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TOPICAL REVIEW

Performance Optimization Techniques on Point Absorber and Oscillating Water Column Wave Energy Converter: A Comprehensive Review

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ABSTRACT In recent years, harnessing renewable energy from different sources of energies readily available to us in different forms such as solar, wind, wave, hydro, tidal, biomass and hydrogen has gained popularity among researchers in different fields to counter the emissions released into the atmosphere by utilization of fossil fuels. Amongst these, wave energy is driving researchers to develop efficient systems due to its remarkably high potential providing a reliable and sustainable energy source both onshore and offshore. This paper provides a comprehensive review of the developments, various design innovations, and performance optimization techniques in the recent years of the two most common wave energy converters installed across the globe i.e., point absorber wave energy converter and oscillating water column wave energy converter. The research papers on numerical modeling, experimental analysis on laboratory scaled models, and hydrodynamic performance simulations using various softwares on both the types of wave energy converters are tabulated in a year wise format. Moreover, a list of all the installed point absorber wave energy converters and oscillating water column wave energy converters are tabulated in a year wise format along with their installed capacities, location of deployment and the country of deployment. Lastly the key advantages of both the wave energy converters are outlined below.

INDEX TERMS Renewable energy, wave energy, point absorber wave energy converter, oscillating water column wave energy converter, performance optimization techniques.

NOMENCLATURE

Abbreviation

AMP	Added Mass Plate.
BBDB	Backward Bent Duct Buoy.
BEM	Boundary Element Method.
CFD	Computational Fluid Dynamics.
CWR	Capture Width Ratio.
EMPC	Economic Model Predictive Control.
FPAWEC	Floating Point Absorber Wave Energy Converter.
GDP	Gross Domestic Product.
GHG	Greenhouse Gas.
IRENA	International Renewable Energy Agency.
LCoE	Levelized Cost Of Energy.
NWT	Numerical Wave Tank.
OVTWEC	Overtopping Wave Energy Converter.
OWCWEC	Oscillating Water Column Wave Energy Converter.
OWSWEC	Oscillating Wave Surge Wave Energy Converter.
PAWEC	Point Absorber Wave Energy Converter.
PTO	Power Take Off.
PV	Photovoltaic.
QCS	Quarter-Circle Shaped.

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SPDWEC	Submerged Pressure Differential Wave Energy Converter.
SPH	Smoothed Particle Hydrodynamic.
TENG	Triboelectric Nanogenerator.
UOWC	U-Shaped Oscillating Water Column.
VOF	Volume Of Fluid.
WEC	Wave Energy Converter.
WEFEL	Wave Energy And Fluids Engineering Laboratory.
W2W	Wave-To-Wire.

I. INTRODUCTION

The increase in population worldwide and combatting climate change caused by the extensive use of conventional sources of energy which generate huge amounts of CO_2 emissions, the need to develop reliable, clean, and sustainable sources of energy has gained the attention of many countries. In 2023 the global carbon emissions increased by 1.1% equivalent to 410 Mt. Reaching a record high of 37.4 Gt. Carbon emission from the excessive usage of coal was responsible for more than 65% of this increase. We would have experienced a decrease in carbon emissions in 2023, however due to the water shortages caused by the droughts, it leads to the less use of generating clean energy from hydro power stations to store the water for the communities. This led to an increase of 170 million tonnes of carbon emissions. The strong GDP growth in India lead to an increase in the emissions by 190 Mt [1]. IRENA reported that the global potential for harnessing oceanic wave energy is approximately 500 GW of electrical power, assuming a 40% efficiency by primary conversion. This estimate is based on utilizing only 2% of the world's 800,000 km of coastline with a wave power density exceeding 30 kW/m [2]. Hence harnessing wave energy has become a primary focus for many researchers. In 2024, IRENA reported that the total installed renewable energy capacity worldwide reached 33,869,705 MW in 2023, accounting for 43% of the global installed power capacity. In 2023, there was an addition of 473 GW of renewable energy. Of this, around 346 GW came from solar energy accounting almost 73%, 116 GW from wind energy accounting 24.5%, only 2 GW from marine energy and with the rest coming from hydro power, biopower and geothermal [3]. The 5423 km long coastline of the Indian subcontinent has a potential to harness 5-15 MW/m of wave energy from the 5.7 million waves received per year [4].

Regardless of solar, wind and hydro energies being major contributors in harnessing clean energy, wave energy has received comparatively less attention when compared to other non-conventional sources of energy. This is due to the fact that the ocean bed is mainly used to develop hybrid offshore wind and solar farms. However, in recent years many countries have started to implement pilot projects to test whether harnessing the wave energy from the ocean is feasible or not. Oceanic wave energy provides a much greater advantage compared to other forms of renewable energy sources due to its huge potential to provide clean energy to the people living near the coasts. Thus far, several reviews have been conducted on WEC systems, offering valuable insights into their development and application.

TABLE 1 highlights the objective, contribution and gaps in literature of these previous reviews. Addressing these gaps could significantly enhance the understanding and efficiency of WEC technologies. The present paper is focused on guidance for the latest developments and optimization techniques used to develop efficient working models for PAWEC and OWCWEC. The contributions of the present work are:

- It classifies WEC's based on capture system, location, and PTO system used in detail. Additionally, the working of all six types of WECs is explained, for better understanding of different types of WECs;
- Comprehensively reviews the recent progress, design innovations, and methods to improve the performance of PAWECs and OWCWECs, summarizing the latest advancements in these technologies;
- It compiles the installed PAWECs and OWCWECs around the globe, giving an overview of real-world applications to guide further research and development.

The rest of this paper is organized as follows: section II explains the classification of WECs based on capture system, location and power take off system. In section III, a comprehensive review of the recent developments, various design innovations, performance optimization techniques in the recent years on the PAWEC, a list of PAWECs tabulated in a year wise format along with their installed capacities, location of deployment and the country of deployment and a list of key advantages of PAWEC. This is followed, in Section IV, by a similar review for OWCWEC. Finally, conclusion and future work are presented in Section V.

II. CLASSIFICATION OF WEC

The WECs are divided into 3 subcategories which are based on capture system, location, and PTO shown in the FIGURE 1.The location chosen to install a WEC primarily decides the type of capture system and PTO system to be implemented accordingly.

A. CLASSIFICATION OF WEC BASED ON CAPTURE SYSTEM

- **PAWEC:** The principle of a PAWEC is based on harnessing the wave energy from ocean waves through a floating buoy that moves in a heaving motion when a wave passes through the it, FIGURE 2. The heaving motion of the buoy is converted into rotational energy by a rack and pinion mechanism which is then converted into useful electrical energy by the generator. This electrical energy can then either be stored in a battery installed on the PAWEC or transmitted to the shore via underwater cables for immediate usage by the communities living near the shoreline. The energy flow diagram for a PAWEC is shown in FIGURE 3.
- **OWCWEC:** An OWCWEC is a partially submerged chamber with one end above the surface and the other

TABLE 1. A chronological overview of previous reviews in WECs.

Year Author(s) Reference	Objective	Contribution	Gap in Literature
2018 Elie Al Shami et al. [112]	To review the latest theoretical, experimental, and technological advancements in PAWEC and mooring systems.	Examine developments in one-body and two-body designs of PAWEC, novel PTO mechanisms, efficiency optimizations and finally some of the mooring analysis done recently of PAWEC were presented.	Limited exploration of environmental impacts and integration challenges for large-scale deployments.
2021 D. Clemente et al. [113]	Explores the synergies, hybridization, and applications of WECs in niche offshore and nearshore markets to enhance their viability and competitiveness.	Identifies potential benefits of co-location, hybridization, and new applications of WECs, such as reducing infrastructure costs, providing coastal protection, and powering marine industries.	Inadequate coverage of the control strategies implemented for the hybrid integrated systems WEC systems.
2021 A.Garcia-Teruel and D.I.M. Forehand. [114]	Review of the advancements in hull geometry optimization of WECs to improve power generation and reduce costs.	Provides insights into best practices, successful approaches, and future recommendations for optimizing WEC hull geometries during early design stages.	Lack of integration of adaptable and complex geometry optimization models using more adaptable with the extensively developed control optimization strategies.
2022 B.Guo et al. [115]	Provides the newest developments in PAWEC, especially focusing on prototypes, hydrodynamics, PTO mechanisms, and control strategies.	Provides a detailed classification of different types of PAWEC and LCoE provides the current LCoE of the PAWEC and compilation of work by others who have attempted to reduce LCoE.	Lack of comprehensive reviews dedicated to the distinct technical and non-technical aspects of PAWECs, despite their broad-based and promising applications.
2022 Kushal A. Prasad et al. [105]	Discusses various WEC systems and highlights the development of a novel hybrid device that combines harnessing of energy from wave and solar energy.	Exploration of various PTO mechanisms, with a particular focus on their application in hybrid systems.	Inadequate coverage of different PTO mechanisms and control strategies proposed for the hybrid system.
2024 M. Rosati et al. [5]	Provides a critical review of numerical modeling and control strategies for OWCWEC and review existing control strategies and their impact on optimizing OWC performance.	Highlights the importance of maximizing overall W2W efficiency through comprehensive control strategies and suggests unexplored control possibilities and advocates for control co-design approaches that integrate system design and cost optimization to minimize the LCoE.	The review highlights energy maximization but does not adequately address minimizing the LCoE, which is critical for the economic feasibility of OWC devices.

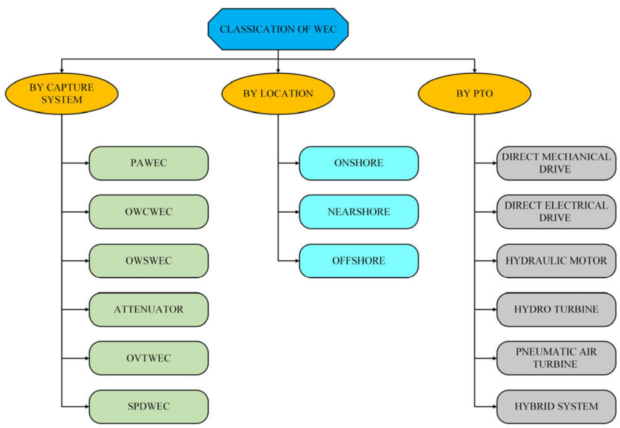

FIGURE 1. Classification of WEC.

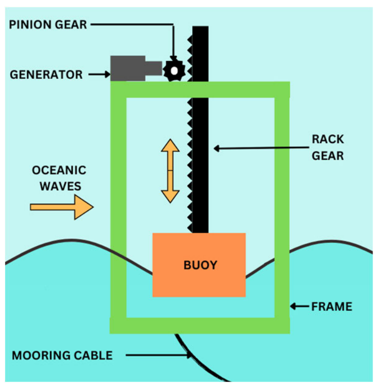

FIGURE 2. Schematic diagram of PAWEC.

end below the water surface, allowing water to enter and exit, FIGURE 4. The air that is trapped inside the chamber is constantly in a state of compression and expansion caused by the swash and backwash of the waves on the shoreline, respectively. This bidirectional airflow is used to drive a turbine which is located above the surface at the other end of the OWCWEC. The turbine is connected to a generator that converts the rotational energy into clean electrical energy.

Generally, Wells turbine is chosen due to its ability to perform rotation in both directions of airflow. There are two types of OWCWECs: fixed and floating. [5] The fixed OWCWECs are installed onshore incorporated with breakwaters. The floating OWCWECs include the BBDB [6] and spar-buoy [7].

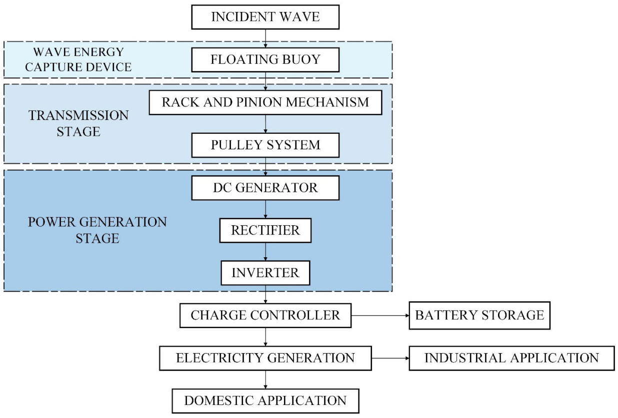

FIGURE 3. Energy flow diagram for a PAWEC.

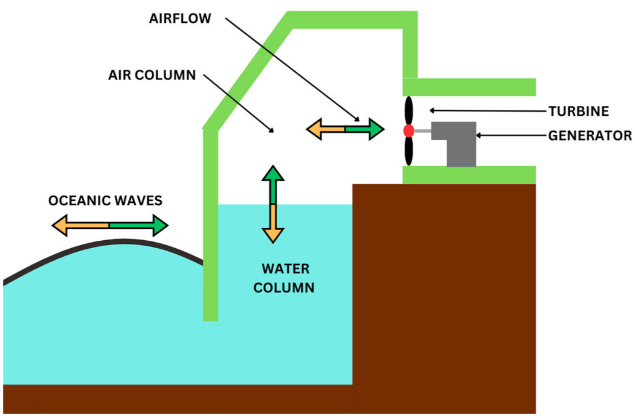

FIGURE 4. Schematic diagram of OWCWEC.

- **OWSWEC:** OWSWEC (also known as terminator) is a structure with one hinged to the ocean bed and the other end is free to move. Either the OWSWEC can be installed near the shore in relatively shallow waters, where it can be partially or fully submerged in water according to the requirement. The swash and backwash cause the OWSWEC pivot and oscillate with the wave motion. This drives the generator to rotate and harness power from the waves. FIGURE 5 shows how the OWSWEC functions. The OWSWEC works only when the direction of the waves is perpendicular to it.
- **ATTENUATOR**: An attenuator is a floating type of WEC which harnesses the wave energy by operating in parallel to the wave direction unlike the OWSWEC which operates perpendicularly to the wave direction. The attenuator consists of several connected segments that flex and bend with the movement of the waves. As the waves pass along the length of the attenuator, the segments move relative to each other, creating mechanical energy from this motion. The attenuator requires a mooring system to secure it from floating away in the ocean. **FIGURE 6** shows how the attenuator functions.
- **OVTWEC:** OVTWEC is a device that harnesses wave energy by directing the waves into a reservoir situated above the sea level, **FIGURE 7**. As the waves approach the OVTWEC, they overtop the wall, hence filling up the reservoir above the sea level. Now the captured ocean water being at a higher potential is then gradually released back into the sea through a turbine. The turbine converts the potential energy of the stored ocean water into mechanical energy which is then converted into clean energy via a generator. Due to this kind of principle implemented the OVTWEC efficiently harnesses wave energy and provide a steady flow of power. Wave Dragon is a very popular example of OVTWEC [8].
- **SPDWEC:** The SPDWEC harnesses energy from the ocean waves by the pressure variations beneath the water's surface, FIGURE 8. The SPDWEC is anchored underwater, as waves travel in the ocean, the difference in pressure causes the device to oscillate and produce clean energy from the ocean. This energy is then transmitted to shore via underwater cables. Archimedes Wave Swing is a popular example of SPDWEC [9].

B. CLASSIFICATION OF WEC BASED ON LOCATION SYSTEM

The WECs are classified into three types, FIGURE 9:

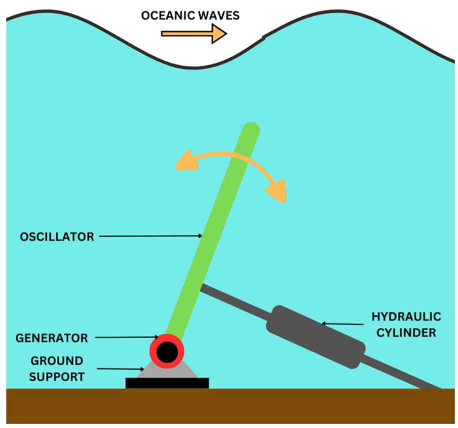

FIGURE 5. Schematic diagram of OWSWEC.

1) Onshore WECs are engineered to be installed on the shoreline, utilizing breaking waves to generate power. However, they face reduced wave energy and potential environmental impacts.
2) Near shore WECs are installed in shallow waters where the depth ranges from 10-25m, offering stronger wave energy than onshore systems while remaining relatively accessible.

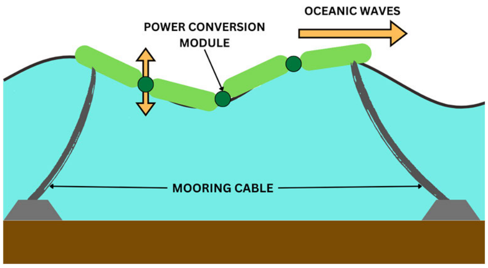

FIGURE 6. Schematic diagram of attenuator.

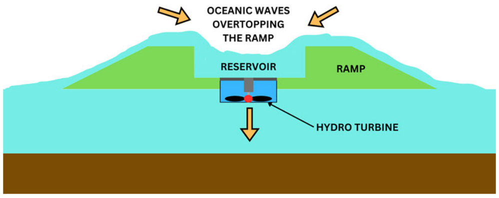

FIGURE 7. Schematic diagram of OVTWEC.

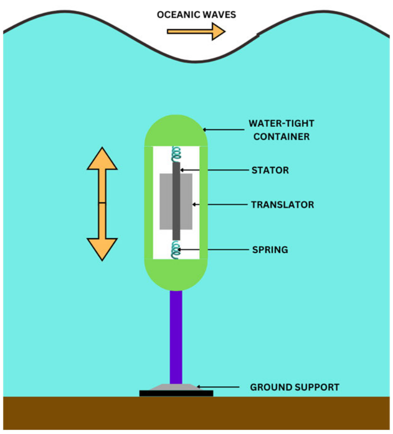

FIGURE 8. Schematic diagram of SPDWEC.

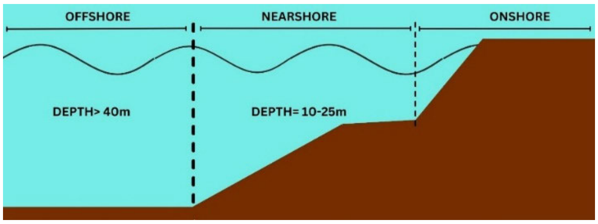

FIGURE 9. Classification of WECs based on location.

3) Offshore WECs are installed deep in the ocean where the depth is greater than 40m, harnessing powerful, consistent wave energy. These systems are costly and complex to install and maintain due to specialized mooring and cabling, they provide high energy output.

C. CLASSIFICATION OF WEC BASED ON PTO SYSTEM

The PTO system is classified in 6 different categories based on their working principle shown in FIGURE 10 and the working principle of each type is explained below.

- **HYDRAULIC MOTOR SYSTEM**

A hydraulic motor system in WECs uses wave motion to drive a pump, pressurizing hydraulic fluid. This pressurized fluid powers a hydraulic motor, which drives a generator to produce electricity. The hydraulic motor system is considered one of the most suitable PTO mechanisms for converting wave energy into electricity [105].

- **PNEUMATIC AIR TURBINE TRANSFER SYSTEM**

A pneumatic air turbine transfer system is another widely recognized type of PTO system for WECs. Typically, these systems use compressed air to drive turbines, which are directly connected to generators to produce electricity.

- **HYDRO TURBINE TRANSFER SYSTEM**

A hydro turbine transfer system uses compressed water to power a hydro turbine, which subsequently drives a generator to produce electricity.

- **DIRECT MECHANICAL DRIVE SYSTEM**

The direct mechanical drive PTO system consists of components such as racks and pinions, slider cranks, screw mechanisms, belt transmissions, belt pulleys, or unidirectional bearings. Harnessing the energy of an oscillating body, this drive system operates through a mechanical setup, including a pulley and gearbox, which drives a rotating electrical generator.

- **DIRECT LINEAR ELECTRICAL DRIVE SYSTEM**

The direct linear electric drive PTO system converts the wave energy directly into electricity using a linear generator, eliminating the need for intermediate mechanical components. The translator, connected to the heaving buoy, moves vertically with the waves, inducing an electrical current in the generator coils.

- **HYBRID SYSTEM**

Integrating multiple renewable energy sources such as solar, wind, and wave energy into a single unit is an emerging concept gaining traction among researchers, who are developing and experimentally testing systems to optimize power capture. Depending on the region and ocean conditions, various configurations such as solar-wave, wind-wave, or solar-wind-wave systems can be designed. Additionally, TENGs provide a promising method for harnessing mechanical energy by leveraging the triboelectric effect and electrostatic induction. The triboelectric effect, also known as contact electrification, occurs when two different materials come into contact, causing electrons to transfer between them and generating opposite static charges on their surfaces. This creates an electrical potential through mechanical motion, which can be stored or utilized to power devices.

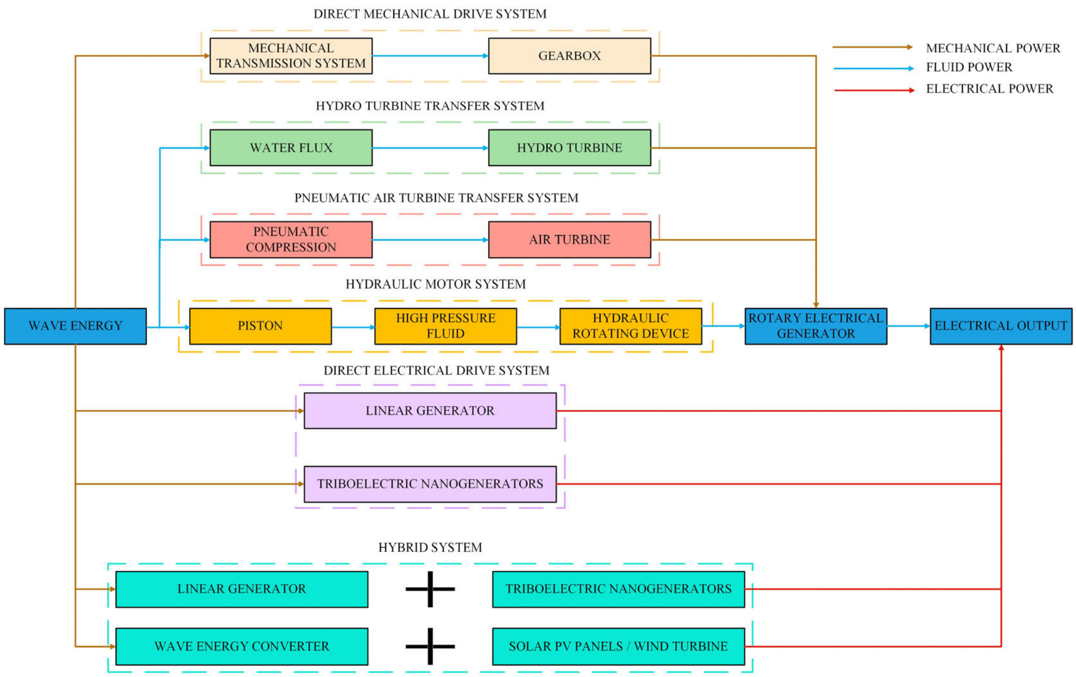

FIGURE 10. Classification of WECs based PTO systems.

D. TYPES OF TURBINES

1) Different types of air turbines are classified in FIGURE 11.

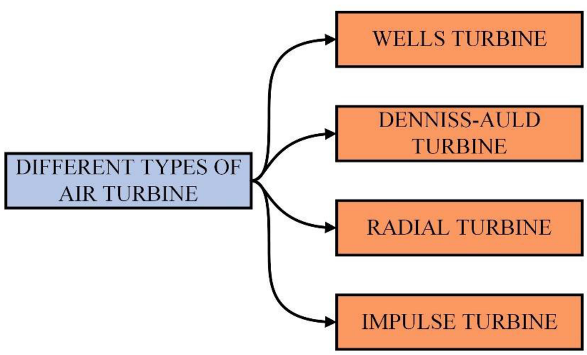

FIGURE 11. Classification of Air Turbine.

2) Different types of hydro turbine are classified in FIGURE 12.

A list of various kinds of linear generators and rotational generators used for the PTO systems are tabulated in TABLE 2.

III. POINT ABSORBER WAVE ENERGY CONVERTER

A. RECENT DEVELOPMENTS, VARIOUS DESIGN INNOVATIONS, AND PERFORMANCE OPTIMIZATION TECHNIQUES

Recent works by various researchers across the globe in PAWECs have focused on improving hydrodynamic efficiency through various computational software such as NEMOH, REEF 3D, MATLAB, WEC-Sim and

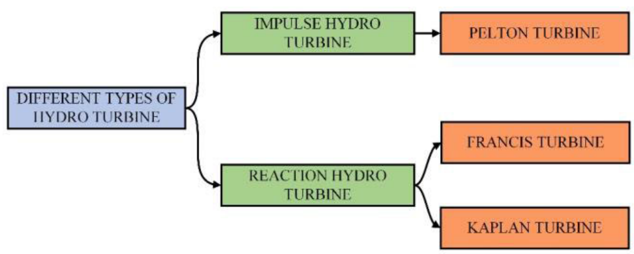

FIGURE 12. Classification of Hydro Turbine.

DualSPHysics. Researchers have also focused on developing several numerical models on PAWEC and wave characteristics to have a better understanding of the physics involved. The compiled work of various researchers in the TABLE 3 provides a comprehensive overview of these technological advancements and their impact on PAWEC performance. Hydrodynamic coefficients are commonly derived using fast computational simulations with BEM software, including ANSYS-AQWA [33], [34], [35], [38] and WAMIT [13], [15], [23]. The software's are based on the boundary element method (BEM) and linear potential flow theory, solving hydrodynamics around the PAWEC's boundaries using only a boundary mesh, making it relatively fast and efficient. A key advantage of utilizing WAMIT for numerical analysis is its ability to utilize the high-order BEM for enhanced computational performance.

B. BOUNDARY CONDITION CONSIDERED FOR PAWEC

A 3D numerical wave tank with a push board wave maker and sponge layer is used, with the model placed at optimal

TABLE 2. Classification of generator.

Permanent Magnet Linear Generator	Rotational Generator	
	Induction Type	Synchronous Type
1) Longitudinal Flux		
2) Variable Reluctance	1) Doubly fed	3) Permanent Magnet
3) Tubular Air-cored	2) Squirrel Cage	4) Field Wound

distances. Symmetry boundaries ensure zero-gradient and zero-velocity conditions. Grid resolution is less than the length and incident wave amplitude, with time steps of 0.001s (initial) and 0.000001s (minimum) for temporal accuracy [11]. Another study assumes a wave period of 2 to 14 seconds and an element size of 1 m as mesh properties [25]. Utilizing the Pierson-Moskowitz spectrum, a significant wave height of 4.06 m and a peak wave period of 13.65 seconds are determined, simulating waves with a 2 m height and a period of approximately 13 seconds [26]. The BBDB SolidWorks model was designed with dimensions of 0.85 m × 0.565 m × 0.6 m. The point absorber's SolidWorks design featured a conical shape with a bottom chamfer angle of 45°, maintaining a distance of 0.185 m between the buoy's bottom surface and the water surface [34]. Mesh convergence tests on seven meshes were conducted before nonlinear WEC modeling to ensure the accuracy of hydrodynamic coefficients from AQWA. Meshes 1–4 used decreasing element sizes for both buoys, while meshes 2,5,6 and 7 varied the outer buoy's mesh size, fixing the inner buoy's at 0.03 m. The minimum element size was 0.005 m, and heave amplitude assessed convergence. The inner buoy's heave amplitude was unaffected by mesh size, but the outer buoy showed strong mesh dependence. Convergence was achieved by mesh 4, and a maximum element size of 0.02 m was applied for further analyses [39].

The number of times different platforms used for numerical investigations and simulations for improving the performance of PAWECs are shown in **FIGURE 13.**

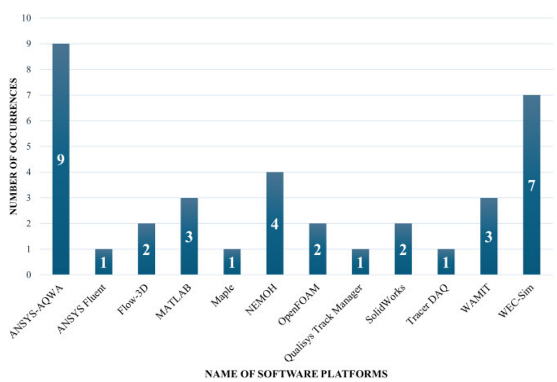

FIGURE 13. Number of occurrences of different platforms utilized for numerical investigations and simulations for PAWEC.

C. LIST OF PAWEC INSTALLED WORLDWIDE

A year wise list of the PAWECs installed throughout the globe, along with their PTO system, installed capacity, location and country is compiled in the TABLE 4.

D. BENEFITS OF PAWEC

The design of PAWEC is pretty straightforward with lesser moving parts when compared to other types of WECs. This helps in reducing the installation time, manufacturing costs, maintenance, and easier deployment. The major advantage that PAWEC holds is its ability to harness wave energy irrespective of the direction of the waves, making it efficient and omnidirectional in various sea conditions. It can be deployed individually or in arrays, depending on the location and energy requirement in that area. PAWEC are designed to withstand harsh marine environments, which enhances their operational lifespan and reliability. The simple design allows for easier access and maintenance when compared to other WECs. The device can be designed to operate efficiently in various wave climates, making it adaptable to different geographic locations and wave conditions. It is generally deployed nearshore or offshore, which minimizes its impact on shorelines and coastal habitats. This is particularly beneficial for preserving coastal ecosystems. The deployment, maintenance, an operation can create jobs in coastal regions, including roles in engineering, construction, and marine services. Since the FPAWEC is floating on the surface of water we can incorporate other renewable energy technologies such as PV panels and VAWT on top of it. This can help in harnessing the maximum amount of renewable energy and supply to the coastal regions. A battery swapping station can be installed directly on the device, simplifying power transmission, and potentially reducing infrastructure costs. This helps in eliminating the use of long underwater cables connecting to the onshore power stations. Since the FPAWEC is not installed on the seabed this helps in preserving the marine ecosystem and natural coral reefs which serve as a home to many marine's lives. Due to the deployment of several PAWECs in an array we can collect the precise data of the oceanic currents throughout the year which helps in predicting the weather patterns and warnings of natural disasters. The FPAWEC can serve as local charging stations for electric boats and as a backup during emergencies caused by natural disasters. They can also work as a standalone system for remote islands where the transmission of electricity through conventional means is not at all feasible.

IV. OSCILLATING WATER COLUMN WAVE ENERGY CONVERTER

A. RECENT DEVELOPMENTS, VARIOUS DESIGN INNOVATIONS, AND PERFORMANCE OPTIMIZATION TECHNIQUES.

Recent works by various researchers across the globe in OWCWECs have focused on improving hydrodynamic

TABLE 3. Comprehensive review of the recent works on PAWEC.

Year Author(s) Reference	Recent Developments, Various Design Innovations, and Performance Optimization Techniques in PAWEC	Platform Utilized
2019 Vijayasankar and Samad [10]	Proposed a new design of a PAWEC with a mechanical driven PTO system. A numerical analysis on the design was performed using WEC-Sim software. They were successful in determining the improved efficiency of the proposed design numerically and experimentally.	WEC-Sim
2019 Hongda Shi et al. [11]	Proposed the optimized design of a conical-bottom floating buoy. They implemented different PTO systems during the CFD simulation which was a two-phase VOF model. Numerical study was performed on the different mass of the conical-bottom floating buoy.	Flow-3D
2019 Rezvan Alamian et al. [12]	Conducted a multi-criteria optimization of the pitch of PAWEC according to the characteristics of waves occurring in the Caspian Sea.	NEMOH
2019 Scott J. Beatty et al. [13]	Performed a numerical and experimental comparison of two self-reacting PAWEC designs for heave motions in irregular waves, utilizing 1:25 scaled model tests with customizable shapes of body of the WEC.	WAMIT
2019 Sung-Jae Kim et al. [14]	Investigated the performance of a hemispherical PAWEC combined with a hydraulic based PTO system.	Real-Time Experimentation
2020 Ruriko Haraguchi and Asai [15]	A novel PAWEC with a tuned inertial mass was proposed. The aim of designing the model was to increase the energy absorbed and broaden the bandwidth significantly. Numerical investigation on the power generated by the proposed PAWEC with the tuned inertial mass was conducted in irregular sea condition.	WAMIT
2020 Xu and Soares [16]	Assessed the performance of two mooring systems (slack mooring and a hybrid mooring) by a hydrodynamic model.	Real-Time Experimentation
2020 Benjamin W. Schubert et al. [17]	A study on hydrodynamic effects on a submerged CETO-shaped PAWEC comparing the fully-nonlinear, pseudo-nonlinear, partially nonlinear, and linear methods was performed.	OpenFOAM NEMOH MATLAB
2020 Eirini Katsidoniotaki et al. [18]	Utilized the OpenFOAM CFD software to study the extreme forces acting on the PAWEC and its dynamic response to it.	OpenFOAM
2020 Yong Ma et al. [19]	Established a heave motion model for a two-body FPAWEC was established. ANSYS-AQWA software was further developed using Fortran programming to account for the PTO effect, enabling the motion simulation of the two-body FPA wave energy converter.	ANSYS-AQWA
2021 Ji Tao et al. [20]	Performed a time domain analysis of three separate PTO systems of a PAWEC in which they considered viscosity into the Morison's equation in irregular movement of the waves and the power harnessed is studied.	WEC-Sim ANSYS-AQWA Flow-3D
2021 Yubin Jia et al. [21]	Proposed an EMPC framework to tackle the constrained optimization problem in WEC systems.	Real-Time Validation
2021 Motohiko Murai et al. [22]	A numerical study on single PAWEC and arrayed PAWEC was performed. They provided methods optimizing the control force parameters such as array arrangements, hydrodynamic interactions, diffraction hydrodynamic interactions, and wave incident angles for the arrayed PAWEC.	Real-Time Validation
2021 Asai and Sugiura. [23]	Proposed a two-body PAWEC with a tuned inerter to increase the amount of energy harnessed from the ocean waves. Their numerical calculations in WAMIT software achieved an 88% higher power generated when compared to the conventional PAWEC.	WAMIT
2021 Piscopo and Scamardella. [24]	A completely different type of PAWEC in the shape of a toroid is proposed.	NEMOH
2022 Prashant Kumar et al. [25]	Presented a specifically optimized model of a PAWEC for deploying it in the Bay of Bengal, near Ennore Port, India. They considered the parameters such as amplitude, significant wave height and time period of the waves based on the data collected by reliable sources.	SolidWorks ANSYS-AQWA
2022 Erfan Amini et al. [26]	Conducted a study aiming to optimize the PTO system parameters of a PAWEC based on wave data from Perth, Western Australian coasts, employing ten optimization approaches to identify the settings that yield the highest power output.	WEC-Sim
2022 Ammar Ahmed et al.	Proposed innovative bulbous-bottomed buoy designs for optimal oscillating-body wave energy converters, demonstrating through frequency-domain analyses and spectral modeling in	ANSYS-AQWA

TABLE 3. ***(Continued.)*** **Comprehensive review of the recent works on PAWEC.**

[27]	ANSYS-AQWA that these designs can achieve 28.1% higher absorption efficiencies compared to non-bulbous shapes.	
2022 Benjamin W. Schubert et al. [28]	Simulated a spherical shaped PAWEC in both submerged and floating conditions for irregular and regular waves, optimizing the linear control parameters.	NEMOH
2022 Ken-Ichiro Yamashita et al. [29]	Proposed a novel PAWEC which utilizes a Magnus effect driven turbine generator.	MATLAB Simulink
2023 Guohui Zhou et al. [30]	Simulated a 1:13.75 model of the "Wanshan" with a maximum capture ratio of 37.7% which is equivalent to the efficiency obtained from the "Wanshan" deployed in the waters of Dawanshan, Guangdong Province, in April of 2017.	Real-Time Experimentation
2023 Vishnu Vijayasankar et al. [31]	Performed PTO damping test, Decay tests, radiation tests, Diffraction tests on a 1:2.2 model of a unique PAWEC equipped with an AMP and unidirectional rotation of the motor. They got a 9.34 W of power with the AMP and 7.12 W of power without the AMP in similar conditions. These findings matched with the ones obtained from numerical analysis.	WEC-Sim AQWA
2023 Suman Kumar et al. [32]	A two-body floating PAWEC of 1:3.3 laboratory scaled model was developed at WEFEL, IIT Madras to calculate the hydrodynamic coefficients acting on the PAWEC. At a significant wave height of 0.15m and peak period of 2.5s they got the highest excitation force of 400N.	WEC-Sim
2023 Aiswaria and Ramakrishnan. [33]	A spherical PAWEC integrated with a chambered breakwater was developed at the Ocean Engineering Laboratory, IIT Bombay and Qualisys motion capture system was utilized to capture the heaving motion of the PAWEC in a variety of wave conditions.	SolidWorks ANSYS-AQWA WEC-Sim Qualisys Track Manager Tracer DAQ
2023 Muhamad Aiman Jalani et al. [34]	Investigated effects of a BBDB with PAWEC on power absorption and heave response amplitude operator across several wave conditions using ANSYS-AQWA.	ANSYS-AQWA
2024 Alejandro Martinez Flores et al. [35]	Three designs of floating buoy used in a floating buoy WEC were designed to improve the energy harnessed from the ocean. ANSYS-AQWA software is used to calculate the frequency and time domain of the three float designs. Their findings showed the power output captured annually by the proposed float design was 135.11 MW.	ANSYS-AQWA
2024 Yu Gao et al. [36]	Aimed to enhance the efficiency of energy captured by the PAWEC by integrating a coupled linear-bistable mechanism.	Real-Time Validation
2024 Ataollah Gharechae et al. [37]	Aimed to equip a cage's floater with PAWEC to harvest energy and reduce its heaving motions in the regular and linear condition of waves.	Maple
2024 Zitti and Brocchini. [38]	Proposed a detailed numerical study of a self-reacting floating PAWEC, similar to PB3 PowerBuoy, for potential installation in the Adriatic Sea.	ANSYS-Fluent ANSYS-AQWA MATLAB
2024 Demin Li et al. [39]	Developed a numerical model of two-buoy and single-buoy FPAWEC using a modified nonlinear version of WEC-Sim.	WEC-Sim

efficiency through various computational softwares such as REEF 3D, OpenFOAM, WEC-Sim and DualSPHysics. Researchers have also proposed unique designs and experimentally tested the water column to maximize the energy harnessed by the OWCWEC. The compiled work of various researchers in the TABLE 5 provides a comprehensive overview of these technological advancements and their impact on OWCWEC performance.

B. OUNDARY CONDITION CONSIDERED FOR OWCWEC

Monochromatic waves with periods ranging from 0.8 to 2.8 s (at 0.2 s intervals) were generated in the numerical simulation, covering all periods from the experimental study, including T = 0.8 to account for resonance phenomena. Three wave heights (0.02, 0.04, and 0.06 m) were applied for each wave period, as in the experimental test plan. The simulation utilized a final mesh with a base cell size of 0.0025 m, comprising approximately 400,000 cells with local refinement near the slot. The simulation domain was defined as a box with dimensions 5.00 m × 0.006 m × 1.42 m, with the initial free surface elevation at 0.42 m from the flume bottom [66]. Expanding on boundary conditions, two geometries were analyzed: one with the pneumatic chamber fully open to the atmosphere (Geometry I) and another with the chamber connected to a turbine duct (Geometry II). In Geometry II, a horizontal bottom extension of 200 m was added in front of

TABLE 4. List of PAWEC installed worldwide.

Year	Name of WEC	Type of PTO	Installed Capacity	Location (Onshore/ Offshore/ Nearshore)	Country	Reference
2003	AquaBuOY 2.0	Hydro-Turbine PTO	250 kW	Offshore	Ireland-Canada-Scotland	[40,41]
2004	Manchester Bobber	Mechanical PTO	5 MW	Offshore	UK	[40,42]
2006	SEAREV	Hydraulic PTO	0.5 MW	Offshore	France	[43,44,45]
2006	FO3	Hydraulic PTO	2.52 MW	Nearshore	Norway	[40,46]
2008	Oregon L10	Hydro-Turbine PTO	10 kW	Offshore	USA	[47]
2009	WaveStar	Hydro-Turbine PTO	600 kW	Offshore	Denmark	[48]
2012	WaveNet	Hydraulic PTO	7.5 kW	Offshore	Scotland	[49,50]
2013	Wavebob	Hydraulic PTO	1 MW	Offshore	Ireland	[40,51]
2014	OPT Powerbuoy	Mechanical PTO	40 kW	Offshore	UK	[52,53]
2014	UNDIGEN	Direct-Drive PTO	200 kW	Offshore	Spain	[40,54]
2014	WaveSurfer	Mechanical PTO	1 kW	Offshore	USA	[55]
2015	CETO	Hydraulic PTO	1 MW	Offshore	Australia	[56]
2015	SINN Power	Hydro-Turbine PTO	3 kW	Nearshore	Greece	[57]
2016	Triton	Mechanical PTO	600 kW	Offshore	USA	[58]
2019	1:30 scale LAM WEC	Mechanical PTO	200 kW	Offshore	Scotland	[59,60]
2017	Wello Penguin	Rotary Generator	0.5–1 MW	Offshore	Finland	[61]
2021	CalWave	Hydraulic Motor System	1 kW	Offshore	USA	[62]
2024	CorPower	Mechanical PTO	10 MW	Offshore	Portugal	[63]

the wavemaker, while the remainder of the wave propagation domain mirrored Geometry I.

The OWC top was connected to a turbine duct, centered on the OWC, with dimensions of 0.75 m in width and 3 m in height [64]. Further refinements in boundary conditions included imposing turbulence kinetic energy and dissipation rates of 10-6 m2/s2 and 10-6 m2/s3, respectively, on the top boundaries of the flume and chamber. Initial conditions featured a free surface at rest (10 m depth), zero velocity components, hydrostatic pressure in water, and atmospheric pressure in air. The Cartesian mesh was designed with 70 elements per wavelength horizontally, incorporating refined regions near the static wave maker (1 m elements) and chamber (0.125 m elements). Intermediate zones featured a gradual variation in element sizes, while vertical meshing employed 25 elements per wave height near the free surface, with sizes gradually increasing toward the top boundary and maintained at the bottom [73]. For 3D simulations, a scaled model domain replicating an NWT with dimensions 11.250 m $\times$ 9.000 m $\times$ 1.200 m was utilized. Linear waves with a constant height of 0.100 m and periods ranging from 1.1 s to 2.5 s (in 0.1 s increments) were analyzed. These waves corresponded to full-scale wave periods of 5 to 10 s, representative of typical low-energy sea state conditions [74]. Numerical setup for a 2D wave flume measuring 45.0 m in length with a water depth of 1.25 m. The flume width was represented by a single cell of 0.01 m. Relaxation zones, each spanning one wavelength (8.0 m), were added at the inlet and outlet to absorb reflected waves, using the highest wavelength of the simulated cases as a reference [81]. A CFD-NWT model was implemented, measuring 20 m in length and consisting of approximately 450,000 cells. No-slip boundary conditions were applied at the NWT bottom and OWC sidewalls, while the water surface was treated as an atmospheric pressure boundary. The free surface area mesh resolution was set to approximately 12 cells per wave height, with a maximum aspect ratio of 2. Careful refinement of the mesh ensured accuracy in the simulations [91]. The number of times different platforms used for numerical investigations and simulations for improving the performance of OWCWECs are shown in Figure 14.

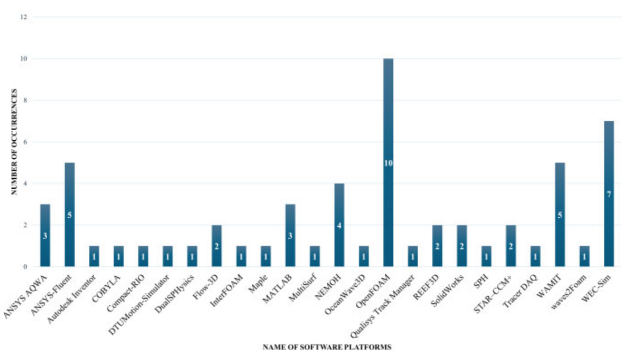

FIGURE 14. Number of occurrences of different platforms utilized for numerical investigations and simulations for OWCWEC.

TABLE 5. Comprehensive review of the recent works on OWCWEC.

Year Author(s) Reference	Recent Developments, Various Design Innovations, and Performance Optimization Techniques in OWCWEC	Platform Utilized
2019 J.M.P. Conde and M.B.S.P. Condeço. [64]	Simulated the waves and airflow of the Mutriku power station located in Spain in the OpenFOAM software and verified the results obtained with the FLUENT code.	OpenFOAM FLUENT
2019 Zhengzhi Deng et al. [65]	Experimental and numerical calculations of the hydrodynamic behavior of a new design of an OWCWEC with a horizontal bottom plate were investigated.	OpenFOAM waves2Foam
2019 K. Rezanejad et al. [66]	Investigated the primary efficiency of OWCWEC under stepped sea bottom conditions numerically and experimentally.	OpenFOAM
2019 Rui P. F. Gomes et al. [67]	Proposed the hydrodynamic optimization of a floating OWCWEC known as the OWC spar buoy device, characterized by its axisymmetric geometry and a draft significantly larger than its horizontal dimension.	REEF3D
2019 S. John Ashlin et al. [68]	Field measurements and an analytical model of the oscillation of the air pressure and water surface were verified against a numerical model inside the air chamber of an UOWC.	REEF3D
2020 Damon Howe et al. [69]	Hydrodynamic experimentation on a model scale of a π-type floating breakwater integrated with multiple OWCWEC to verify its performance.	Real-Time Validation
2020 Koley and Trivedi. [70]	A numerical and mathematical model was developed for an OWCWEC positioned on an undulated bed to verify the hydrodynamic performance.	MATLAB
2020 J.C.C. Portillo et al. [71]	Two types of OWCWECs: spar-buoy and coaxial-duct, were designed and tested experimentally on smaller-scale versions to accurately simulate the real-world conditions observed in fully-scaled models.	Real-Time Experimentation
2020 M. Gradowski et al. [72]	Investigated the resonance frequency of a Floating OWCWEC which is primarily dependent on the added mass of its OWC. To reduce the costs, they proposed reducing the length of the spar tube while finding alternative ways to achieve the desired OWC added mass.	WAMIT COBYLA
2020 Lucas A. Gaspar et al. [73]	Two types of OWCWECs with different front and back wall slopes were numerically analyzed to verify the performance individually.	FLUENT
2021 Robert Mayon et al [74]	Proposed a unique cylindrical shaped OWCWEC and a parabolically shaped wave reflector, achieving a substantial breakthrough in hydrodynamic performance.	OpenFOAM
2021 Zhen Liu et al. [75]	Established an integrated numerical model that incorporates both the self-rectifying and air chamber turbine, which links several energy-conversion stages.	ANSYS-Fluent
2021 Chen Wang et al. [76]	Proposed the concept of a dual-chamber OWCWEC with a pitching front lip-wall.	Real-Time Validation
2021 Xuanlie Zhao et al. [77]	The hydrodynamic performances of single-, dual- and triple chambered OWCWEC were experimentally investigated.	Real-Time Experimentation
2021 Nicolas Quartier et al. [78]	A numerical modelling of an OWCWEC using DualSPHysics software was studied.	DualSPHysics
2022 A.K. Güths et al. [79]	Proposed a new design for OWCWEC by which they aim to have improved efficiency compared to the conventional design of OWCWEC.	FLUENT
2022 Mandev and Altunkaynak. [80]	Proposed and experimented on a new type of OWCWEC with a streamlined chamber where they got a 31% higher power output when compared to the conventional OWCWEC.	Real-Time Experimentation
2022 Gadelho and Soares. [81]	A numerical study on the CFD of a dual chamber floating OWCWEC using wave flume model was presented.	OpenFOAM

TABLE 5. ***(Continued.)*** **Comprehensive review of the recent works on OWCWEC.**

2022 S.R. Durai Eswaran et al. [82]	To concentrate the oceanic wave energy within a finite depth from the surface a horizontal plate is incorporated for inducing wave shoaling. They experimentally studied the optimal plate length for efficient shoaling and fixed an OWC over the plate which resulted in a 10% increase in hydrodynamic efficiency.	Real-Time Experimentation
2022 Trivedi and Koley. [83]	A time domain analysis of QCS OWCWEC was investigated to understand its working mechanism. The study showed that the OWCWEC could harness and hold the oceanic wave energy for a longer duration.	Real-Time Validation
2023 Bárður Joensen et al. [84]	Evaluated the hydrodynamic performance of an OWCWEC, focusing on evaluating conventional two-way energy capture to one-way energy capture, where only the down-stroke or up-stroke is used to rotate the turbine.	MultiSurf WAMIT DTUMotion-Simulator
2023 by Chen Wang et al. [85]	CFD simulations were conducted on an array of 5 identical OWCWEC integrated into a breakwater to analyze the power harnessed from the waves.	STAR–CCM+ OpenFOAM
2023 Guixun Zhu et al. [86]	Conducted extensive computational tests to study the effects of geometrical parameters on the wave loading and the hydrodynamic performance of the UOWC incorporated with a breakwater.	SPH OceanWave3D
2023 Afsaneh Shahsavarizadeh et al. [87]	Investigated the performance of offshore OWCWEC by applying three physical models with a scale of 1:60, three submergence depths, and six wave frequencies under different conditions.	Real-Time Experimentation
2023 Antonio Martín-Alcántara et al. [88]	Investigated a novel idealized system based on an inverted OWC immersed in a mass of water as a potential mechanism for energy storage. Their system consisted of a cylindrical tube divided into two chambers by a moving disc.	Real-Time Validation
2024 Rohaizad Hafidz Rozali et al. [89]	Aimed to understand how the air duct design influences the power harnessed by an OWCWEC.	Autodesk Inventor CFD
2024 R. Manimaran. [90]	The objective was to compare CWR, and pressure drop between rectangular and trapezoidal OWCWECs in both tandem and single configurations.	OpenFOAM InterFOAM
2024 Vaibhav Raghavan et al. [91]	Proposed a new framework utilizing input from a high-fidelity nonlinear numerical model to enhance the accuracy for fixed type of OWCWEC, simultaneously keeping minimum computational costs.	OpenFOAM
2024 Yong Cheng et al. [92]	Introduced an integrated concept involving long floating breakwater and multiple OWCWECs in their study. They examined hydroelastic interaction problems, gap resonance and associated energy extraction.	Star-CCM+
2024 J.F.M. Gadelho et al. [93]	Utilized a wave flume to investigate a scaled model of a stepped bottom dual-chamber OWCWEC installed onshore.	Compact-RIO

C. LIST OF OWCWEC INSTALLED WORLDWIDE

A year wise list of the OWCWECs installed throughout the globe, along with their installed capacity, location and country is compiled in the TABLE 6.

D. BENEFITS OF OWCWEC

The turbine rotor being the only moving part of the OWCWEC, additionally being situated above sea level makes it convenient during the installation process and regular maintenance of the OWCWEC. The high rotational speed of the turbine eliminates the installation of a gearbox significantly reducing the overall cost of the converter [5]. The OWCWEC experiences the least stresses and forces when compared to the other WECs, this is because the OWCWEC indirectly harnesses the wave energy from the air. The spring like effect of the air significantly reduces the structural stress and fatigue experienced by the PTO system [5]. OWCWEC can use a valve in series with the turbine for peak shaving control. This helps maintain power production over a broader range of oceanic wave conditions. An alternative, though less effective, method is utilizing a bypass valve in parallel with the turbine to limit the available power [5]. The OWCWEC can be installed at an existing breakwater in coastal regions. This can significantly help in reducing the construction and maintenance costs [97].

TABLE 6. List of OWCWEC installed Worldwide.

Year	Name of OWCWEC	Installed capacity	Location (Onshore/ Nearshore/ Offshore)	Country	Reference
1987	Kvaerner Multiresonant	500 kW	Onshore	Norway	[94,95]
1991	Vizhinjam	125 kW	Onshore	India	[96,97]
1992	Sakata	60 kW	Nearshore	Japan	[95,98,99]
1998	Mighty Whale	110 kW	Offshore	Japan	[100,101,102]
200`0	LIMPET	500 kW	Onshore	Island of Islay, Scotland	[95,103]
2001	Guangdong OWC	100 kW	Onshore	China	[104]
2005	Pico	400 kW	Onshore	Portugal	[95,105]
2005	Port Kembla	500 kW	Nearshore	Australia	[106]
2010	Oceanlinx Mk3	2.5 MW	Offshore	Australia	[95]
2011	1:4th-scale BBDB (OE BUOY) OWC	1750 KW	Offshore	Ireland	[107,108]
2014	Oceanlinx greenWAVE	1 MW.	Onshore	Australia	[109]
2015	Bottom-Standing Plant	500 kW	Nearshore	South Korea	[95]
2015	1:10 scale LEANCON	600 kW	Offshore	Denmark	[110]
2019	Wave Swell	200 kW	Nearshore	Australia	[111]

V. CONCLUSION AND FUTURE SCOPE

In this article, a detailed review was conducted on the recent developments, various design innovations, and performance optimization techniques of the PAWEC and OWCWEC. The paper emphasizes the importance of numerical modeling, experimental analysis on laboratory scaled models, and hydrodynamic performance simulations using software such as WEC-Sim, NEMOH, REEF 3D, DualSPHysics, OpenFOAM, ANSYS-AQWA, and WAMIT. These approaches are crucial for enhancing device efficiency, improving survivability, and reducing costs of developing prototypes.

Additionally, a list of all the installed PAWEC and OWCWEC were tabulated in a year wise format along with their installed capacities, location of deployment and the country of deployment. The analysis of the classification of WECs shows that the WEC can be classified into six categories based on capture system, three categories based on location and also six categories based on PTO systems. The PAWEC and OWCWEC are the most popular WEC because of their simple design and higher energy captured efficiencies from the ocean waves.

Numerous countries around the globe are actively working on technologies to harness wave energy. This is because of its huge potential to eradicate the use of conventional sources of energy and to reduce the carbon emissions caused by the burning of fossil fuels. In conclusion, wave energy possesses substantial power potential, but the technologies to harness it are still in the developmental stages. Consequently, the findings are summarized as follows:

- The selection of an appropriate WEC mainly depends on various factors, such as wave energy density, depth of ocean bed, weather, government policies, etc.
- Choosing an optimal PTO system depends on the size, shape and installed capacity of the WEC. Generally, most WECs have one of the three following PTO systems: direct-mechanical drive type, hydro-turbine type, or hydraulic motor type.
- Researchers in recent years focused on offshore type converters due to a higher wave energy available deep inside the ocean when compared to onshore and nearshore types.
- Wave energy plays a crucial role especially for the sustainable development of remote islands where transmission of electricity is economically not a viable option. This helps in meeting the electricity demands and promoting tourism.
- Countries like USA, Scotland, Australia, and Japan have been leading in the research and development of different and unique types of WECs. India, with its long peninsular coastline, has an immense potential to harness energy from the ocean. By investing into wave energy technologies, India can significantly diversify its energy mix, reduce dependence on fossil fuels, and move towards sustainable energy solutions. Additionally, the development of WECs can spur economic growth, create jobs in coastal regions, and contribute to the country's goals of reducing greenhouse gas emissions and combating climate change.

To encourage further research in this field, the following perspectives are proposed based on an in-depth review of the literature and future development trends:

- Integrating WECs with PV and VAWT on shared platforms can optimize performance but requires effective control strategies to manage hydrodynamic interactions and ensure stability.

- Developing and integrating AI algorithms onboard the WECs can help predict the weather patterns, fault diagnosis, and optimize energy capture in real time.
- Development of corrosion resistant materials that can counter the harsh effects of the like dissolved oxygen, pressure, and salinity on the outer body of the WEC can significantly reduce maintenance costs and improve the service life of the overall system.
- Sharing mooring points, PTO systems, or arrays of WEC can significantly lower costs incurred. However, refining interaction models to account for varying submergence depths and incorporating economic indicators is essential for large-scale deployment.
- Analysis investigating other types of WECs such as OWSWEC, attenuator, OVTWEC, SPDWEC and hybrid systems can also be conducted in the future.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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