Assessment of the Operational Feasibility of Wave Energy Technologies at Potential Sites in Panama

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Abstract– This research assesses the technical feasibility of harvesting wave energy in Panama by evaluating the performance of three Wave Energy Converters (WECs): point absorbers, attenuators, and Oscillating Wave Surge Converters (OSWEC). Using oceanographic data from the Copernicus Marine Service for three strategic sites (Punta Burica, Playa Venao, and Santa Catalina) the resource was characterized using Airy Linear Wave Theory and spectral analysis. The results indicate that the OSWEC technology achieves the optimal coupling for the region, with Punta Burica reaching a peak absorption of 58.42 kW. While point absorbers and attenuators show lower efficiencies, the study highlights that Panama's long energy periods (T_s) offer a consistent but low-intensity resource. The paper concludes that while current global technologies face coupling challenges in tropical regimes, there is a significant opportunity for regional energy diversification through the development of specialized devices tuned to the specific kinematics of the Panamanian coastline.

Keywords—wave energy converters. point absorbers, attenuators, oscillating wave surge converter

I. Introduction

Wave energy is defined as one of the oceanic renewable energy alternatives associated with the energy content hosted in surface waves, generated by the transfer of energy between the wind and the sea surface. From a hydrodynamic context, this resource is characterized by the coexistence of kinetic and potential energy components linked to the oscillatory movement of fluid particles, the magnitude of which depends on parameters such as significant wave height, period, and fluid density. This energy resource can be harnessed through the implementation of various devices whose purpose is to transform the mechanical energy of waves into electrical energy [1].

The study of this resource dates to 1799 in France, where Pierre-Simon Girard obtained the first documented patent (No. 1BA110) titled "Divers moyens d'employer les vagues de la mer comme moteurs" for the exploitation and development of oceanic energies at the time. Modern development of these technologies began in 1940 with Japanese researcher Yoshio Masuda, who investigated navigation buoys based on the oscillating water column (OWC) principle, laying the foundations for current Wave Energy Converters (WECs) [1],[2].

Subsequent milestones, such as the creation of the European Marine Energy Centre (EMEC) in Scotland (2003) and the inauguration of the Aguçadoura farm in Portugal (2008) (the first commercial-scale operating system) have driven the maturation of various devices for this resource. Unlike other renewable sources, wave energy has not yet converged toward a standard design, leading to three fundamental operating principles: [1],[2]:

Oscillating Water Columns (OWC): These use changes in water level to compress air and drive a pneumatic turbine.

Oscillating Bodies: These employ the relative motion (two-dimensional or three-dimensional) of floating or submerged components to activate electrical generators.

Overtopping Devices (OD): These capture water from wave crests into an elevated reservoir to release the potential through conventional hydraulic turbines.

Furthermore, these devices are classified according to their location: Onshore (on the coast, utilizing shallow waters), Nearshore (moderate depth waters, between 10 and 40 m), and Offshore (deep waters, greater than 40 m), where seabed friction is negligible and the energy potential is maximized [3],[4].

Within this context, this research evaluates the performance of three specific devices (attenuator, point absorber, and oscillating surge wave energy converters (OSWEC) under the oceanographic conditions of the Panamanian coastline. The objective is to determine the effective mechanical and energetic coupling for the exploitation of this resource, allowing for the proper identification of these technologies for possible implementation, becoming a sustainable energy alternative that enables the secure diversification of Panama's energy matrix

II. Methodology and Theorical Framework

Panama possesses a coastline exceeding 2,900 km, representing an extensive scenario that could possess significant oceanographic conditions for the exploitation of wave energy resources. Due to its latitudinal location (between the geographic equator and the Tropic of Cancer), the wave regime in territorial waters is of moderate intensity compared to higher latitudes. However, considering the results of the prospecting phase previously conducted in the study: "Evaluation of the Potential of Oceanic Energies in Panama for Electric Power Generation" [5], three potential sites were identified along the Pacific coast that meet the technical parameters to guarantee the exploitation of this resource through the conversion, production, or generation of electrical energy. Therefore, the implementation of wave energy technologies is feasible.

The identified sites are Punta Burica, Playa Venao, and Santa Catalina (see Table I). For these locations, this research integrated oceanic data corresponding to January 27, 2026, through the Copernicus database [5],[6].

Table I
Oceanographic data of potential sites.

Sitio	H_s (m)	T_p (s)	T_e (s)	P_w (kW/m)
Punta Burica	2.01	12.44	11.8	23.37
Playa Venao	1.91	9.71	12.78	22.85
Santa Catalina	0.96	12.48	11.12	5.02

The mentioned locations represent input nodes for the comparative analysis of the selected technologies. Furthermore, using Equation (1), the wave energy potential is estimated based on oceanographic variables associated with the predictive estimation of stored energy and their variability regarding each site.

The variables integrated for the wave energy estimation are significant wave height (H_s) and energy period (T_e) [7],[8]. It is important to note that the formulation employed is based on Airy Linear Wave Theory, adapted for irregular sea states through spectral analysis developed by Longuet-Higgins. A factor of 1/64 is utilized for irregular waves, ensuring a conservative and realistic estimation of the wave resource [7],[8].

$$P_w = \frac{\rho g^2}{64\pi} H_s^2 T_e \quad (1)$$

Where:
ρ: density
g: gravity
H_s (m): significant height
T_p (s): peak period
T_e (s): energy period
P_s (kW/m): wave power

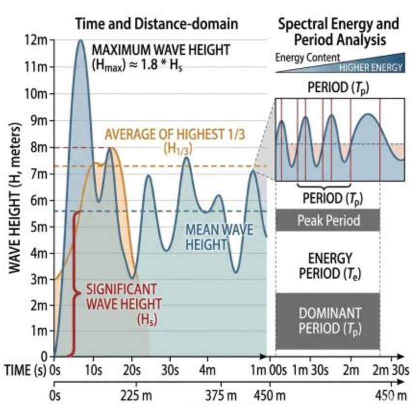

Fig. 1. Representation of significant height and energy period.

Based on the oceanographic parameters and the estimated energy potential for each of these sites, the electrical generation potential of attenuators, point absorbers, and OSWECs is analyzed. The purpose of this analysis is to address the central research question: What is the degree of kinematic complementarity and energy extraction potential of WEC converters (Attenuators, Absorbers, and OSWECs) under the low-enthalpy wave regimes characteristic of the Panamanian coasts?

Subsequently, the selection is based on the technology readiness level and the availability of global implementation data, allowing a robust comparative validation. Table II defines each of the alternatives to provide a clearer understanding of their respective operations.

Table II
Definition of wave energy devices

Point Absorbers	These consist of structures, commonly buoys, that can operate in either floating or submerged modes. These devices capture energy from the vertical motion (technically known as heave) induced by the passage of wave crests and troughs relative to a reference point or base connection. While these systems can be deployed across various depth ranges, their location directly influences the technical complexity of installation and logistical maintenance requirements. [9].
Attenuators	These are essentially plates or segments positioned parallel to the direction of the wave flow. Through this movement, they generate energy from the flexing of the joints placed between each plate. It is important to consider that efficiency is directly related to the size of the plate, as the dimensions of the plates must be proportional to the wavelength. [10].
Oscillating Surge Wave Energy Converters (OSWEC)	These devices capture the kinetic energy of the orbital wave flow through the back-and-forth motion of an oscillating flap or arm. This mechanical oscillation is transferred to a Power Take-Off (PTO) system, which transforms the rotary or linear motion into electrical energy via a generator. Generally, these devices operate fully or partially submerged in nearshore (shallow water) zones, where the horizontal movement of water particles is more pronounced, thus optimizing resource harvesting [11].

This selection of wave energy devices is based on the implementation feasibility and the generation capacity of each relative to the bathymetry of the Panamanian Pacific coast, which, for the three sites evaluated in this research, ranges from 2 m to 50 m in depth. [6].

Furthermore, Panama's oceanic territory in the Pacific Ocean features a bathymetry ranging from -10 m in areas closest to the coast to -400 m at 18 km from Playa Venao. Using this same reference point, it is possible to find zones with a depth of 50 m at 7 km from the coast. This is considered the optimal zone for the installation of point absorbers and attenuators, as it is an area minimally affected by tidal height variations. Additionally, the depth is sufficient to create the necessary height differential to avoid drag between the prototype and the seabed generated by water movement [6,][12].

It is essential and indispensable to understand that each device, according to its geometry, operates under different operational conditions, as explained by Babarit [13]. Moreover, to determine the correct dimensions for each system or device, it is necessary to integrate the concept of characteristic dimension (B) into the design considerations. [13].

For the case of point absorbers, B represents the diameter or width at the waterline. For attenuators and OWSCs, B is the primary dimension of the energy-capturing body (width or length). The characteristic dimensions (B) for the three devices were selected based on representative values from the Babarit database, specifically from Tables 4, 5, and 7. This ensures that the devices remain within the scale ranges of the prototypes validated in the literature (between 5 m and 20 m). Consequently, the following dimensions are obtained for each technology [13]:

Table III
Characteristic dimensions of each device

Device	Dimension
Point Absorbers	10 m diameter
Attenuators	5 m wide/diameter
Oscillating Surge Wave Energy Converters (OSWEC)	10 m flap width

Characteristic dimensions are a crucial factor to consider due to the abrupt changes occurring in Panama's Pacific maritime space. Predominant tidal variations reach a maximum level of 5.49 m and a minimum level of -0.27 m, the latter reflected in the receding water level from the shoreline.

To estimate the absorbed power, the Capture Width Ratio (CWR) is utilized. For each of the devices, the following values are assigned [13]:

Table IV
Capture Width Ratio

Device	Dimension
Point Absorbers	15% - 25%
Attenuators	10% – 15%
Oscillating Surge Wave Energy Converters (OSWEC)	20% – 30%

The CWR constitutes the fundamental non-dimensional indicator for evaluating the hydrodynamic efficiency of a wave energy converter. Determining this parameter is crucial, as it quantifies the intrinsic capacity of each device to intercept and absorb the energy flux transported by the waves, thus allowing for a normalized comparison between different technologies [13].

Finally, to calculate the coupling percentage of the devices, a comparison is made between the estimated potential and the nominal generation potential. Table V contains the nominal generation values for each device; these generation data were obtained through various studies [13],[14],[15].

Table V
Nominal Generation Capacity

Device	Generation
Point Absorbers	50 – 200 kW
Attenuators	30 – 75 kW
Oscillating Surge Wave Energy Converters (OSWEC)	300 – 600 kW

III. Results

Energy Potential Estimation

To perform the analysis of the alternatives at the selected sites, equation (2) is used. This allows to make the estimation of the absolute power calculated from the variables defined above; these values are presented in Table II. It is important to note that these results reflect the theoretical potential available and not the energy delivered to the grid.

$$P_{abs} = P_w * B * CWR \tag{2}$$

Table VI
Estimation of Absorbed Power (Pabs) Per Device in kW

Site	P_{abs} Point Absorbers	P_{abs} Attenuators	P_{abs} OSWEC
Punta Burica	37.39	16.36	58.42
Playa Venao	36.56	15.99	57.12
Santa Catalina	8.03	3.51	12.55

For a better perspective of the results, Figure 1 presents the bar chart for each alternative.

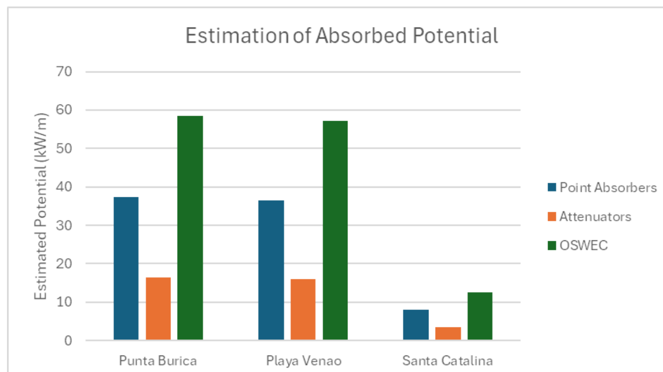

Fig. 2. Estimation of the power absorbed for each of the evaluated sites.

By estimating the coupling percentage of each alternative (using Tables V and VI), it is possible to predict whether the local generation capacity matches the generation capacity of the studied devices, thereby determining the feasibility of their implementation. Table VII shows the results of this calculation, performed using the mean value between the nominal generation limits presented in Table V as a reference.

Table VII
Device Coupling Percentage (η_{acc})

Site	P_{abs} Point Absorbers	P_{abs} Attenuators	P_{abs} OSWEC
Punta Burica	30%	31%	13%
Playa Venao	29%	30%	13%
Santa Catalina	6%	7%	3%

The results obtained successfully address the central research question of this study. While the findings confirm that Oscillating Wave Surge Converters (OSWEC) offer the most effective mechanical and energetic coupling for the low enthalpy conditions of the Panamanian Pacific with an estimated absorbed power of 58.42 kW at Punta Burica and 57.12 kW at Playa Venao. The findings also reveal a critical technology gap. Current commercial devices are primarily designed for high-intensity swells characteristic of mid-latitudes, leading to a relatively low coupling efficiency in tropical waters. The following table provides a comparison for a better perspective.

Table VIII
Comparison of ideal conditions versus real conditions in Panama for the WEc devices studied.

Variables	Ideal conditions	Actual conditions
Significant height (H_s)	1 – 5 m	0.96 – 2.01 m
Energy period (T_e)	6 – 12 s	11.8 – 12.78 s

Through this comparison, it becomes evident that while energy periods can be considered ideal for wave energy generation, significant wave height could pose a challenge due to variations throughout the year, driven by both weather inclemencies and lunar phases. As previously mentioned, tides in Panama can range from very high to excessively low, representing a direct obstacle for the implementation of currently studied wave energy devices. Furthermore, the climatic inclemencies in the country tend to be quite severe due to the various typhoons, storms, and hurricanes that form in the Pacific Ocean and directly affect our coastlines

Consequently, the path toward a sustainable wave energy branch within Panama's energy matrix does not rely solely on the importation of existing technology, but on the development of regional adaptations. Future designs must prioritize high-torque Power Take-Off (PTO) systems and resonance tuning for long energy periods (T_s) nd conservative wave heights (H_s), as previously stated. This research establishes the technical baseline for developing a proprietary technological framework capable of transforming Panama's moderate wave resource into a consistent pillar of renewable energy.

Conclusion

Wave energy remains a highly sustainable resource in the Republic of Panama; however, it requires an extensive and rigorous research and development process given the conditions of the Panamanian Pacific oceanic scenario. Panama offers an ideal setting for the wide development of these technologies, and research such as this establishes the initial foundations to achieve this integration.

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