic systems. It represents systems in terms of state variables, which capture the system's current status, and equations that describe how these states evolve over time. This approach is particularly useful for systems that can be described by linear or nonlinear differential equations [4].

State Variables: These are the variables that describe the state of the system at any given time.

For an Oscillating Water Column (OWC), state variables include the air pressure inside the chamber, the water surface elevation, and the velocity of the oscillating water. These variables determine the energy transfer efficiency from wave motion to the turbine.

In a Point Absorber, the state variables involve the vertical displacement of the floating buoy, its velocity, and acceleration. These variables are crucial for tracking the device's interaction with wave forces and optimizing the energy extraction process from wave motion [9-10].

State Space Representation

State-space representation in sea wave energy converters (OWECs) is a mathematical framework used to model and control the dynamic behavior of the system. It expresses the system's dynamics using state variables, inputs, and outputs in a compact form, often enabling real-time control and optimization.

It is represented using two key equations (1)

$$X^{\prime}(t) = A\,X(t) + B\,U(t) \tag{1}$$

$$Y(t) = C\,X(t) + D\,U(t) \tag{2}$$

From State Equation (1)

$$X^{\prime}(t) = A\,X(t) + B\,U(t)$$

A: is the system matrix (nxn).
B: is the input matrix (nxm)

From output equation (2)

$$Y(t) = C\,X(t) + D\,U(t)$$

C: is the output matrix (pxn)
D: is relevant of output with input matrix

This form captures the system's dynamics and outputs in a compact way [4]

4. Mathematical Modeling on MATLAB

Some Math model, Fig. 3, shows the hypothetical formulas below

Wave Elevation, eta = H/2 * cos (omega * t)
Power = damping * velocity^2
total_power = trapz (t, power)
average_power = total_power / (t(end) - t(1))

Efficiency_OWC = Power_OWC / Power_wave;
Efficiency_PA = Power_PA / Power_wave;
Power_wave = (1/16) * rho_water * g^2 * H^2 * c_g
c_g = g * T / (2 * pi); % Group velocity of wave (m/s) [10]

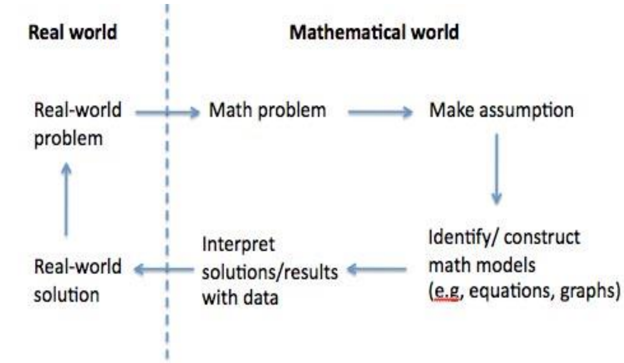

Fig. 3: Functional diagram

5. Results

The Wave Elevation graph shows a sinusoidal wave with a period of 10 seconds and a wave height of 2 meters, representing the incoming wave profile. The Point Absorber Response plot illustrates the buoy's oscillatory motion, which increases in displacement as the system stabilizes. The response matches the wave period but shows amplification due to resonance effects. The Power Generated graph shows the energy output from the absorber, peaking during higher wave elevations, with a total power of 12.8 MJ and an average power output of 128.1 KW over 100 seconds.

The Wave Elevation graph shows a consistent sinusoidal wave with a period of 10 seconds and a height of 2 meters, representing the incoming wave profile. The OWC Response illustrates the displacement of air in the chamber, oscillating between ±35 meters as the waves interact with the chamber. The Power Generated plot shows the turbine's power output, peaking with the air chamber's oscillations. The system generates a total energy of approximately 3.5 MJ, with an average power output of 34.99 kW over the 100-second simulation. So from Fig. 4 and Fig. 5, we can say that when we given to same wave characteristics over time, than the point absorber is highly efficient than the oscillating water column. In terms of maximum power output, point absorbers often have the advantage because they can adapt to varying wave heights and periods more effectively. However, the specific power output will depend on the design, site conditions, and technology used.

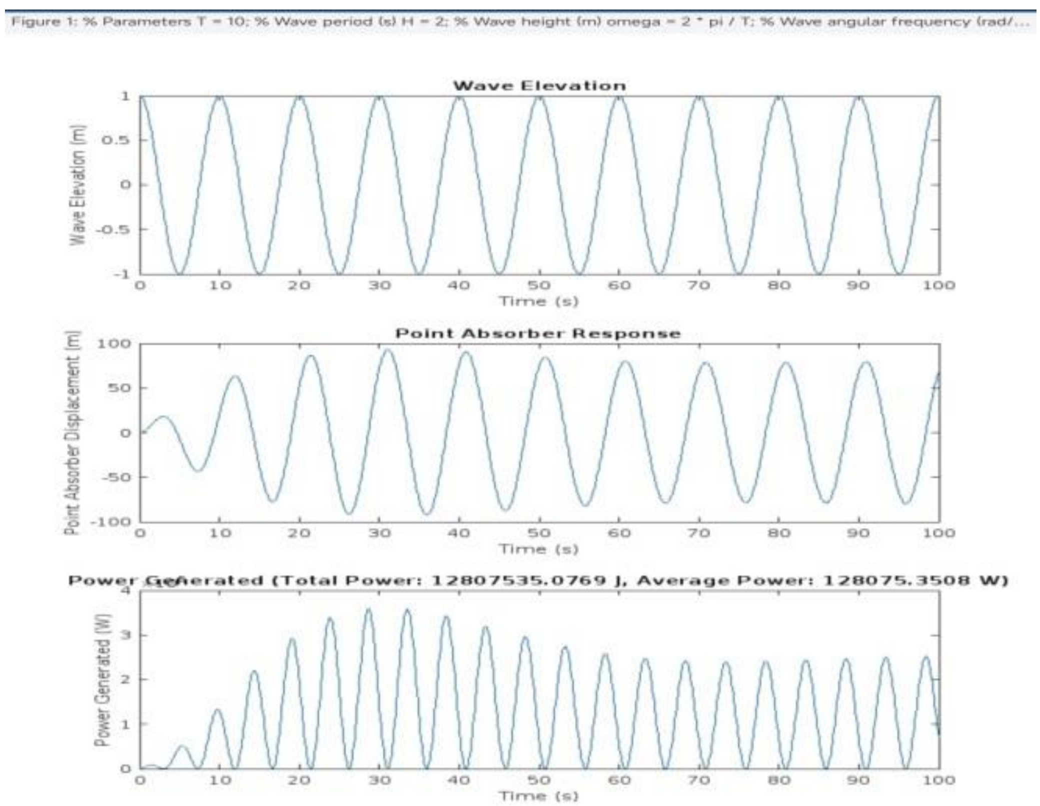

Fig. 4: Wave elevation, PA, Power generated v/s Time

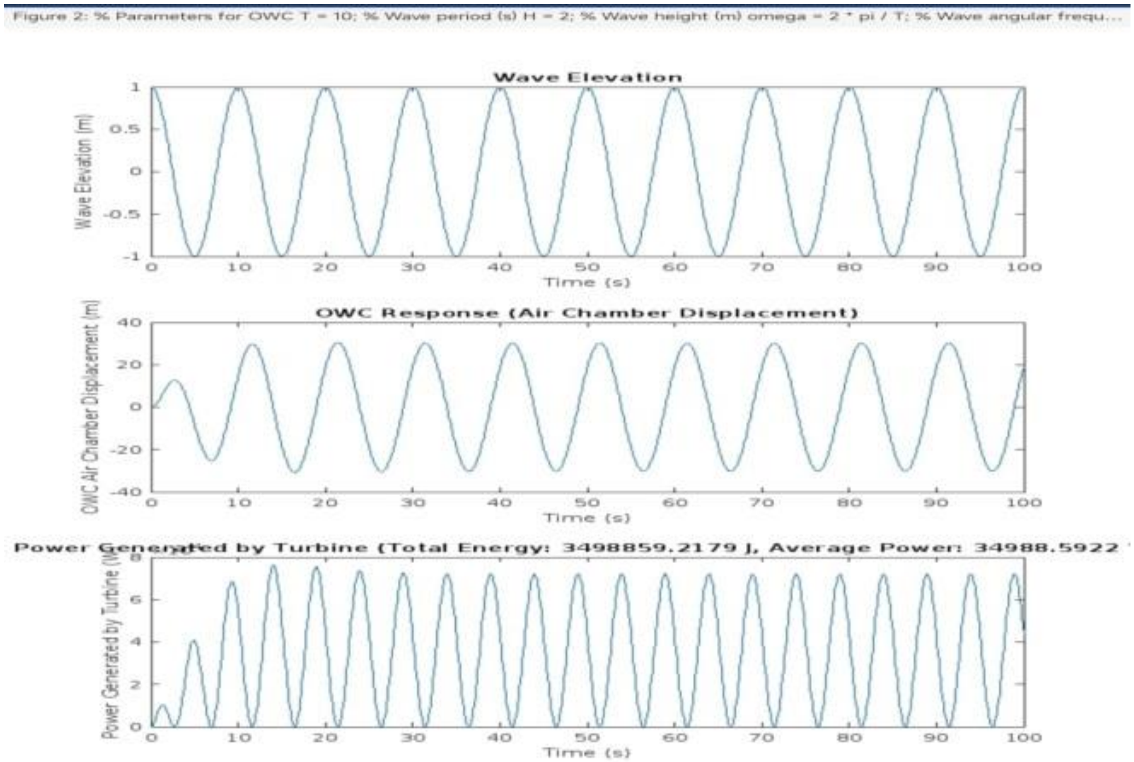

Fig. 5: Wave elevation, OWC ,Power generated v/s Time graph

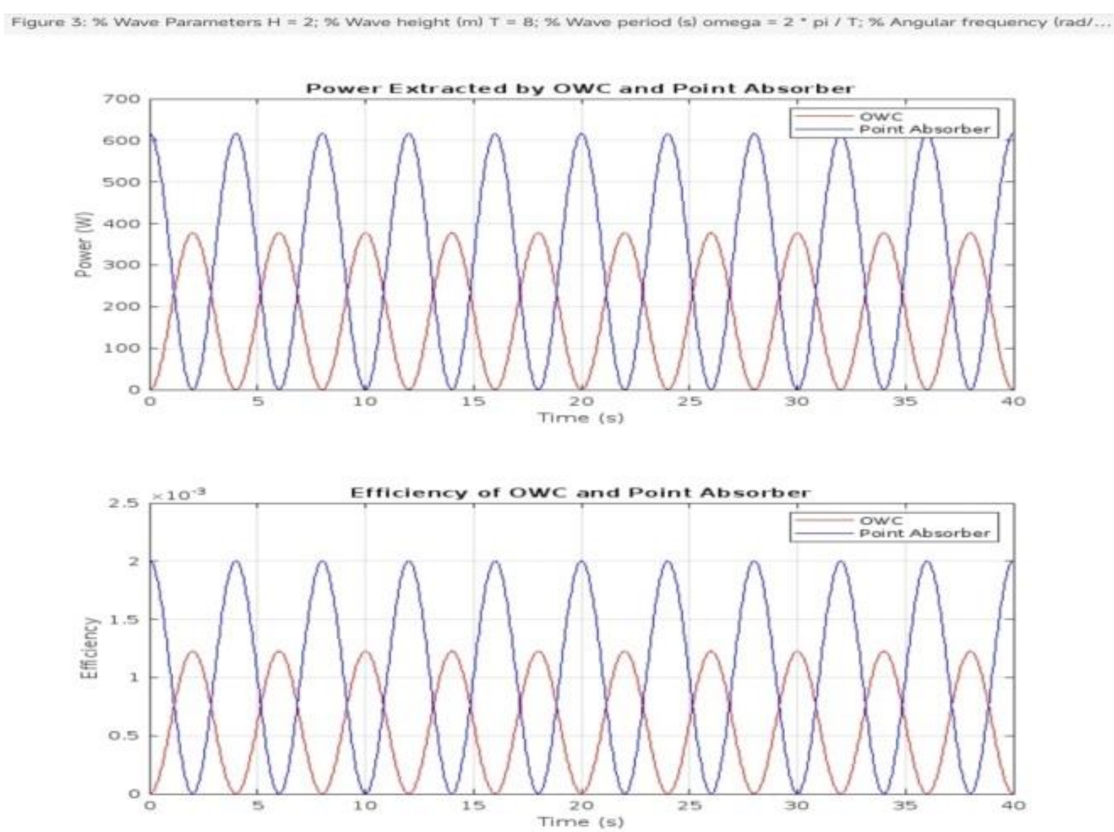

Fig. 6: Power, efficiency v/s Time of OWC & PA graph

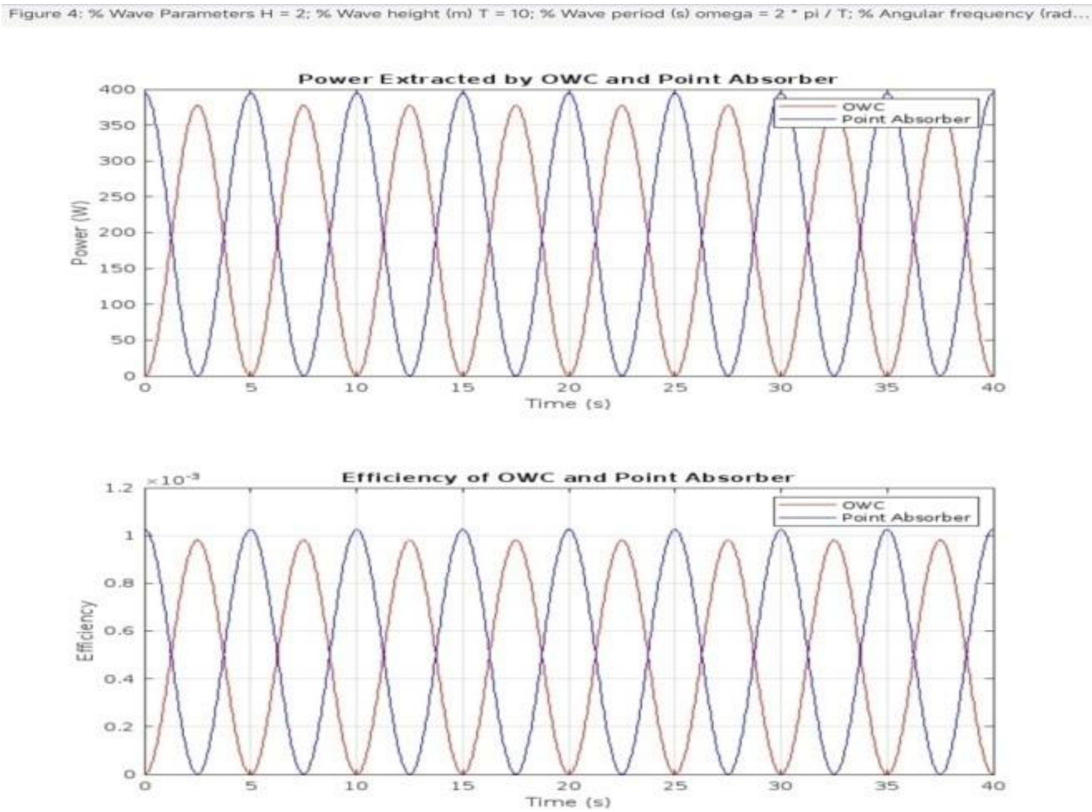

Fig. 7: OWC & PA Performance of power, efficiency v/s Time

From Fig. 6, the graphs shows a comparison between the power extracted and the efficiency of an Oscillating Water Column (OWC) and a point absorber over time, when we given same input[wave height (H=2, Wave period T=8)]. In the top graph (Fig. 6), the blue line represents the power extracted by the point absorber, which significantly exceeds that of the OWC (red line). The point absorber exhibits higher power peaks and overall energy capture.

In the lower graph (Fig. 6), the efficiency of both devices is compared, with the point absorber once again outperforming the OWC. This suggests that point absorbers can extract more power and are more efficient under the given wave conditions.

From Fig. 7, The graphs compare how much power is generated and how efficiently two wave energy devices, the Oscillating Water Column (OWC) and a point absorber- perform over time.

In the first graph (Fig. 7), the blue line shows that the point absorber captures more power than the OWC, which is represented by the red line. The point absorber consistently produces more energy, with higher peaks throughout the period. In the second graph (Fig. 7), we see the efficiency of both devices, and again, the point absorber performs better than the OWC. This means that under the current wave conditions (H=2,Wave period T=10), the point absorber not only generates more power but also operates more efficiently.

6. Conclusion

Mathematical modeling plays a pivotal role in the design and optimization of Ocean Wave Energy Converters (OWC) and point absorbers. Through the formulation of dynamic equations based on physical principles, engineers can simulate and analyze the behavior of these systems under various wave conditions.

Models allow for accurate predictions of energy conversion efficiency, enabling designers to evaluate how well a system will perform in real-world scenarios. By tweaking model parameters, engineers can optimize designs for maximum energy extraction, leading to more effective and economically viable wave energy converters. IT can adapt to changing environmental conditions, enhancing the reliability of energy production.

Conflict of interest

The authors declared 'No conflict of interest'.

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