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Evaluating Wave Potential and Assessing the Economic Viability of Wave Energy Converters in the South Java Seas

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Abstract

As an archipelagic nation, Indonesia holds substantial potential for wave energy as a renewable resource. Certain coastlines of islands facing the Indian Ocean, particularly in the western and southern regions, exhibit significant wave energy throughout the year. To identify suitable locations for Wave Energy Converter (WEC) installation, it is essential to assess wave hindcast data. This study utilizes NOAA and ERA5 reanalysis wave data to analyze wave characteristics in Indonesia from 2008 to 2018. Data processing with Ocean Data View is employed to estimate key wave parameters at various locations, including significant wave height, mean wave period, and mean wave direction. Two locations in the South Java seas were identified for WEC installation based on this research. The average values for the period 2008 to 2018 indicate a significant wave height of around 2m, with a maximum height of 5m, a wave period of 10–14s, and a wave direction of 195–210 degrees. Notably, NOAA data suggests a higher estimation of significant wave height compared to ERA5 data. The average annual wave power potential based on ERA5 and NOAA is 164.43 MW/m and 252.15 MW/m, respectively. Furthermore, this study incorporates an economic simulation for the construction of a multi-point absorber WEC. The objective is to offer insights into the Levelized Cost of Electricity (LCOE) and compare it with other WEC technologies. Assuming a WEC capacity of 130 kW, the total construction cost is estimated at $2,093,725, resulting in a Levelized Cost of Energy (LCOE) of $91/MWh.

1. Introduction

The transition to renewable energy has become a widely discussed global topic in recent times. The limited availability of conventional energy sources such as oil and coal has become a pressing concern as Indonesia's energy needs continue to rise. This necessitates the exploration of alternative, renewable, and environmentally friendly energy sources to ensure a green and sustainable future. Additionally, addressing climate change can be achieved through transitioning to new and renewable energy sources, prioritizing energy security and affordability.

Several potential renewable energy sources, including waves, currents, wind, and solar power, offer sustainable alternatives. It is crucial, therefore, to understand the characteristics of sea waves in Indonesia to effectively harness the potential of this renewable energy source [1], [2]. This knowledge is vital for fostering a comprehensive approach to energy transition, ensuring not only environmental sustainability but also energy security for the nation's future. Among these, wave energy stands out as a promising and largely untapped reservoir of clean energy. Research on wave energy converters is advancing remarkably well [3]–[7]. The South Java Seas, renowned for their dynamic and consistent wave patterns, emerge as a prime candidate for the deployment of wave energy converters [8]. This manuscript undertakes a comprehensive evaluation of the wave potential within the South Java Seas, coupled with a meticulous assessment of the economic viability of implementing wave energy conversion technologies in this region.

Indonesia, as a maritime nation, boasts approximately 70% of its territory as water and possesses the second-longest coastline globally, indicating a significant potential for harnessing wave energy. Furthermore, with a population of around 280 million, making it the fourth most populous country globally, Indonesia faces substantial energy demands, exacerbated by ongoing developmental efforts. Despite these factors, a considerable portion of Indonesia's energy still relies on coal, a situation inconsistent with the commitments outlined in the National General Energy Plan or "Rencana Umum Energi Nasional" (RUEN). This reliance on coal raises environmental concerns due to pollution and contributes to the limited nature of fossil fuel resources. Notably, Indonesia is surrounded by two major oceans, the Indian Ocean and the Pacific Ocean, amplifying its potential for wave energy. According to various studies, the estimated wave energy potential in Indonesia reaches up to 70 kW/m in certain locations. If effectively harnessed, this energy source could prove immensely beneficial for the nation [9].

However, the current utilization of marine energy potential in Indonesia remains suboptimal [10]. The underutilization of this vast energy resource underscores the need for a more concerted effort to explore and implement wave energy technologies, aligning with Indonesia's commitment to transitioning towards sustainable and environmentally friendly energy sources. Addressing this untapped potential not only aligns with global goals for renewable energy adoption but also positions Indonesia to meet its growing energy needs in a cleaner and more sustainable manner.

This research aims to analyze the wave energy potential in Indonesia based on data from the National Oceanic and Atmospheric Administration (NOAA) [11] and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis 5 (ERA5) [12] using hindcasting methodology. By utilizing this data, the goal is to obtain accurate information regarding the wave energy potential in Indonesia, coupled with an economic analysis. This information can serve as a foundation for the planning and development of wave energy production systems in Indonesia. Additionally, the research findings can offer insights into the climate and weather conditions in Indonesia, factors that influence wave energy potential. Waves, driven by wind and influenced by complex oceanographic factors, offer a persistent and reliable energy source. Recognizing the need for a thorough analysis, this study employs advanced modeling techniques and data-driven methodologies to quantify the wave energy potential in the South Java Seas. The aim is to provide a detailed understanding of the spatial and temporal variations in wave energy, laying the foundation for informed decision-making in the deployment of wave energy converters.

In addition to assessing the theoretical wave potential, this manuscript goes beyond theoretical considerations to scrutinize the economic feasibility of wave energy projects in the South Java Seas. Factors such as capital and operational costs, energy conversion efficiency, and potential revenue streams are meticulously examined to gauge the economic viability of deploying wave energy converters in this maritime region. By integrating engineering, economic, and environmental perspectives, our study aims to offer a comprehensive framework for stakeholders and policymakers, facilitating informed decisions in the pursuit of sustainable energy solutions.

As the global community strives to transition towards a low-carbon future, the findings presented in this manuscript contribute valuable insights to the ongoing discourse on renewable energy. The convergence of cutting-edge research methodologies, regional specificity, and economic pragmatism positions this study as a significant resource for advancing the dialogue on the practical implementation of wave energy converters in the South Java Seas.

2. Methods

2.1. Wave potency reanalysis method

So far, advancements in meteorological analysis have enabled more accurate weather and sea wave condition predictions. Some available meteorological sources include the European Centre for Medium-Range Weather Forecasts (ECMWF), also known as ERA5, and the National Centers for Environmental Prediction or NOAA.

In this study, the focus is on the western part of Indonesia, specifically the waters south of Java Island. This area faces the Indian Ocean directly, resulting in a greater energy potential compared to other seas in Indonesia. Data processing is conducted using Ocean Data View software. Two specific points will be identified, as illustrated in Figure 1 and detailed in Table 1.

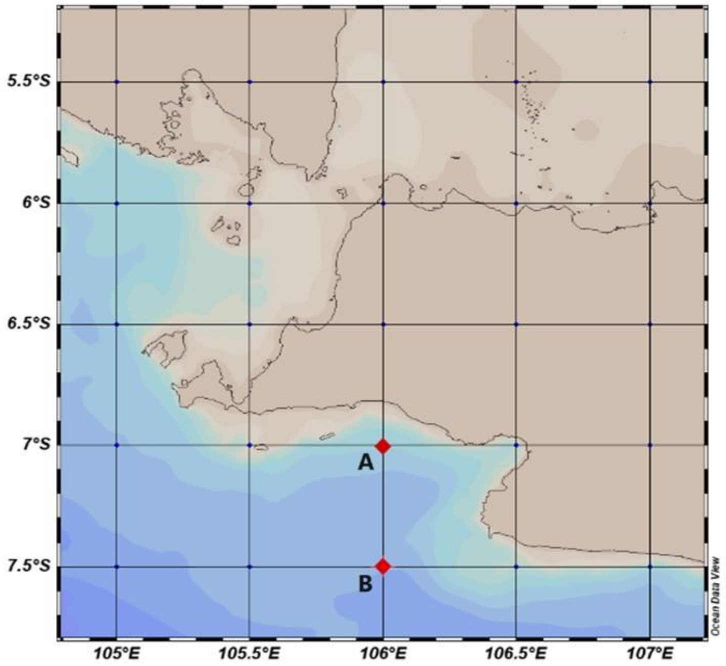


Figure 1. Coordinate of the locations in the South Java Seas

Table 1. Two locations in the South Java seas

Parameter	Point A	Point B
Latitude	-7°	-7.5°
Longitude	106 °	106 °
Bathymetric	750 m	2200 m
Distance from the shore	17 km	45 km

The wave reanalysis data were collected from January 1st, 2008 to December 31st, 2018 by downloading data from ERA5 https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form & NOAA https://www.ncei.noaa.gov/thredds-ocean/catalog/ncep/nww3/catalog.html. The data were retrieved at 3-hour intervals and subsequently averaged daily. The utilized data are mean wave direction in degree (°), mean wave period in second (s), significant height of combined wind waves and swell (m), and bathymetric (m).

Here is the method for processing data in this study. First, the wave period data is calculated into energy periods using the following formula [1].

$$1.12\mathrm{T_e} = 1.29\mathrm{T_z} = \mathrm{T_p} \tag{1}$$

With T_p representing the wave period and T_e being the energy period. Afterward, the energy period data can be used in conjunction with Significant Wave Height data to calculate wave potency. The following is the formula for calculating this potency

$$\mathrm{P} = \frac{\rho g^2}{64\pi}\mathrm{H_{m0}^2 T_e} \approx \left(0.5\frac{\mathrm{kW}}{\mathrm{m^3 \cdot s}}\right)\mathrm{H_{m0}^2 T_e} \tag{2}$$

With P being the wave energy flux per unit crest length, H_{m0} representing Significant Wave Height, T_e indicating the wave energy period, ρ denoting water density, and g representing gravitational acceleration. When Significant Wave Height is expressed in meters and the wave period in seconds, the result is wave power in kilowatts (kW) per meter of wave length.

Table 2. Parameter Data

Data	Unit
Latitude	-7.5°
Longitude	106 °
Bathymetri	2200 m
Distance from the shore	45 km

2.2. Economic Analysis

Economic analysis in the development of Wave Energy Converters (WECs) using calculated wave potential data is conducted by identifying the technical specifications of the WEC to estimate the cost of the materials used. The WEC used in this study is in the form of a multi-point absorber with a width of 2 meters and a total of 5 absorbers capable of generating 130 kW, with a lifespan of 20 years.

Economic analysis involves assessing the financial and economic aspects of a decision, project, or policy. This analysis aims to identify and evaluate the economic implications of an action or decision. Utilizing appropriate analytical tools, economic analysis assists in making more rational decisions and provides comprehensive information about the financial implications of an action or policy [13].

Capital expenditure (CAPEX) refers to the investment in fixed assets or expenditures to enhance a company's production capacity. It involves the purchase or construction of long-term assets such as land, buildings, equipment, machinery, vehicles, and infrastructure. CAPEX is vital in corporate financial planning as it influences long-term cash flow and impacts a company's growth and profitability. Wise and effective CAPEX decisions can help companies improve efficiency, competitiveness, and the ability to meet market demands. The installation cost from various sources ranges from 33% to 40% of the initial device cost [14].

Operating expenditure (OPEX) refers to a company's operational expenses. OPEX encompasses all costs related to daily business operations, such as employee salaries, raw material costs, utility costs (electricity, water), rent, maintenance costs, marketing costs, and more. OPEX relates to continuous costs occurring in the company's daily operations. Effective OPEX management is crucial in maintaining a company's financial balance. Efforts to control and optimize OPEX can help companies improve efficiency, reduce unnecessary costs, and enhance profitability. In some references, operational costs usually range from 1% to 5% of CAPEX [15].

LCOE, short for levelized cost of electricity, is used to calculate the estimated production cost of electricity per unit of energy over a specific period, typically in kilowatt-hours (kWh). LCOE is a commonly used tool to compare the production costs of electricity from various energy sources, both conventional and renewable. LCOE considers various factors in its calculation, including initial investment costs (CAPEX), operational and maintenance costs (OPEX), system efficiency, project lifespan, interest rates, and other relevant factors [13].

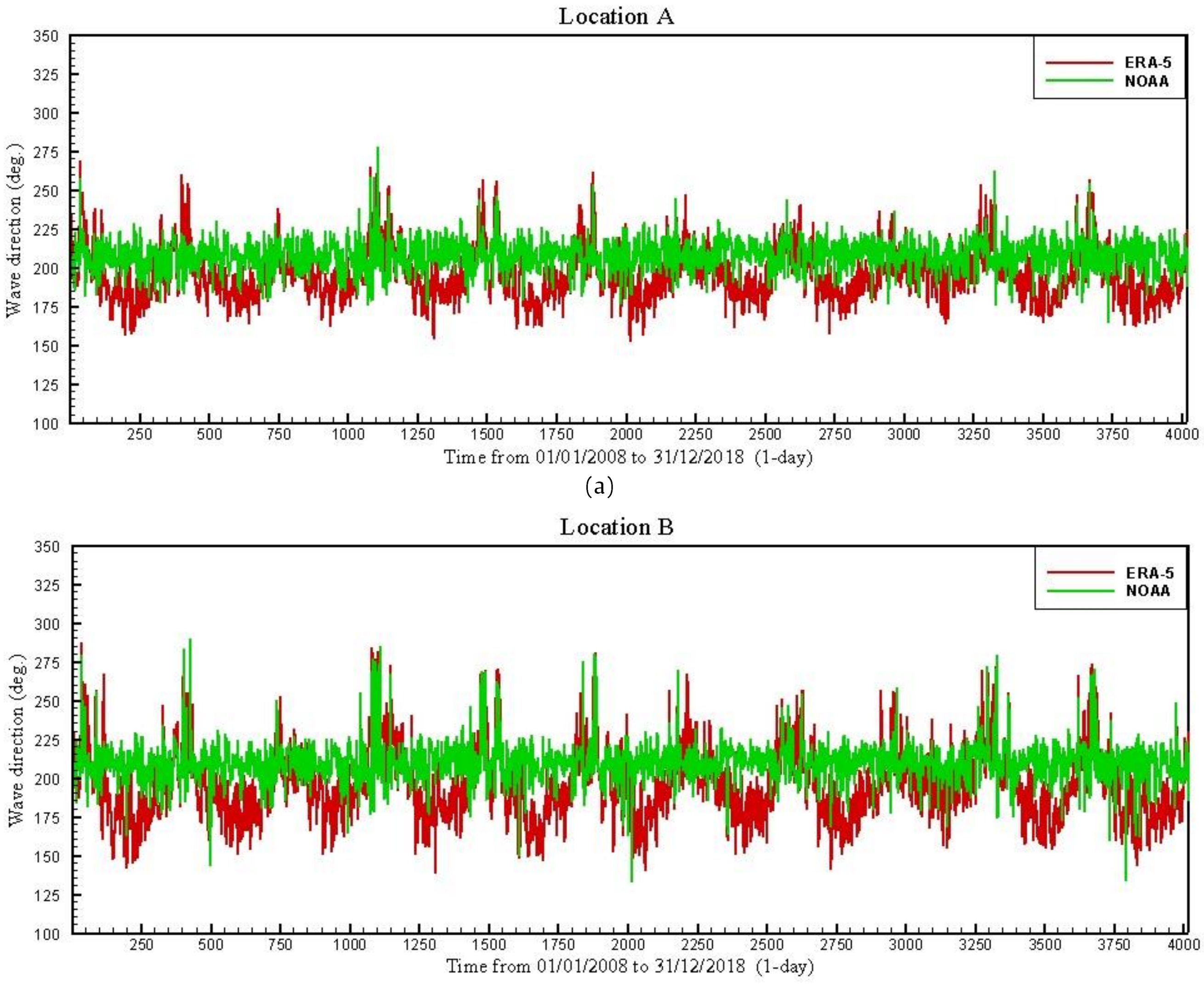
$$LCOE = \frac{Total\ Costs\ (\$)}{Total\ Energy\ Produced\ (MWh)} \tag{3}$$

LCOE allows for a direct comparison of the production costs of electricity from different energy sources, aiding in energy investment decision-making. Energy sources with lower LCOE are generally more economical and may be a better financial choice. LCOE can also be used as a tool to examine trends and developments in electricity production costs over time, aiding in understanding financial changes and competitiveness among various energy sources in the power industry.

3. Results and Discussion

3.1. Wave data reanalysis from 2008 to 2018

The average wave data is presented from January 1, 2008, to December 31, 2018 (Figure 2). This parameter represents the average direction of ocean waves. The unit is in degrees, signifying the direction relative to the North Pole. It indicates the wave's direction, with 0 degrees is coming from the north and 90 degrees is coming from the east. The average Wave Direction based on ERA5 at Point A is 195.41 degrees, and at Point B, it is 195.23 degrees. Meanwhile, based on NOAA, at Point A, it is 208.09 degrees, and at Point B, it is 210.06 degrees. According to this data, it is observed that the ERA5 data tends to decrease in value around mid-year, in contrast to the NOAA data, which appears relatively stable. In the future, this data can be utilized to determine the most optimal position for the Wave Energy Converter (WEC).

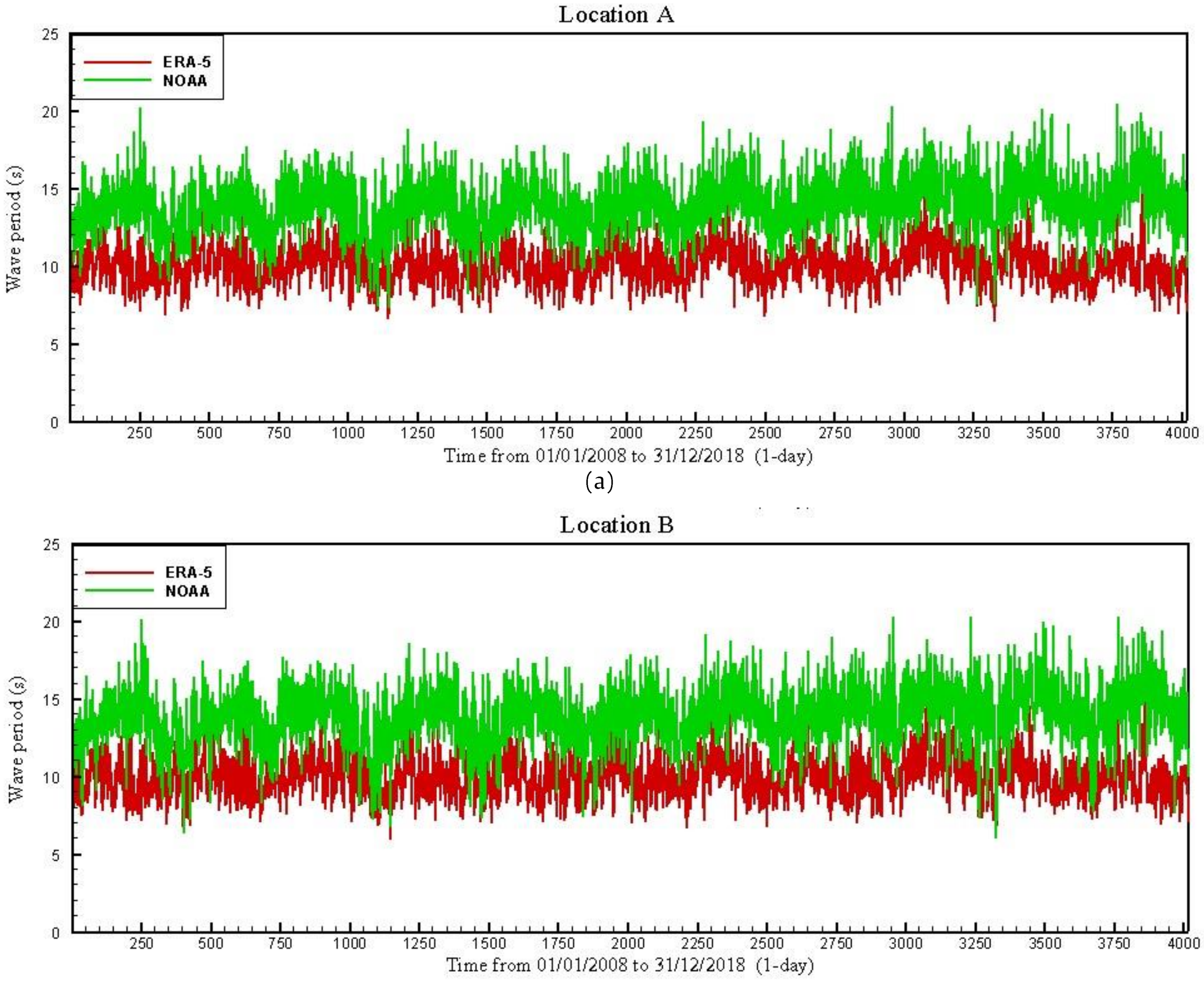


(a)

(b)

Figure 2. Wave direction at location points A and B from January 1, 2008, to December 31, 2018

This parameter represents the average time taken by two consecutive wave crests, at the sea surface, to pass a fixed point, measured in seconds. Lower values indicate faster and shorter waves. Based on the graph above, the average Wave Period according to ERA5 at Point A is 10 seconds, and at Point B, it is 9.88 seconds(Figure 3). Meanwhile, based on NOAA, at Point A, it is 13.88 seconds, and at Point B, it is 13.79 seconds. Additionally, it is observed that both data sources show a decrease towards the end of the year and an increase at the beginning of the year. Furthermore, it can be noted that NOAA has larger wave period data compared to ERA5.



(a)

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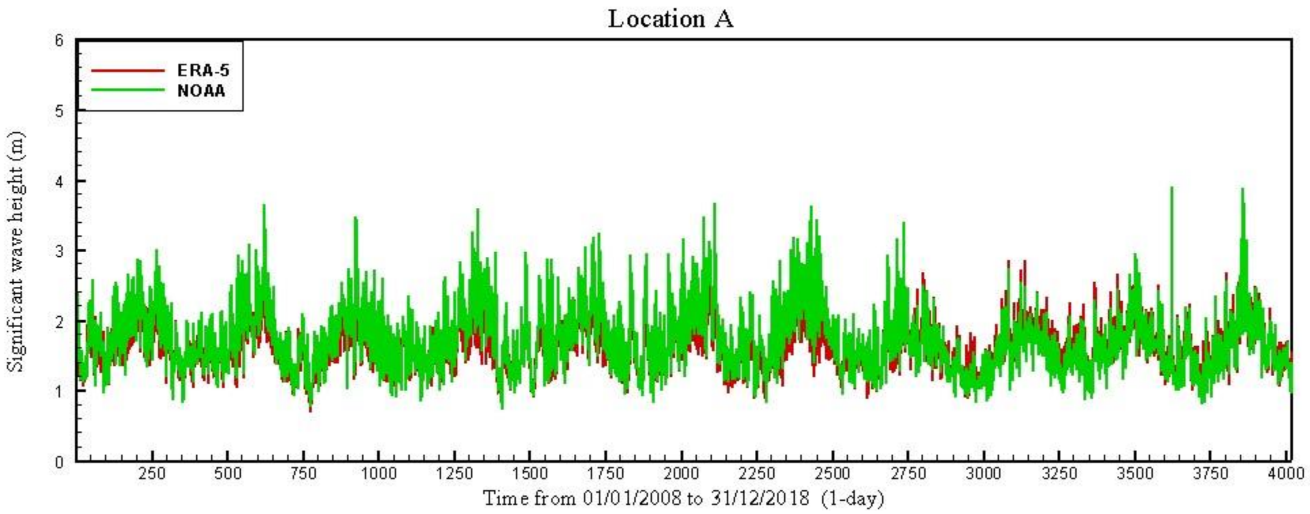
Figure 3. Wave period at location points A and B from January 1, 2008, to December 31, 2018

This parameter represents the average height of the highest one-third of ocean wave surfaces generated by wind and large waves. It represents the vertical distance between the wave crest and the wave trough. More precisely, this parameter is four times the square root of the integral for all directions and frequencies of the two-dimensional wave spectrum. Based on the graph above, the average Significant Wave Height according to ERA5 at Point A is 1.63 meters, with the highest value being 3.55 meters, and at Point B, it is 1.99 meters, with the highest value being 4.28 meters. Meanwhile, based on NOAA, at Point A, it is 1.72 meters, with the highest value being 3.89 meters, and at Point B, it is 2.06 meters, with the highest value being 5.06 meters. Both sources generally show a similar increasing trend from around May to October, suggesting a predictable trend in the future. The Significant Wave Height data will be used in conjunction with wave period data, as both data sets contribute to calculating the available wave potential (Figure 4).



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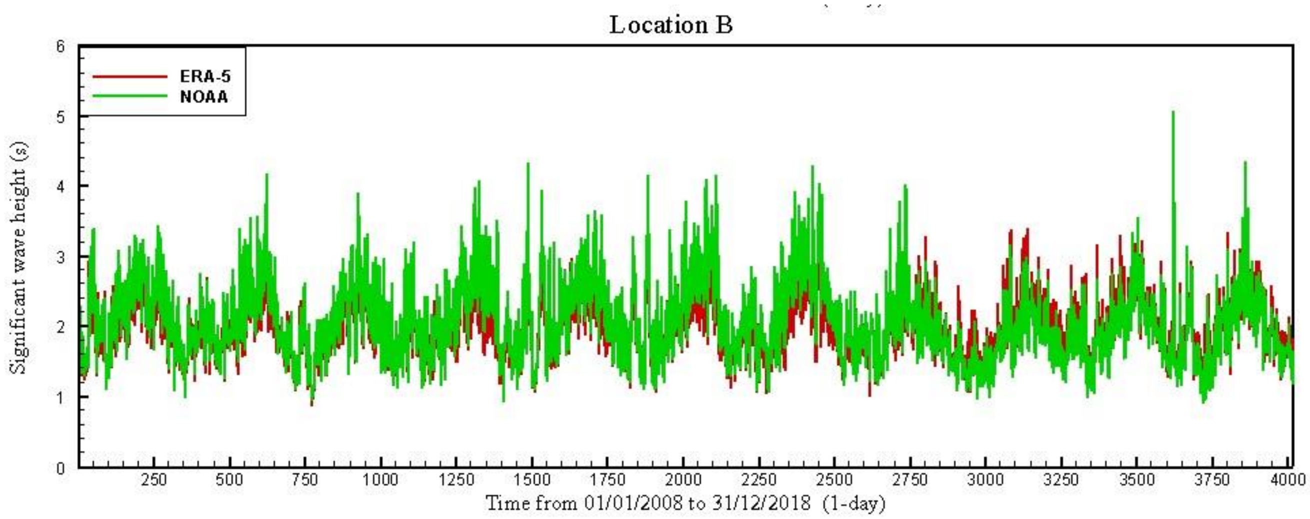
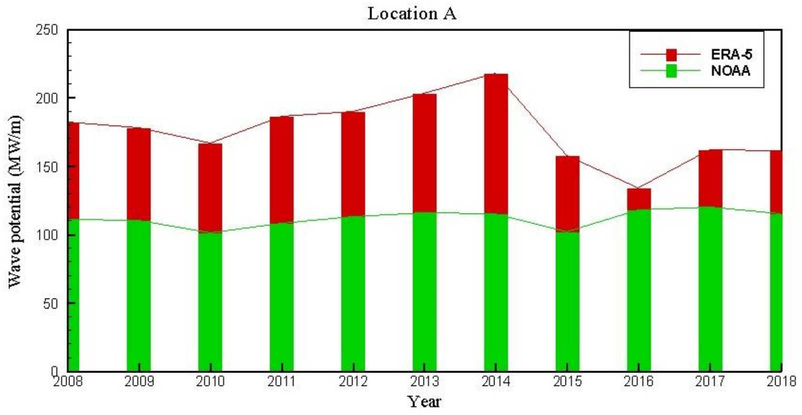


(b)

Figure 4. Significant wave height at location points A and B from January 1, 2008, to December 31, 2018

Subsequently is to calculate the wave potential for the two points from 2008 to 2018 based on the obtained Wave Period and Significant Wave Height data. The average measured wave potential per year according to ERA5 is 111.93 MW/m at Point A and 164.43 MW/m at Point B. Meanwhile, based on NOAA, it is 176.34 MW/m at Point A and 252.15 MW/m at Point B (Figure 5). Additionally, based on the graph, it is evident that NOAA has higher data compared to ERA5.



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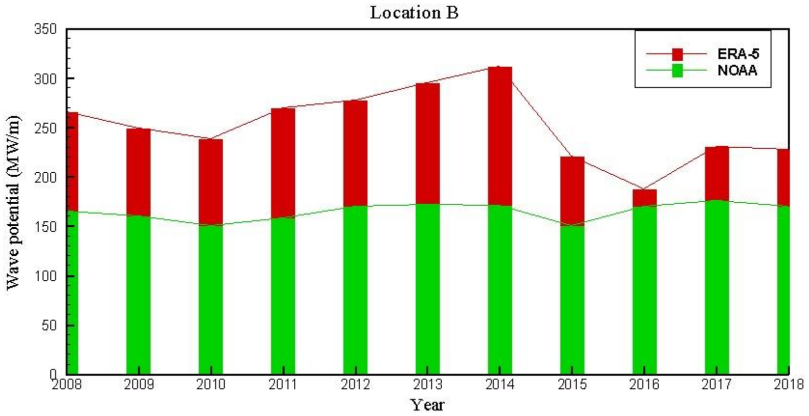

(b)

Figure 5. Wave potential at location points A and B from January 1, 2008, to December 31, 2018

The statistical analysis in Table 3 is an examination of the influence between the variables of significant wave height and wave period on the resulting wave potential. The results, as seen in the Multiple R column at 0.97, indicate a high correlation. Furthermore, the Adjusted R Square column falls around 0.94, suggesting that significant wave height and wave period explain 94% of the wave potential, with the remainder attributed to other factors. In conclusion, it can be inferred that significant wave height and wave period have a significant impact on the resulting wave potential.

Table 3. Statistical analysis of significant wave and wave period with respect to wave potential.

Data	Multiple R	R^2	Adjusted R^2	Std. Error	Observation
ERA5 A	0.973	0.946	0.946	1.582	4018
NOAA A	0.970	0.942	0.942	3.097	4018
ERA5 B	0.972	0.945	0.945	2.421	4018
NOAA B	0.971	0.943	0.943	4.315	4018

3.2. Economic analysis

Wave data is crucial in designing the Hydraulic Power Take Off (HPTO) to effectively capture wave energy (Figure 6). Information about wave height, period, and direction is needed to optimize the design and adjust HPTO parameters to match the characteristics of waves at a specific location. Wave data also plays a role in the operational control of HPTO. Information about wave conditions helps determine when HPTO should be active or deactivated to maximize energy absorption and protect the system from damage during extreme conditions. Therefore, precise adjustments based on wave data can enhance the performance and operational lifespan of HPTO.

Figure 6. Multi-point absorber WEC design [16]

Based on the wave data, the WEC used in this study is a multi-point absorber with a width of 2 meters and a total of 5 absorbers, capable of generating 130 kW and having a lifespan of 20 years, with deactivation in waves exceeding 5 meters. Next is to conduct an economic analysis, for which the following equipment specifications are required in this WEC.

Table 4. Specifications of the HPTO model of the WEC

Descriptions (unit)	Value
Hydraulic Cylinder	
Piston Area (m^2)	0.0031
Piston Stroke (m)	1
Check Valve	
Cracking Pressure (bar)	5
Max Opening Pressure (bar)	360
HP Accumulator	
Volume Accumulator (L)	32
Precharge pressure (bar)	5000
Spesific Heat Ratio	1.4
LP Accumulator	
Volume Accumulator (L)	32
Precharge pressure (bar)	3000
Spesific Heat Ratio	1.4
Hydraulic Motor	
Displacement (cc/rev)	19
Nominal Shaft Angular Velocity	4000 rpm
Oil Properties	
Viscosity (cSt)	50
Density (kg/m^3)	850

After obtaining the specifications of the WEC, the material costs can be estimated in Table 5 as follows

Table 5. Estimation of material price

Material	Biaya (usd)	Unit	Jumlah	Total (usd)
Steel	1000	Ton	1000	1000000
Fiberglass	12	m^2	50	600
Rubber damper	100	m^2	5	500
Wave sensors	2000	Set	1	2000
Hydraulic cylinders	350	Item	5	1750
Check valve	175	Item	20	3000
Motor hydraulic	1100	Item	1	1100
Hydraulic oil	1500	package	1	1500
Hydraulic hose	1000	package	1	1000
Hydraulic power pack	2500	package	1	2500
Accumulator	2500	Item	2	5000
Generator	500	kW	130	65000
Battery	20000	100 kWh	2	40000
Total				1,124,450

After obtaining the estimated device prices, the next step is to calculate CAPEX. The total CAPEX for constructing this power plant is calculated by adding the installation cost, which is 33% of the material cost [15].

Table 6. CAPEX evaluation

Item	Total (usd)
Material	1,124,450
Instalasi (33%)	371,068
Total	1,495,518

Next is to calculate Operational Expenditure (OPEX) at 2%. The following in Table 7 represents the OPEX and total cost in the construction of this power plant. Assuming $1 is equivalent to Rp 15,000 [15].

Table 7. OPEX evaluation

Item		Total (usd)
CAPEX		1,495,518
OPEX	2%	29,910
Lifetime	20 years	598,207
Total	IDR 31,405,875,000	2,093,725

In determining the Levelized Cost of Energy, the total cost and total capacity of the power plant are required. The following in Table 8 represents the total energy produced [13].

Table 8. Power generation capacity of the WEC

Parameter		Unit		Unit
Capacity	130	kW	0.13	MW
Lifetime	20	Year	175,200	Jam
Energy	22,776,000	kWh	22,776	MWh

After the total cost and total energy are obtained, the next step is to calculate the Levelized Cost of Energy for the power plant.

Table 9. LCOE evaluation

	Cost	Unit
Cost of Energy	$ 0.09	/kWh
	$ 91.93	/MWH

With the assumption that the multi-point absorber WEC has a capacity of 130 kW, the total cost required for construction is $2,093,725, and the Levelized Cost of Energy (LCOE) is $91/MWh. However, the total cost, including LCOE, may be higher than the obtained data due to fluctuating material prices. Next, based on the calculated Cost of Energy, it can be compared with other wave energy power plant technologies. The comparison is shown in Figure 7.

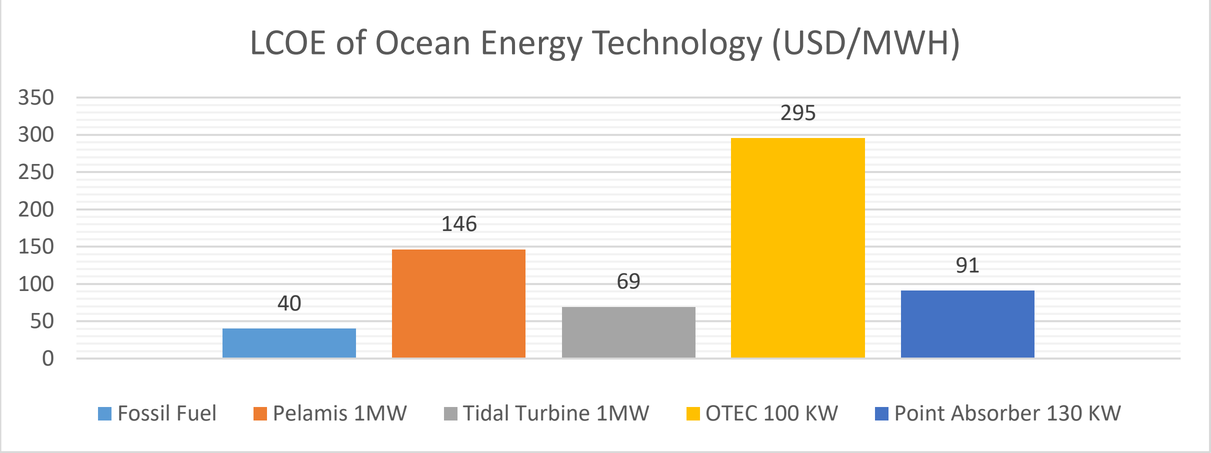

Figure 7. LCOE of ocean energy technology

It can be seen that the 130 kW Point Absorber has a Levelized Cost of Energy (LCOE) of $91/MWh, which is still higher compared to the 1 MW Tidal Turbine at $69/MWh. However, it is lower than the LCOE of the Pelamis 1 MW, which is $146/MWh, and the OTEC 100 kW with an LCOE of $295/MWh [13].

4. Conclusion

From the results of wave data reanalysis using ERA5 and NOAA from 2008 to 2018, and also the economic analysis of WEC, the following conclusions are obtained.

The average Significant Wave Height recorded by ERA5 at Point A is 1.63 meters, reaching its peak at 3.55 meters, while at Point B, it is 1.99 meters, with the highest value reaching 4.28 meters. In contrast, NOAA reports the Significant Wave Height at Point A as 1.72 meters, peaking at 3.89 meters, and at Point B, it is 2.06 meters, reaching its highest at 5.06 meters. The average Wave Period calculated from ERA5 data is 10 seconds at Point A and 9.88 seconds at Point B. In comparison, NOAA indicates a Wave Period of 13.88 seconds at Point A and 13.79 seconds at Point B. The average Wave Direction from ERA5 data is 195.41 degrees at Point A and 195.23 degrees at Point B, while NOAA records the Wave Direction at Point A as 208.09 degrees and at Point B as 210.06 degrees. NOAA provides more extensive data than ERA5, yet both sources exhibit the same trend of an increasing Significant Wave Height from May to October. The annual average wave potential based on ERA5 is 111.93 MW/m at Point A and 164.43 MW/m at Point B, while NOAA reports 176.34 MW/m at Point A and 252.15 MW/m at Point B.

Assuming a WEC in the form of a multi-point absorber with a capacity of 130 kW, the total cost required for construction is $2,093,725, and the Levelized Cost of Energy (LCOE) is $91/MWh which is still higher compared to the 1 MW Tidal Turbine at $69/MWh. However, it is lower than the LCOE of the Pelamis 1 MW, which is $146/MWh, and the OTEC 100 kW with an LCOE of $295/MWh.

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