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Potential of Ocean Wave Energy in the Northern Waters of Central Java as a Renewable Energy Source

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Abstract: Global efforts to reduce reliance on fossil fuels and greenhouse gas emissions increasingly emphasize the potential of marine energy as a renewable resource. This study analyzes the characteristics of significant wave height and estimates of wave energy and wave power in the northern waters of Central Java, Indonesia, during 2024. ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) were processed using Python to generate monthly maps of wave height and wave energy, daily time series of energy and power, and boxplots of monthly wave-energy distribution. The annual significant wave height ranged from 0.1 to 1.6 m, with the highest values occurring in December and March and the lowest in April and November. Monthly wave energy exceeded 1,200 J m^{-2}, while daily wave-energy density reached up to 3,000 J m^{-2} and daily wave power peaked near 6 kW m^{-1} during the west monsoon season. The highest variability occurred in March and December, reflecting the influence of monsoonal wind forcing. These findings demonstrate that the northern Central Java Sea has promising, relatively stable wave-energy potential, particularly during the west monsoon. They may contribute to Indonesia's clean-energy transition, coastal resilience, and small-island electrification, in alignment with Sustainable Development Goals 7 and 13.

Keywords: Wave Energy, Significant Wave Height, ERA5 Reanalysis, Monsoon, Renewable Energy

Introduction

The use of renewable energy has become a global strategic priority to address the energy crisis, rising greenhouse gas emissions, and environmental degradation caused by the exploitation of fossil energy sources. The IPCC report (2021) emphasizes that to limit global warming below 1.5 °C, the transition to low-carbon energy sources must be carried out quickly and massively. Ocean energy, including wave energy, is a renewable energy source increasingly considered because it is sustainable and does not depend on sunlight or wind, unlike solar and wind energy. Studies on the potential of ocean energy in the context of sustainable energy transition have been conducted by several researchers, such as Aderinto and Li (2018), who presented a comprehensive review of wave energy technology and its implementation challenges in developing countries, and Neill et al. (2009), who emphasized the importance of spatial characterization of tidal and wave energy potential.

These studies affirm that integrating marine energy sources, such as waves and currents, into national energy systems is essential for diversifying energy sources and reducing dependence on fossil fuels.

Indonesia, as an archipelagic country with more than 81,000 km of coastline, has significant marine energy potential, including tidal energy, ocean currents, temperature differences for Ocean Thermal Energy Conversion (OTEC), and ocean waves. Among these types of ocean energy, wave energy is considered the most promising in terms of energy density and wave regularity. This energy is generated by the transfer of wind momentum to the sea surface, which then propagates as waves, with energy quantified by wave height and period. The characteristics of wave energy include periodicity, stability, predictable intensity, and slight variation with day or night. Falcão (2010) and Cruz (2008) emphasized that the energy density of ocean waves can reach more than 20–70 kW/m in potential locations, making it one of the most promising forms of ocean energy in terms of technical and economic aspects.

In addition to its technical advantages, wave energy's potential is highly relevant to geopolitics and energy security. Remote or outermost coastal areas, which are difficult to reach by conventional electricity networks, can benefit directly from ocean energy conversion technology. In Indonesia, small islands in eastern regions such as Nusa Tenggara, Maluku, and Papua are ideal candidates for community-based marine energy development. However, the utilization of this potential is still faced with challenges of data, infrastructure, and limitations of spatial research. Therefore, spatial-temporal potential mapping is essential to ensure that development is carried out in a targeted and sustainable manner.

Spatial differences in wave characteristics across Indonesia show that energy potential is not evenly distributed. The southern coast facing the Indian Ocean receives large and energetic waves, while the northern waters of Java are more influenced by monsoonal winds, producing moderate but more stable wave energy throughout the year (Ribal et al., 2020; Badriana et al., 2021). This spatial contrast is essential to understand because it affects the direction of marine energy development and the selection of suitable technologies for each region.

Geographically, the Java Sea is a shallow, semi-enclosed sea located between the islands of Java, Kalimantan, and Sulawesi. Although it does not have a wind fetch as wide as the Indian or Pacific Oceans, the Java Sea is still influenced by the seasonal circulation of monsoon winds, which help form dynamic sea wave patterns. The northern part of Central Java, which directly borders the Java Sea, is a coastal area with dense activity, including the economy, ports, fisheries, marine transportation, and tourism. This region, particularly the coastal zones of Jepara, Pati, and Rembang, has not been widely studied for its ocean energy

potential, even though it has high, year-round, stable energy demand. Its consistent wave regime offers realistic opportunities for small-scale or nearshore energy systems that can support coastal electrification and industrial needs (Guillou et al., 2022; Anggraini & Santoso, 2023).

In the context of national policy, Presidential Regulation No. 112 of 2022 on the Acceleration of Renewable Energy Development emphasizes the importance of optimizing the potential of local resources in the national energy mix. However, most renewable energy development roadmaps in Indonesia still focus on land-based sources (solar and wind power), while marine potential has not been fully utilised. This study helps fill that gap by providing a spatially detailed assessment of wave energy in northern Central Java. This region has not been the focus of previous marine energy studies. The findings are also relevant to Sustainable Development Goals (SDGs) 7 and 13, which encourage the expansion of affordable clean energy and climate change mitigation (IPCC, 2021; Putra et al., 2018).

Along with the development of remote sensing technology and the availability of global reanalysis data such as ERA5, opportunities to study the potential of ocean energy in greater detail and more efficiently are increasingly available. The ERA5 dataset provides high-resolution atmospheric and oceanographic data for continuous estimation of significant wave height, period, and direction. This allows potential energy analysis to be carried out with broad temporal and spatial coverage and high precision. With Python-based processing and open-source geospatial software, this analysis can be replicated and further developed to support decision-making at the regional and national levels.

Several studies in Southeast Asia have shown the urgency of spatial approaches in analyzing wave energy potential. Research by Astariz and Iglesias (2015) in the western European coast showed that spatial mapping of wave energy potential combined with cost-location analysis could increase the efficiency of marine energy development in coastal areas. Such studies have not been widely conducted in Indonesia, especially in the waters of the Java Sea. In fact, with a high coastal population and increasing energy demand, the utilization of ocean wave energy can be a strategic solution to support low-carbon development in the region.

With this background, this research focuses on analyzing the potential of ocean wave energy in the waters of northern Central Java using significant wave height data from the ERA5 reanalysis product for 2024. This study aims to: (1) determine the spatial and temporal distribution of significant wave height in the study area; (2) calculate ocean wave energy potential based on ocean physics approaches; and (3) identify the most promising times and locations for sustainable ocean wave energy development in coastal areas. The results of this analysis are expected to strengthen scientific understanding of regional wave energy

patterns and support the planning of marine-based renewable energy programs for sustainable coastal development in Indonesia.

Methods

This study applies a quantitative–descriptive approach with spatial and temporal perspectives to evaluate the potential of ocean wave energy in the northern waters of Central Java. This approach was chosen because it can represent the complexity of ocean dynamics influenced by geographical, oceanographic, and meteorological factors, both spatially and temporally. By leveraging global reanalysis data and Python-based modelling, this research contributes to the development of a marine-energy database to support the transition to renewable energy in coastal Indonesia.

Study Area

The study area is located in the northern waters of Central Java, geographically covering coordinates 106.5°–115.5° East Longitude and 8.5°–3.5° South Latitude. The region represents a semi-enclosed tropical sea with dynamic seasonal patterns driven by monsoonal circulation. These dynamics produce measurable variations in wave height and energy that can be linked to local coastal morphology and wind exposure (Ribal et al., 2020; Badriana et al., 2021). To facilitate spatial segmentation, this area is divided into eight sub-regions based on coastal zones and their geographical characteristics, as shown in **Figure 1**:

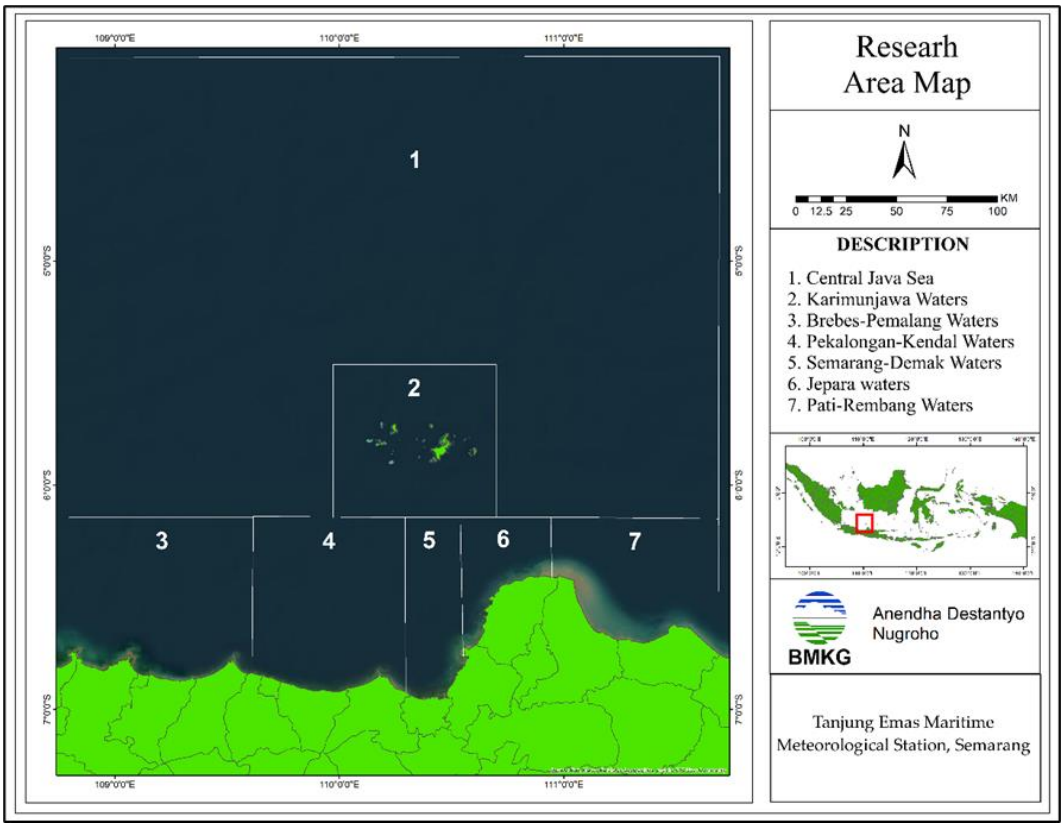

Figure 1. Research Area Map

This division follows the spatial zoning concept used in previous wave resource studies (Guillou et al., 2020), allowing the identification of specific coastal areas with higher energy potential that may be suitable for small-scale installations (Guillou et al., 2022).

Data and Sources

The primary data used in this study were ERA5 Reanalysis products developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 is the fifth-generation reanalysis that provides global atmospheric and oceanic estimates with a spatial resolution of 0.25° × 0.25° and a temporal resolution of 1 hour. Data were obtained in NetCDF format from the Copernicus Climate Data Store (CDS) for the period January to December 2024.

Two key parameters were used:

1. Significant Wave Height (SWH), in meters, representing the average height of the highest one-third of waves.
2. Mean Wave Period (MWP), in seconds, representing the average period between successive wave crests.

ERA5 data were selected because they have been widely validated for tropical and monsoonal regions, showing good agreement with satellite altimeter and buoy observations (Badriana et al., 2021; Wang et al., 2024). The integration of high-resolution atmospheric and ocean models in ERA5 allows a consistent reconstruction of wind–wave interactions across time and space, making it suitable for regional-scale energy assessments (Ribal et al., 2020).

Data Pre-processing and Processing

Data processing was performed using Python. Several systematic steps were applied:

1. Domain extraction: Global ERA5 data were clipped to the study-area boundaries to reduce file size and improve processing efficiency.
2. Time conversion: ERA5 numerical time units were converted to ISO 8601 format for consistency during temporal aggregation.
3. Land masking: Land grids were removed using Natural Earth topographic shapefiles at a 1:10 million scale. This was conducted with the geopandas and shapely libraries to avoid distortion of values in statistical calculations and visualizations.
4. Resampling and temporal aggregation: Hourly SWH and MWP were aggregated into daily and monthly means using arithmetic averaging to capture seasonal and daily variability.
5. Quality checks: Statistical functions in numpy and pandas were used to identify extreme values, distribution, and inter-parameter correlations. Detected anomalies were analyzed visually with graphs and distribution maps to ensure representativeness and accuracy.

These steps are consistent with standard practices in ocean wave modelling (Guillou et al., 2020; Clemente et al., 2020), ensuring that the resulting datasets accurately reflect the spatial and temporal variability of wave energy in the study area. The workflow was implemented in an open-source environment, making it reproducible for further scientific and policy applications (Anggraini & Santoso, 2023).

Estimation of Wave Energy and Power

The estimation of wave-energy potential was based on two main parameters: wave energy per unit area (J/m²) and wave power per unit crest length (kW/m).

1. Wave Energy (J/m²)

The total energy per unit area of the sea surface is calculated based on the linear wave formula:

$$\boldsymbol{E = \frac{1}{8}\rho g {H_s}^2}$$

Where:

- $\boldsymbol{E}$ = wave energy per unit area (J/m²)
- $\boldsymbol{\rho}$ = seawater density (1025 kg/m³)
- $\boldsymbol{g}$ = gravitational acceleration (9.81 m/s²)
- $\boldsymbol{H_s}$= significant wave height (m)

This equation quantifies the total potential and kinetic energy per unit area stored in wave motion (Falcão, 2010; Cruz, 2008).

2. Wave Power (kW/m)

Wave power is the energy transferred by waves per unit time and per unit wavelength. The formula used is:

$$\boldsymbol{P = \frac{p g^2 {H_s}^2 T}{64\pi}}$$

Or in another form that is more commonly used:

$$\boldsymbol{P = E.c_g}$$

Where:

- $\boldsymbol{P}$ = wave power per unit crest length (W/m)
- $\boldsymbol{T}$ = mean wave period (s)
- $\boldsymbol{c_g}$ = the group velocity of deep-water waves, calculated by: $\boldsymbol{c_g = \frac{gT}{4\pi}}$

by substituting $\boldsymbol{E}$ and $\boldsymbol{c_g}$ into the equation $\boldsymbol{P = E.c_g}$ The explicit form is obtained:

$$\boldsymbol{P = \frac{p g^2 {H_s}^2 T}{64\pi}}$$

This formula estimates the transport rate of wave energy per meter of wave crest, representing the practical energy available for conversion (Aderinto & Li, 2018; Guillou et al., 2022). All computations were performed for each grid cell in the ERA5 dataset and aggregated spatially to obtain daily, monthly, and annual averages. Seasonal variation was analyzed to capture the contrast between monsoonal periods, while spatial distribution maps were used to identify coastal hotspots for wave energy extraction (Tung & Chien, 2023).

Spatial-Temporal Visualization and Analysis

Visualization is carried out to present the results intuitively and support scientific interpretation. Two main approaches are used:

a. Spatial visualization: monthly and annual distribution maps for the parameters H_s and wave energy, using thematic color palettes from the cmocean library and masking land areas so that the visualization results focus on the ocean.
b. Temporal visualization: daily trend graphs and monthly boxplots showing fluctuations in wave power and energy throughout 2024. This is important for identifying the seasons or months with the highest energy.

Validation and Limitations

Validation was carried out internally through three approaches:

1. Verification of dimensions and units: ensuring that the spatial and temporal dimensions of the extracted data are consistent with the study area configuration, and that the parameter units such as SWH (meters) and MWP (seconds) are standardized and aligned with the analysis requirements.
2. Extreme values and physical consistency check: inspecting very high or very low wave values to ensure that no numerical errors are present, and confirming that the values remain within logical limits and are consistent with the characteristics of tropical waters.
3. Statistical evaluation across parameters: conducted to assess coherence between interrelated parameters, for example, the correlation between wave height (Hs) and wave period (T) in the context of the western and eastern monsoon seasons. Statistical inconsistencies may indicate issues with input data or processing errors.

Although no in-situ buoy data were available for direct validation, the reliability of ERA5 for the Java Sea has been confirmed in previous regional studies (Ribal et al., 2020; Badriana et al., 2021). The main limitations of this study are the spatial resolution and the absence of directional spectrum analysis, which will be addressed in future work through higher-resolution modelling and field calibration campaigns.

Results and Discussion

A. Monthly Distribution of Significant Wave Height (SWH) in the Northern Java Sea, 2024

Significant wave height (SWH) is a primary parameter widely used in oceanographic studies and marine planning because it represents the average height of the highest one-third of waves measured within a given time interval. Statistically, SWH is directly related to ocean energy conditions and the risk of high waves to human activities in coastal and marine areas. In this context, the analysis of SWH is crucial not only for estimating wave energy but also for developing early warning systems, designing marine structures, and managing the coast.

The general formula to calculate significant wave height from the wave energy spectrum is:

$$H_s = 4 \cdot \sqrt{m_0}$$

where m_0 The zero moment of the wave spectrum represents the total energy in the spectrum. There is also an empirical relationship between SWH and maximum wave height, namely:

$$H_{max} \approx 1.86 \cdot H_s$$

In this study, the seasonal and spatial patterns of significant wave height in the northern Java Sea during 2024 were analysed. The objective was to identify the periods with the most active wave energy conditions and to determine areas that consistently experience high waves throughout the year. This pattern also serves as a basis for assessing the spatial potential of wave energy utilization in the region. The results of the visualization are presented in **Figure 2** below:

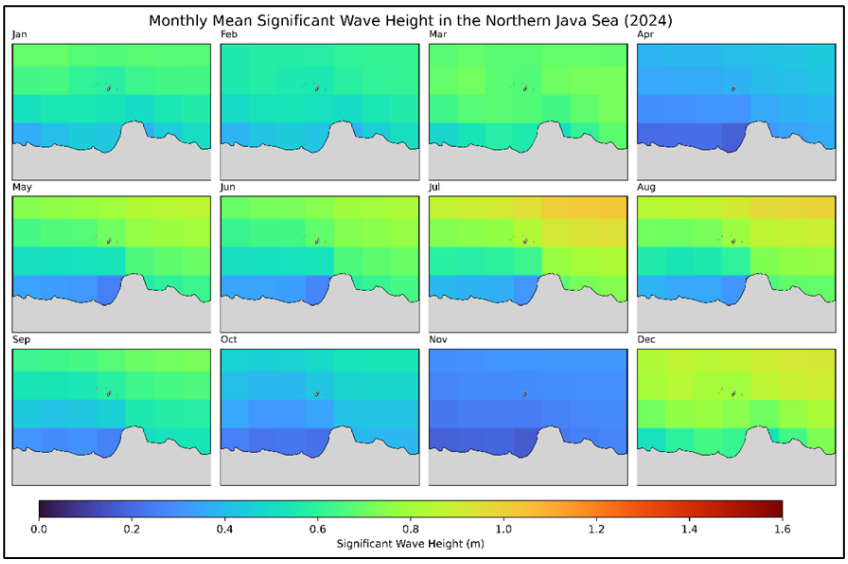

Figure 2. Monthly Mean Significant Wave Height (SWH) in the Northern Java Sea 2024

In this study, the seasonal and spatial patterns of significant wave height in the northern Java Sea during 2024 were analysed. The objective was to identify the periods with the most active wave energy conditions and to determine areas that consistently experience high waves throughout the year. This pattern also serves as a basis for assessing the spatial potential of wave energy utilization in the region.

The analysis shows that the highest SWH occurred in December, as indicated by dominant yellow-to-orange colours, particularly in the northern waters of Jepara, Demak, and Rembang. The maximum value this month exceeded 1.1 meters. A similar pattern was also observed in March, although with a slightly more limited distribution, with SWH values ranging from 1.0 to 1.1 meters.

On the other hand, the lowest SWH occurred in November and April, with average wave heights below 0.5 meters, as shown by light to dark blue colours. This reflects a relatively calm period during the transition between monsoons, when wind speeds are relatively low, and no dominant wind direction is observed.

Spatially, the central to eastern part of the northern Java Sea, particularly the waters north of Demak, Jepara, and Pati, tends to have higher SWH values than the western part, such as north of Brebes and Pemalang. This distribution indicates the influence of coastal topography and direct exposure to northwesterly monsoon winds that strengthen wave generation during the rainy season.

These results support the findings of Ardhuin et al. (2011) and Morim et al. (2019), which show that tropical ocean waves are strongly influenced by seasonal wind variability. A study by Tung et al. (2023) in Vietnamese waters also found that the highest waves occur during the western monsoon season, while the lowest occur during transitional seasons. Thus, the northern Java Sea exhibits wave characteristics consistent with the oceanographic dynamics of Southeast Asia.

B. Monthly Distribution of Wave Energy in the Northern Java Sea, 2024

The monthly average wave-energy distribution in 2024 is shown in **Figure 3**. Seasonal variability is clearly observed, reflecting the influence of monsoonal wind circulation. The highest values were recorded in December, exceeding 1,200 J/m², particularly in the northern waters of Jepara, Pati, and nearby regions. March also showed elevated values of 800–1,000 J/m², reflecting the strengthening of the west monsoon.

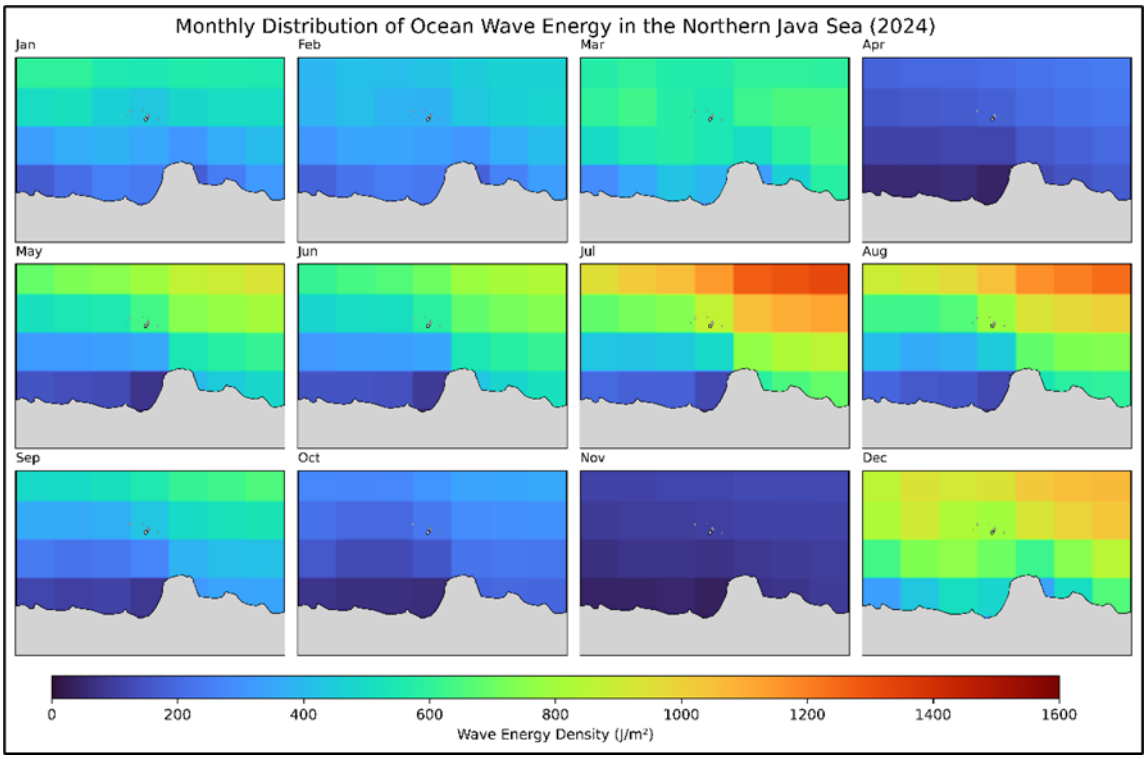

Figure 3. Monthly Distribution of Ocean Wave Energy in the Northern Java Sea 2024

In contrast, April and November displayed the lowest values, generally below 300 J/m², indicating calm conditions during the transitional monsoon period. Spatial analysis further shows that the central and eastern northern Java Sea, especially the waters off Kendal, Demak, and Rembang, consistently received greater wave energy than the western areas, such as Brebes and Pemalang.

These findings confirm that wave-energy potential in the northern Java Sea is strongly seasonal and spatially uneven, with December–March as the peak period and the central–eastern coastal waters as priority zones for renewable-energy development.

C. Daily Trends of Wave Energy in the Northern Java Sea, 2024

The daily trend of wave energy throughout 2024 is presented in Figure 4 in units of J/m². This graph illustrates the temporal dynamics of wave intensity that determine the available ocean energy for potential conversion into renewable energy. It highlights how fluctuations in wave activity correspond to monsoonal wind patterns and seasonal atmospheric variability that directly affect marine energy potential. Such temporal analysis is essential for understanding when ocean-energy systems can operate most efficiently.

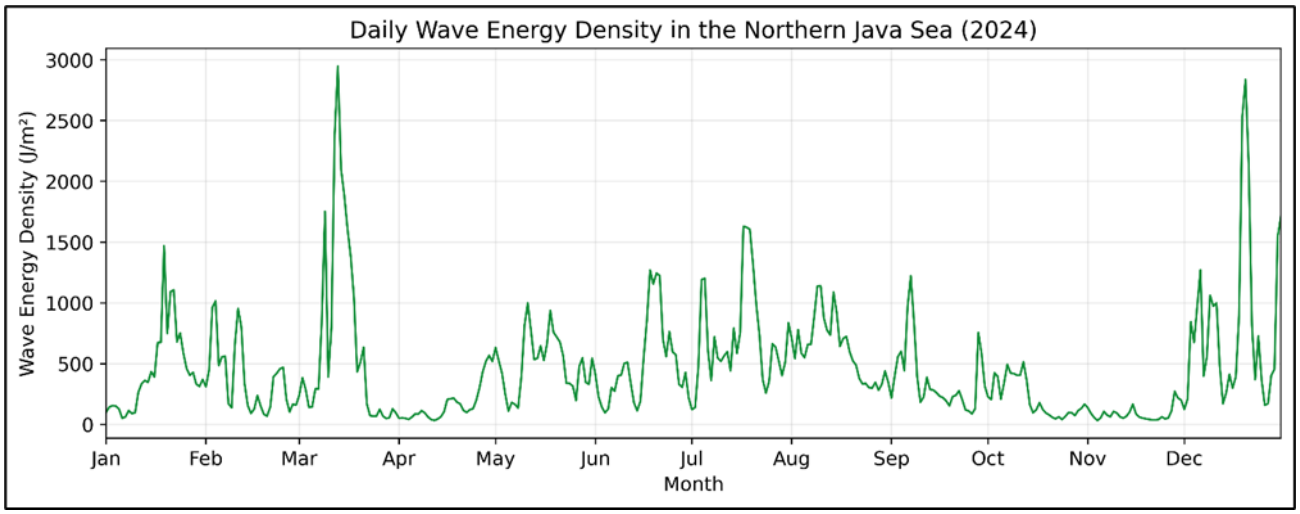

Figure 4. Daily Wave Energy Density in the Northern Java Sea 2024

In general, the highest wave energy occurred in March and December, with daily values reaching approximately 2,800–3,000 J/m². Secondary peaks were also observed in January–February and July–August, typically ranging from 800 to 1,500 J/m². These peaks correspond to the influence of the west monsoon, when stronger northwesterly winds enhance wave generation across the northern Java Sea. Conversely, the lowest wave-energy levels were recorded in April and November, with most values below 200 J/m², reflecting calm sea conditions during the inter-monsoonal transition period.

Overall, this pattern indicates that December–March is the primary high-energy season, while July–August is a secondary period of moderate energy potential. These results suggest that the timing of renewable wave-energy exploitation in the northern Java Sea should prioritise months with enhanced ocean-energy activity. From a policy perspective, this seasonal predictability provides an opportunity to integrate wave-energy systems into local grids during peak months, supporting small-island electrification and sustainable coastal development. Aligning such initiatives with the goals of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) would help strengthen Indonesia's transition toward low-carbon energy systems and enhance the resilience of coastal communities against climate-related challenges.

D. Monthly Distribution of Wave Energy in the Northern Java Sea, 2024

The statistical distribution of wave energy during 2024 is shown in Figure 5 as boxplots, with median values, interquartile ranges, and outlier counts for each month. This visualization provides a more straightforward overview of the temporal variability of wave-energy intensity across the northern Java Sea. It also helps identify periods of high variability that coincide with monsoonal transitions and extreme weather events. By examining the spread and outliers, the graph reveals how wave energy responds to short-

term atmospheric fluctuations. The wider boxes during active monsoon months indicate unstable ocean conditions, while the narrower ones reflect more stable seas. Such statistical representation helps determine operational windows for wave-energy conversion systems and for evaluating the reliability of potential installation sites.

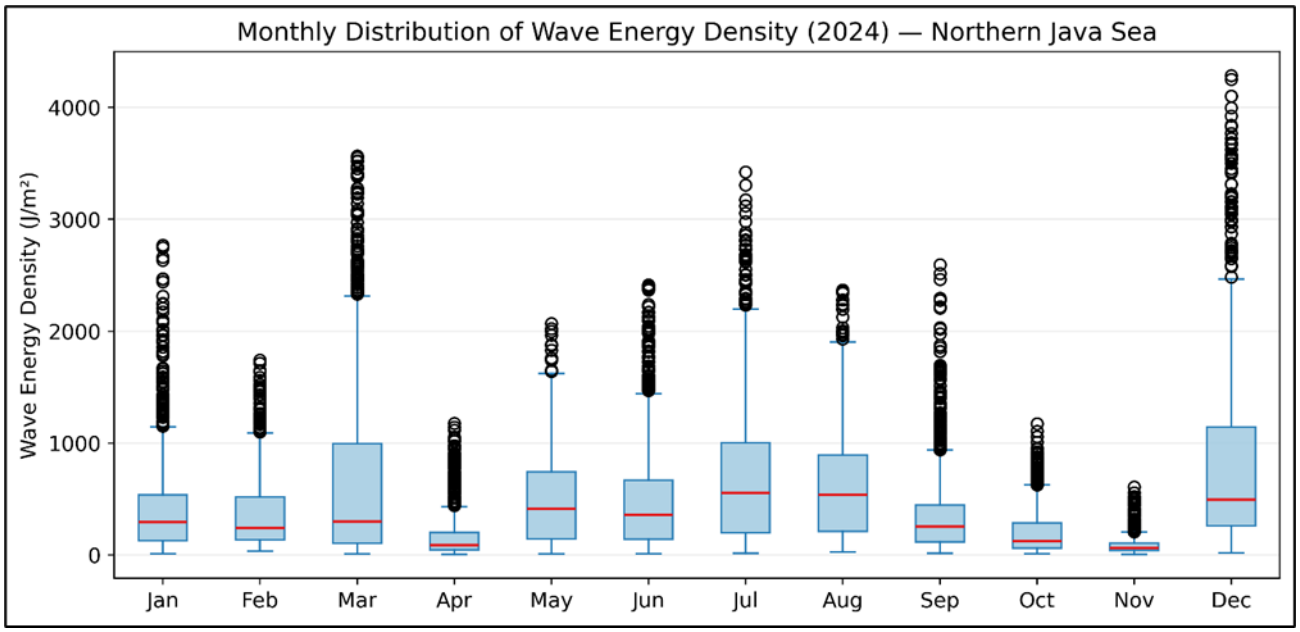

Figure 5. Monthly Distribution of Wave Energy Density in the Northern Java Sea 2024

The results indicate that March and December recorded the highest fluctuations, with median energy values between 400 and 500 J/m² and maximum values exceeding 4,000 J/m². A large number of outliers during these months suggests more frequent high-energy wave events. Conversely, April and November exhibited narrower distributions and lower median values, mostly below 150 J/m², indicating calmer ocean conditions. The remaining months, particularly July and August, showed moderate variability with median values around 400–600 J/m². Overall, these results emphasize the strong seasonal pattern of wave energy in the northern Java Sea, primarily governed by monsoonal wind cycles, with high-energy periods occurring during the west monsoon (December–March) and relatively stable conditions during the transitional months (April and November).

This seasonal pattern implies that coastal regions such as Jepara, Demak, and Rembang could serve as priority zones for pilot-scale renewable energy projects. Integrating wave-energy systems during high-energy months would enhance local electricity supply stability while supporting the diversification of Indonesia's renewable energy mix. Moreover, such initiatives align with the objectives of Sustainable Development Goals (SDG 7 and SDG 13), promoting affordable clean energy and climate resilience in coastal communities.

E. Daily Trends of Wave Power in the Northern Java Sea, 2024

The daily trend in wave power throughout 2024 is shown in **Figure 6**, in units of kW/m. This parameter describes the amount of energy that can be converted per meter of wave crest length and serves as a key indicator of the potential for ocean-wave energy conversion. Monitoring daily wave-power variability is essential for estimating reliable operational periods and understanding how seasonal ocean dynamics influence the stability of renewable energy in coastal areas.

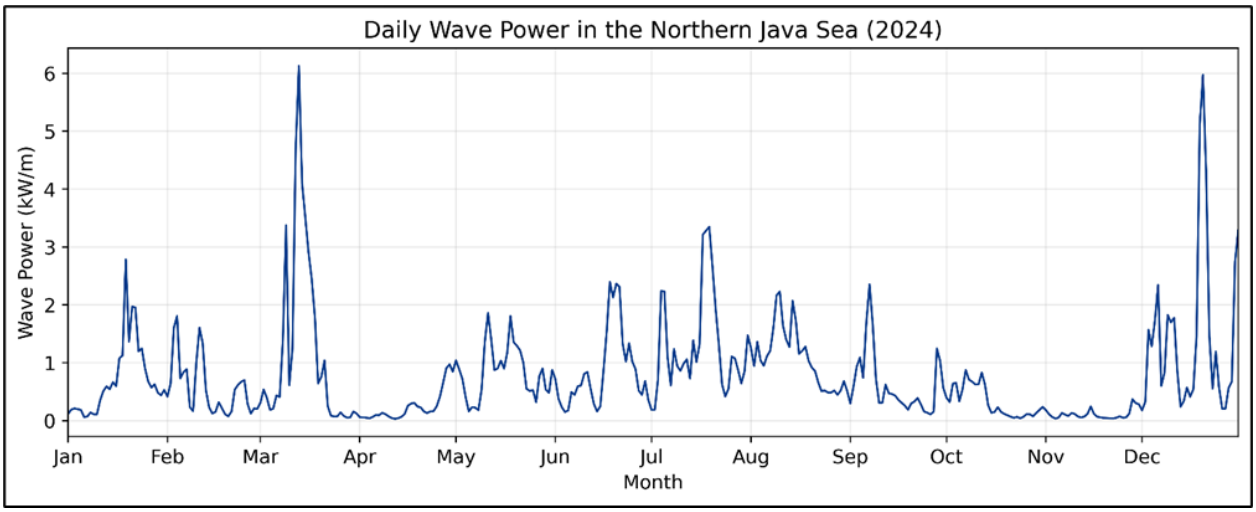

Figure 6. Daily Wave Power in the Northern Java Sea 2024

The results show that the highest peaks occurred in March, with daily values reaching around 6 kW/m, followed by another increase in December, when wave power exceeded 5 kW/m. These peaks coincide with the west monsoon season when stronger northwesterly winds enhance wave formation across the northern Java Sea. Secondary peaks were also recorded in January–February and July–August, ranging from 1 to 3 kW/m, indicating moderate energy potential. In contrast, from April to October, wave power remained relatively stable at lower levels, mostly below 1 kW/m, reflecting calm seas during the inter-monsoonal and dry-season periods.

Overall, this pattern confirms that December to March represents the main operational window for wave-energy utilization in the northern Java Sea. The temporal distribution of wave power closely corresponds to the west-monsoon intensity, which drives the variability of ocean kinetic energy. These findings highlight the importance of adaptive energy strategies that align harvesting operations with seasonal peaks. Incorporating wave-energy systems during these high-power months could improve coastal electricity reliability, particularly for small islands and fishing communities. Such an approach also supports the goals of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by promoting clean energy production and strengthening climate resilience in Indonesia's maritime regions.

Comparison with Similar Studies in Other Tropical Regions

When comparing this study's results with similar research in other tropical coastal regions, such as Sulawesi, the Philippines, and Thailand, the findings are consistent with global trends in wave energy distribution. Research conducted by Ribal et al. (2020) in Indonesian waters and by Tung and Chien (2023) in central Vietnam showed that regions influenced by strong, consistent monsoonal winds tend to have higher wave energy potential. Similarly, studies in the Philippines and Thailand reported that coastal areas exposed to seasonal monsoon systems demonstrate significant temporal variation in wave energy intensity, with higher peaks during the wet season and calmer conditions during the inter-monsoon transition (Clemente et al., 2020).

In comparison, the northern coast of Central Java exhibits a distinct pattern, with wave energy potential remaining relatively moderate yet stable throughout the year. This stability provides a predictable, consistent renewable energy source, which is advantageous for integrating marine energy systems in regions where other renewables, such as wind or solar, exhibit greater variability. The predictability of wave energy in this area also supports Indonesia's broader transition toward sustainable coastal energy solutions, aligning with the objectives of SDG 7 and SDG 13 to expand clean energy access and enhance resilience to climate variability.

Contributions to Sustainable Energy Goals

This study's results contribute directly to Indonesia's goal of increasing the share of renewable energy in its national energy mix, as stipulated in Presidential Regulation No. 112 of 2022 on the Acceleration of Renewable Energy Development for the Supply of Electricity. The findings from this research can assist policymakers and energy developers in identifying suitable locations for wave energy projects and in designing energy systems that can support the national grid, particularly in regions with limited access to other renewable resources. Furthermore, by promoting the development of marine-based renewable energy, this study supports the implementation of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), both of which emphasize the transition toward sustainable and climate-resilient energy systems in Indonesia's coastal and island regions.

Conclusion

The northern coast of Central Java has demonstrated significant potential for developing wave energy systems. By analysing substantial wave height (SWH) data and the corresponding wave energy distribution, this study has identified key coastal areas with high energy potential, particularly during the monsoon season. The findings indicate that

December to March are the peak months for wave energy generation, with regions like Jepara, Demak, and Rembang showing the highest potential.

These results not only highlight the potential of wave energy in the region but also support the viability of small-scale, localized energy solutions for remote coastal and island communities. Wave energy systems can contribute to the electrification of small islands, providing a reliable, sustainable energy source that supports the national goal of diversifying energy resources. The spatial and temporal consistency of wave energy in the northern Java Sea offers a unique opportunity for renewable energy development, aligning with Indonesia's energy transition goals and contributing to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

Future research should focus on technical feasibility, including the integration of small-scale wave energy converters into local energy infrastructure, and on assessing the environmental impacts of such systems. Further studies on the long-term sustainability of wave energy as a renewable source and its compatibility with other renewable energy sources will be critical to advancing marine-based energy systems for the future.

Furthermore, this study provides a valuable reference for policymakers, guiding the site selection for wave energy projects in the northern Java Sea and offering insights into potential impacts on local economies and socio-economic resilience.

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