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Quantification of the Wave Energy Potential of the Gulf of Fonseca Coastline in Honduras

Abstract— **In accordance with quarterly data released by the National Electric Energy Company (ENEE), it can be discerned that the year-on-year growth in demand exhibits a linear pattern. When scrutinizing data pertaining to the maximum and total demands of a given year, it consistently manifests higher values during the months of that year compared to the corresponding months of the preceding year. This circumstance, coupled with the fact that slightly over 30% of Honduras' energy matrix is derived from firm energy sources, poses a critical challenge in meeting forthcoming energy demands during specific high-demand quarters in Honduras. This research seeks to contribute to the scientific knowledge of a relatively underexplored field, specifically the energy potential inherent in the waves lapping the country's coastlines. Consequently, this study is conceived as a modest segment of a plausible implementation of technology adept at harnessing this valuable resource. The research undertook an assessment of the ocean wave energy potential through the collection of physical parameters influenced directly by meteorological data in the region. Parameters such as wave height and intervals between waves, in conjunction with constants like seawater density and Earth's gravity, were considered to determine the theoretical potential value. These collated data, when applied in the wave power formula, ascertain the energy flux conveyed by waves in a given zone. Additionally, the study factored in the total and theoretically available length of the southern coasts of Honduras, considering the coastline lengths of the Valle and Choluteca departments, as well as the perimeter of Amapala Island, to establish the maximum theoretical power capacity.**

Keywords: Energy potential, wave power, installation capacity

I. INTRODUCTION

Wave energy has recently become the interest of many researchers around the world [1]. According to various global potential estimation studies, the available global power from wave energy reaches a value of 2 TW, with a total energy that could be generated in a year approximately an amount of 17,500 TWh/year [2]. Wave energy has a high potential for use to transform it into electricity, because it is 5 times more concentrated than wind energy, 10 to 30 times more concentrated than solar energy, and electricity can be produced constantly 8,760 hours of the year, guaranteeing the continuity of the electrical energy supply [3]. The Gulf of Fonseca is located on the Pacific Ocean coasts of Central America, shared by three countries: Nicaragua, Honduras, and El Salvador, covering a water surface area of 2,210 km2, bordered by 439.85 kilometers of coastline; of which the Honduran coast spans 253.4 km. The comparison of energy demand values in Honduras for the years 2021-2022-2023 [4] has been consistently increasing, making the establishment of new power generation plants highly attractive. This research conducted a comprehensive analysis of a potential resource identified in the region, laying the foundation for the establishment of a suitable study area for the eventual implementation of emerging technologies in electricity generation in the country. In 2020, a study was conducted in Argentina [5] analyzing the wave energy potential on the coasts of Mar de la Plata, Buenos Aires, for a possible future installation of power generation plants exploiting the resource. The research [6] examined the energy potential on the coasts of the city of Veracruz, Mexico. This current investigation shares similarities with the mentioned studies, differing only in the study area, which focuses on the coasts of the Gulf of Fonseca bordering the departments of Honduras, Valle and Choluteca. The southern areas of Honduras, bordering the Pacific Ocean, harbor an untapped wave energy potential. Despite this promising opportunity, the absence of comprehensive research on the dynamics of waves and their capacity for electricity generation has posed a significant obstacle to the sustainable development and implementation of this form of energy in the region. This research will analyze the coasts of Honduras facing the Pacific Ocean to determine the wave energy potential in that area. The study examined specific meteorological parameters applicable in various mathematical models as a research methodology. Thus, this research can be used for subsequent feasibility analyses of resource exploitation. Similarly, the research focused on providing relevant information for future investigations, aiming to add value to this specific type of renewable energy.

II. CONTEXT

A. Background

A report by the Economic Commission for Latin America (CEPAL) notes that the kWh average cost in Central America in 2016 was $13.48 cents, meanwhile the kWh average cost in Honduras was higher than the average cost of the region, being $13.77 cents [7]. The current instability of the energy supply in Honduras is a reality that has grown over the years (1994-2023). In the National Electric Power Company, due to increased demand, technical and non-technical losses began to exceed 30%, surpassing the established limit of 15%. With the purpose of modernizing the electric subsector and helping the National Electric Energy Company (ENEE, by its Spanish acronym) to retrieve the costs of supplying electricity to the consumers, the time of use (TOU) tariff has been established through the Regulation of Tariffs [8]. This led to prioritizing other areas over maintenance and improvement of transmission lines and energy generation management, causing instability in the electricity supply. As a result, various alternatives for energy production have been explored [9].

By May 2023, in Honduras, electricity generated from renewable sources accounts for 64.5%, as reported in the Statistical Bulletin issued by the ENEE [3]. In the medium term, the goal is to achieve 80% of electricity generation from renewable sources by 2038 [10], in line with the objectives outlined in the Roadmap for the year 2050. Hondurans bear the highest tariff adjustment among Central American countries, with a cost of $0.24/kWh. Comparisons in tariffs, effective from April/May of each year, have consistently increased, with April 2023 marking the highest tariff compared to previous years for the same month [11].

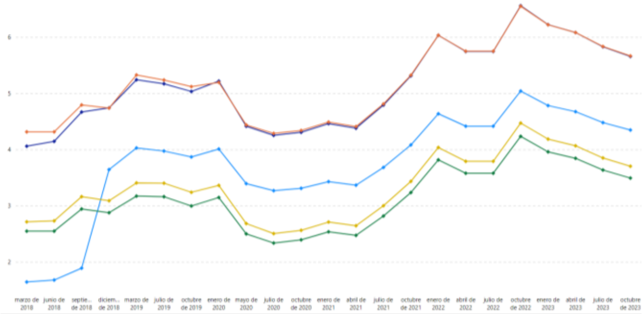

Figure 1: Energy demand growth in Honduras
Source: CREE, (2023)

This graph illustrates the growth of demands from the year 2018 to 2023 in the time vs. Tariff [HNL/kWh] relationship. Starting from the first year of measurement, the lowest data point corresponds to the tariff for residential consumption below 50 kWh, followed by the high-voltage tariff, the medium-voltage tariff as the third data point, the tariff for residential consumption above 50 kWh as the fourth data point, and the highest tariff representing low voltage.

Due to imminent increases in energy tariffs [12] and the plan to achieve a more sustainable energy matrix, new ways have been sought to implement electricity projects through renewable sources. However, it is a fact that the focus on renewable energies has shifted towards certain more developed technologies (as indicated in Figure 2), while wave energy is not part of Honduras' energy matrix.

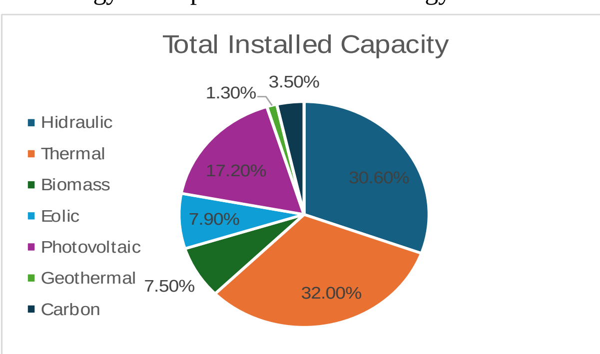

Figure 2: Installed Capacity in the National Interconnected System of Honduras.
Source: ENEE, (2023).

There is no precedent for the investigation of wave energy resources along the south coasts of Honduras. However, in previous months, the undergraduate student from UNITEC, Jonathan Amador, initiated research on the resource along the coasts of the Atlantic Coast of Honduras.

B. Justification

In recent years, the price of energy for residential tariffs has steadily increased. The demands in all recorded months until August 2023 exceeded those of the previous year, 2022 [3]. The demand will continue to grow imminently, as seen in previous years when measures were taken to rationalize electricity supplies. Despite having sufficient installed capacity to meet the country's energy demand, power plants couldn't keep up because only 33.5% of the generated energy is firm, not intermittent or variable like solar and wind energy.

Considering a scenario where the energy matrix is insufficient to meet those demand peaks at night is logical. In response, the research aims to open the possibility of implementing a new technology into the country's energy matrix. The study serves as a starting point for future projects that harness wave energy resources in Honduras [13].

C. Theory

Waves in seas and oceans are a phenomenon derived from the sun. Radiation from the star causes uneven heating of the Earth, leading to the displacement of air masses and the formation of winds that create waves. When a wave approaches the coast, it slows down, decreases in wavelength, and increases in height. Most of the energy is lost in friction with the seafloor, and only a fraction reaches the shore. A wave contains both kinetic and gravitational potential energy. The power carried by the wave depends on its height and period, usually given in power units per length units (W/m). It is crucial not to confuse deep-water waves with the waves breaking against the seacoasts or beaches.Waves receive, store, and transport energy. They travel over long distances with minimal energy loss, so when a wave approaches the coast, it loses speed and wavelength but gains height. The ability of waves to generate energy is measured through the energy flux and power per meter of wave front [14].

The formula for wave power is presented as follows:

$$P = \frac{pg^2Th^2}{32\pi}$$

Where P is the wave energy flux expressed in W/m, p is the water density (in this case, seawater): 1027 kg/m^3, g is gravity: 9.81m/s^2, T is the wave period [s], and H is the average wave height at a specific measurement time [m].

III. III. METHODOLOGY

A. Approach

The research adopts a quantitative approach, involving the application of mathematical models to calculate wave energy potential along the coasts of the Gulf of Fonseca in Honduras. Simultaneously, data collection through numerical measurements is crucial for developing solutions related to the predefined research questions.

B. Research Variables

Variables play a crucial role in the development of any research. In this study, two fundamental categories will be considered: independent and dependent variables.

- Independent Variables

The foundations of any quantitative research lie in independent variables as they influence the values obtained for dependent variables. For this study, the following independent variables are considered:

a. Density: The density of sample water is represented by the physics standard value of 1.025 g/cm3 [15].

b. Gravity: Gravity is a fundamental force that attracts two objects with mass toward each other. On Earth, the acceleration due to gravity (g) is approximately 9.8m/s^2 [16].

- Dependent Variables

Dependent variables are inherently influenced directly by the conditions established by independent variables.

a. Wave Height: Wave height emerges as a determining factor in calculating wave energy potential, as this dimension establishes the magnitude of the phenomenon. Any variation in wave height directly impacts the final potential, making it a crucial aspect to consider in the evaluation of this magnitude.

b. Wave Intervals: Intervals of waves will be supplied by the Windfinder and Windy.App measurement software. Including this data in our mathematical model is fundamentally important as it captures the temporal span during which wave height remains constant.

C. Research Methodology

Given the quantitative orientation of this research, it is necessary to calculate the variables influencing wave energy potential. To obtain this information, it is essential to identify all relevant aspects and carry out necessary evaluations, including:

1. Data Collection: The following data will be gathered via WindyApp: wave height, wave intervals, wave speeds, and wave crest-to-crest length.
2. Calculator Development: A Microsoft Excel sheet will be created to organize and correctly compile independent variables. The Excel sheet will also include previously established formulas and link values extracted from the Windfinder and WindyApp databases to estimate the energy potential.
3. Results Matching: A summary sheet will be generated where data collected by both departments and from both formulas used (wave power formula and wave energy formula) will be aligned and compared.
4. Results Evaluation: Present the established results and declare whether it is worthwhile to continue the study or, conversely, if it is a resource not worth exploiting for electricity.

IV. Analysis and Results

This section compiles results obtained from data collection, such as wave height and the time interval during which the wave travels from point A to point B. Data were collected at three-hour intervals each day, resulting in an average of the studied waves during each minute compiled into a single data point every 3 hours. This implies a total of 8 measurements in a day (00:00, 03:00, …, and 21:00) for each measurement location, totaling 56 measurements per week. There are three measurement locations: Amapala, San Lorenzo (Valle), and Monjarás (Choluteca), resulting in the collection of 168 data points per week.

Additionally, the 7 data points for the same hour in a week were averaged to better understand the behavior of the wave energy resource according to the time of day, inspired by the curve formed in solar energy studies. This means that each week presents 8 data points for each measurement location (the 8 measured hours of the day), where each data point is an average of that same hour of measurement over 7 days of the week, resulting in a total of 24 energy flux data points per week. Subsequently, the already averaged data points for power values at a specific hour in a week were summed to obtain the resource (in kW/m) of the theoretically extractable power in the resource in a single week for each measured city.

A. Evaluation of Wave Energy Power in Cities

- WEEK 1

Using data collected from cities along the southern coast of Honduras, the mathematical model of the wave power formula was applied. Week 1 spans from November 19 to November 25, 2023, encompassing average wave power data at specific hours of the week.

Hour	Amapala	Monjaras	San Lorenzo
00:00	2.5268	0.4175	0.5326
03:00	2.7495	0.3562	0.6017
06:00	2.0971	0.3573	0.4743
09:00	2.0901	0.4056	0.4802
12:00	2.0929	0.4057	0.4636
15:00	2.3037	0.4208	0.3612
18:00	2.4075	0.4209	0.3833
21:00	2.3644	0.4271	0.4786

Table 1: Energy Potential of Cities in Week 1
Source: Own Elaboration

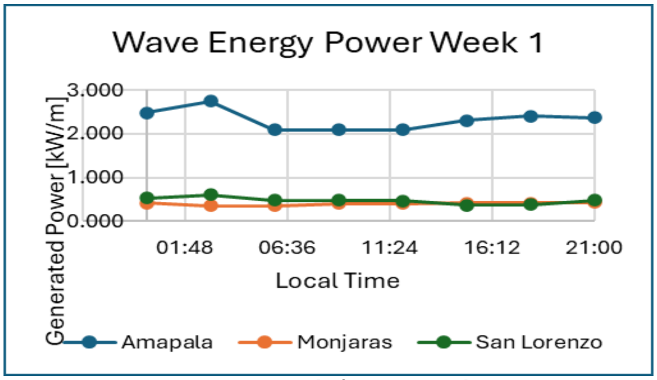

Figure 3: Energy Potential of Cities in Week 1
Source: Own Elaboration

- WEEK 4

Utilizing data collected from cities along the southern coast of Honduras, the Wave Energy Power mathematical model was applied. Week 4 ranges from December 10 to December 16, 2023, covering average wave power data at specific hours of the week.

10/12/2023 - 16/12/2023			
Energy Flow [kW/m]			
Hour	**Amapala**	**Monjaras**	**San Lorenzo**
00:00	1.4452	0.1723	0.2907
03:00	1.3304	0.0966	0.2114
06:00	1.3640	0.0970	0.2105
09:00	0.9541	0.0978	0.2476
12:00	0.9972	0.1381	0.2935
15:00	1.2365	0.3340	0.3407
18:00	1.6720	0.3600	0.3744
21:00	1.4185	0.2570	0.3164

Table 2: Energy Potential of Cities in Week 4
Source: Own Elaboration

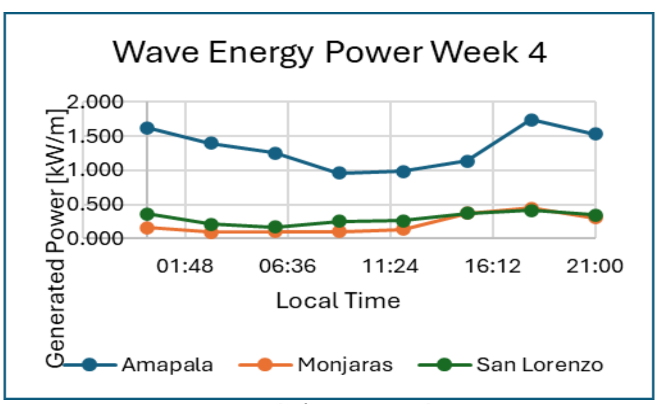

Figure 4: Energy Potential of Cities in Week 1
Source: Own Elaboration

B. Average potential in each city

- WEEK 1

Using the calculated data from the wave energy potential assessment section, we sum all the values of the averaged hours in a week to obtain the total average power of the waves in different cities.

19/11/2023 - 25/11/2023		
Amapala	**Monjaras**	**San Lorenzo**
18.5873	3.2112	3.7755

Table 3: Total Power of Waves in Cities Week 1
Source: Own Elaboration

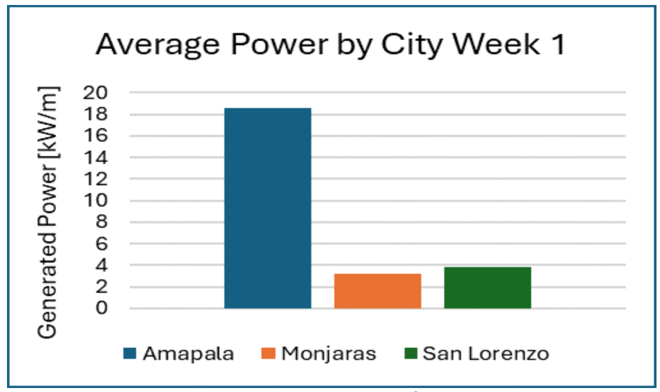

Figure 5: Theoretical Wave Power of Cities Week 1
Source: Own Elaboration

- WEEK 4

10/12/2023 - 16/12/2023		
Amapala	**Monjaras**	**San Lorenzo**
10.6208	1.6994	2.3837

Table 4: Total Power of Waves in Cities Week 4
Source: Own Elaboration

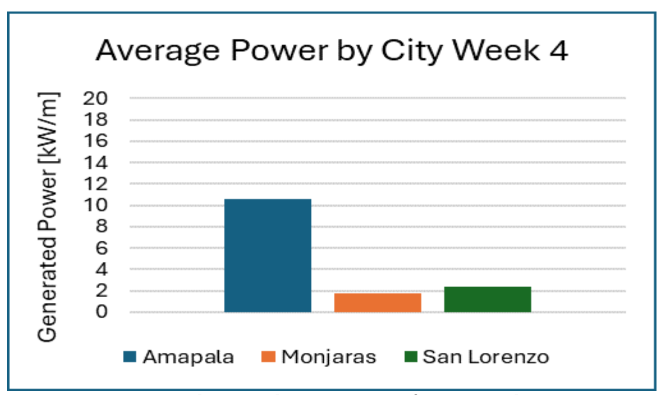

Figure 6: Theoretical Wave Power of Cities Week 4
Source: Own Elaboration

C. Average Potential in each City

To obtain the theoretical total power existing in the area, we use the data obtained in the previous section. The data for the theoretical power existing in the area is multiplied by the lengths of the coastlines. In other words, in the first week, if Amapala has a resource X in wave energy, Monjaras and San Lorenzo have resources Y and Z, respectively. Then, the total power resource existing in the area is the sum of the products of the coastline length of Amapala (10.49 km) and resource X, with the length of the southern coastline of Honduras (133 km) multiplied by the sum of resources Y and Z. This value is expressed in MW because it is the result of working with kW/m and km.

$$P = (Pot.Amapala * L.Amapala) + (L.Costa\,Sur)(Pot.Monjarás + Pot.SL)$$

- WEEK 1

The formula was employed to determine the total potential of the area, using the previously calculated data for each week.

Recurso Total	1124.68

Table 5: Theoretical Power of the Area Week 1
Source: Own Elaboration

This value is understood as the possible wave energy potential. It represents a hypothetical scenario in which all waves entering Honduran waters are harnessed with a technology capable of extending along the more than 133 km of the southern coast of Honduras. If realized, this data is the installed capacity of power in that measurement week.

- WEEK 4

The formula was employed to determine the total potential of the area, utilizing previously calculated data for each week.

Recurso Total	619.75

Table 6: Theoretical Power of the Area Week 4
Source: Own Elaboration

D. Total Average Potential of the Area

This section displays all the theoretical powers of the area for each measured week to demonstrate variations in behavior based on the dates.

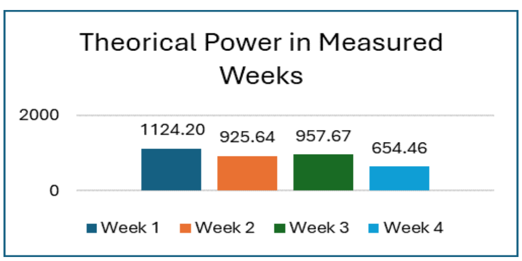

Figure 7: Theoretical Powers for Different Weeks
Source: Own Elaboration

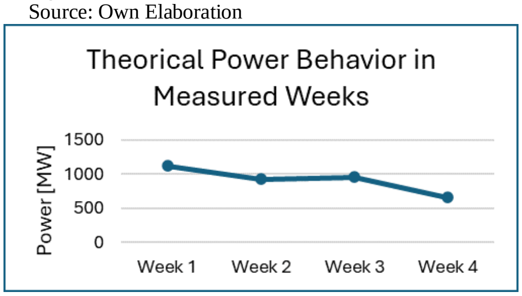

Figure 8: Behavior of Theoretical Powers Across Weeks
Source: Own Elaboration

E. Wave Height According to Time Intervals

From the outset, wave height directly influences the calculation of resources; therefore, we study the behavior of waves based on measurement intervals. The behavior of averaged waves over a specific time on different days of the week is illustrated in the three measurement locations.

- WEEK 1

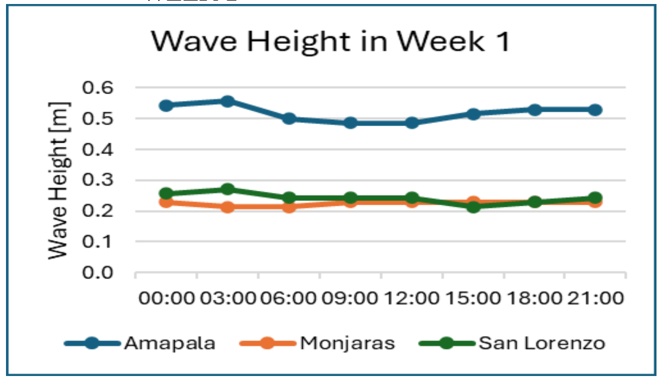

Figure 9: Wave Behavior in Cities Week 1
Source: Own Elaboration

- WEEK 4

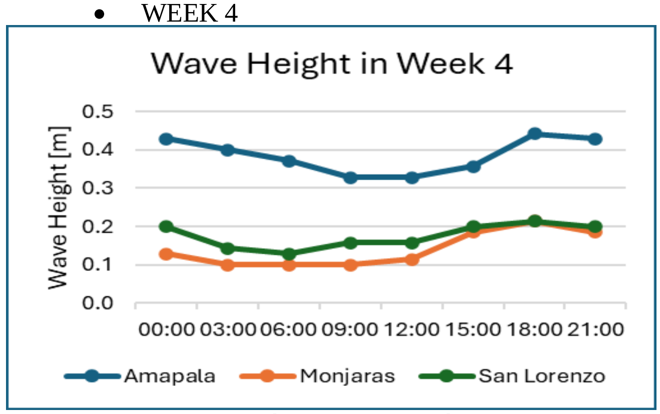

Figure 12: Wave Behavior in Cities Week 4
Source: Own Elaboration

- ALL MEASURED WEEKS

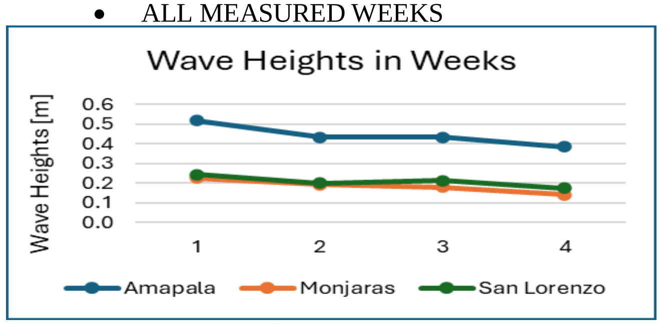

Figure 13: Wave Behavior in Cities
Source: Own Elaboration

V. CONCLUSIONS

The wave energy potential was evaluated along the South Coast of Honduras in the cities of San Lorenzo, Monjarás, and Amapala. These departments constitute a substantial part of the total coastline in the Valle and Choluteca departments.

The research spans a total of 10 weeks, although, for academic purposes at the time of submission, it represents a study of 10 weeks. However, a 4-week duration (almost a month) proves sufficiently satisfactory and useful for anticipating subsequent results since the research period unfolds, from start to finish, during the winter season in the southern zone of Honduras. With the results obtained thus far, it has been determined that there is indeed a potential wave energy that can be harnessed in the South Zone of Honduras. The research concludes specific points that:

1. Different meteorological data on wave activity were collected and utilized as physical parameters. Waves on Amapala Island did not exceed 0.7 meters in height, while waves in the municipalities of Monjarás and San Lorenzo did not surpass 0.4 meters in height, reaching minimum heights of 0.1 meters. Finally, the parameter that defines the time between one wave crest and another, showed high variations in all three cities, ranging from a minimum of almost 4 seconds to maximums of nearly 12 seconds.
2. The collected data were implemented in the Wave Energy Power mathematical model, evaluating the possibility that the waves in the South Zone of Honduras could carry up to more than 3 kW/m of energy flow in Amapala and 0.8 kW/m in Valle and Choluteca.
3. The energy flow data were then used to estimate the theoretical total power of the entire area and thus obtain the real wave energy potential. It was studied that considering the over 133km of existing coastline in the South Zone of Honduras, there is a resource of up to 1120 MW in the best-case scenario.

This research considered several limitations, such as the possibility of certain protected areas due to mangroves in the region. This would reduce the total theoretical installed capacity, as well as the social and touristic limitations that may be involved in implementing emerging technology in the area. The data will always be subject to variations such as meteorological phenomena that are not possible to determine or estimate in the long term.

It was determined that this research serves as a foundation and reference for future investigations in the field of electricity generation and the use or estimation of wave energy potential in an area. It is recommended to leave a variation of ±7.3% to the calculated data. This is because the waves come from south to north along the mainland coast of Honduras, but around Amapala Island, waves come from all directions, and only a portion is theoretically considered from south to north, while, for pragmatic purposes, this research considered 100% of the waves in the same direction. It is recommended to use the coast on Amapala Island for smaller projects, and try the implementation of the oscillating water column [17]. This recommendation arises from the fact that the wave height on the island is consistently higher than on the mainland.

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