Spatial temporal analysis for potential wave energy resources in Indonesia

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Abstract. Future energy becomes a concern all over the country. The fossil energy resources are decreasing now, and the exploitation these resources leave behind environmental problems. It was increasing the gas emission of CO₂ and affected global warming. Renewable and environmentally friendly energy resource is the right choice to solve the problem. Wave power is one of the marine resources that have an advantage in high density and continuity. This research aims to investigate the spatial-temporal distribution of wave power potency. This study location between 90°E – 150°E; 15°N – 15°S. We used a hindcast data simulation of WAVEWATCH-III with 0.125° (~14 km) spatial resolution and six-hourly data for 25 years (1991-2015). We determine the potential wave power resources by considering the wave flux, Presence of Exceedance (PE), Coefficient of Variation (Cv), Monthly Variability Index (MV), and Seasonal Variability Index (SV). The result shows that in the open sea, such as the Indian Ocean and Pacific Ocean, contains higher wave power density. The level of stability shows that this area is more stable than the inner sea. The power density changes periodically conducted with the monsoonal cycle. The highest energy flux in the Indian Ocean achieved when Australian monsoon and lowest when Asian monsoon, whereas in the Pacific Ocean, the peak of power density reaches when Asian monsoon onset and the lowest in June-July-August. The most stable level coherent with the highest power density, and the lowest level is in the transition period. Based on this analysis, the most potential areas for wave power development are in Enggano, Lampung, Banten, West Java, Central Java, DIY, East Java until Bali.

1. Introduction

The energy necessity is increasing in line with industrial development, economic, and population growth. Electric power necessity in Indonesia projected growth 8.7% annually through 2024 [1]; fossil fuel still pledged for its fulfillment [2]. The extraction and exploitation of fossil fuel derive environmental problems such as increasing CO₂ emission, which is indicated to affect global warming [3]. Producing electricity with coal power plants predicted to doubled CO₂ emission in 2024 compared to 2015 [1]. Problem-solving is using renewable energy. There are several renewable energy sources in Indonesia, such as solar energy, wind power, biomass, geothermal, tidal power, hydropower, nuclear, ocean current energy, ocean thermal energy conversion (OTEC), and wave power [4].

Wave power is one of the environmentally friendly renewable energy source [5]. It does not produce carbon emission (zero emission). Marine wave energy has excellency in high density and continuity [6], so it is potential to be developed. There are two main approaches in treated the source of energy [3]: (1) wave energy converters design [7]; and (2) potential site assessment for wave power development (
This research uses the second group approach, which the aim is to investigate the spatial and temporal distribution of potential areas for wave power development.

Wave power per unit length (energy flux per unit of the wave crest length, P) calculated based on equation 1. The energy flux depending on significant wave height and their period [13].

\[ P = \frac{\rho g^2 H_m^2 T_e}{64 \pi} \approx \left( 0.5 \frac{\text{kW}}{\text{m}^3 \cdot \text{s}} \right) H_m^2 T_e \]  

(1)

\( P \) is energy flux per unit wavelength, \( H_m \) is significant wave height, \( T_e \) the wave period, \( \rho \) is water density, and \( g \) is gravity. Wave flux linearly with a square of significant wave height and wave period. The significant wave height is in meter, and the period is in seconds. So the energy flux is in kW m\(^{-1}\) [14].

PE calculated based on the value of relative frequency, such as formula 2.

\[ FR = \frac{\sum fi}{\sum fi} \times 100\% = \frac{fi}{n} \times 100\% \]  

(2)

where \( fi \) is a count of specific data, and \( n \) is a count of total data. The lowest wave power density calculated in this research is 0.8 kW/m, with the presence of exceedance up to 2.5%. The grids with wave power density below 0.8 kW/m and PE more than 2.5% were ignored [9]. So, we only analyzed the areas which qualify any requirement, 1) the distance is up to 50 nautical mile from coastal and 2) PE on wave power density below 0.8 kW/m is less than 2.5%.

Wave energy flux represents the potential of an area. This potency classified based on Zheng et al., 2012 [15] and Yaakob et al., 2016 [16]. There are differences in classification both of them, and we modify to combine their class. The entire class showed in Table 1.

| No. | Wave energy flux | Class   |
|-----|-----------------|---------|
| 1.  | > 1 kW/m        | Very low|
| 2.  | 1-2 kW/m        | Low     |
| 3.  | 2-6 kW/m        | Enable  |
| 4.  | 6-15 kW/m       | Medium  |
| 5.  | >15 kW/m        | High    |

Source: Zheng et al., 2012; Yaakob et al., 2016

2. Data and method

The research location includes all over the Indonesia area. Every location has special potency and character, so we must analyze and classify each of them. WAVEWATCH-III was used in this study to generate 25 years reanalysis of Indonesia waters. Langondan et al., 2016 [17] reported at least 10 years of data needed to assess potential regional sites accurately. A regular latitude-longitude grid with 0.125° resolution was applied. Six hourly significant wave height (Hs) and period (T) used to calculate the wave energy flux. We only analyze the area 50 miles from the coast. Wind data reanalysis from Cross Calibrated Multi-Platform (CCMP), Navy Operational Global Atmospheric Prediction System (NOGAPS), and Navy Global Enviromental Model (NAVGEM) were used for input WAVEWATCH-III model. Global and regional domains are uses for model nesting simulation. The global domain covers 70° N-70° S and 0-360° with 0.75° x 0.75° spatial resolution. The regional domain covers 20° N-20° S and 90° E-150° E and 0.125° x 0.125° grid resolution. The data used in this research is from 1991-2015.

Wave energy stability level is an essential factor in determining the site suitability of the wave power plant. Areas with a high level of stability are chosen to ensure the sustainability of the electricity produced [3]. The energy stability analyzed based on the Presence of Exceedance (PE) [9], Coefficient of Variation (Cv), Monthly Variability Index (MV), and Seasonal Variability Index (SV) [18].

Coefficient of Variation calculated by formula 3 and 4.

\[ Cv = \frac{S}{\overline{x}} \]  

(3)

\[ S = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}{n-1}} \]  

(4)

where \( \overline{x} \) is an average of total data, and \( S \) is the standard deviation.
The lower value of $C_v$ represents the high stability area on wave energy flux [19]. The concept of monthly and seasonal variability indices is used to analyze the variability of wave power flux more accurately. The calculations are shown in formula 5 and 6:

$$MV = \frac{P_{M1} - P_{M12}}{P_{\text{year}}},$$

$$SV = \frac{P_{S1} - P_{S12}}{P_{\text{year}}},$$

MV is monthly variability indices, $P_{M1}$ is the highest monthly average of wave power density, $P_{M12}$ is the lowest monthly average of wave power density, and $P_{\text{year}}$ is the annual average of wave power density. SV is seasonal variability indices, $P_{S1}$ is the highest seasonal average of wave energy flux, $P_{S12}$ is the lowest seasonal average of wave power density. These indices show the stability level of an area. The low indices indicate the high stability of wave power density; contrariwise, the high indices indicate that area is unstable [18]. The temporal variation analyzed based on the monthly average of data point (21 locations).

3. Result and discussion

Wave energy potency climatologically evaluated based on wave power density. In general, the energy flux in the open sea (the Indian Ocean and the Pacific Ocean) is higher than in the inner sea, such as the Java Sea, the Banda Sea, and the Arafura Sea. Figure 1 shows that the potential area is bordering with the open sea (the Indian Ocean and the Pacific Ocean). The South China Sea, the Arafura Sea, and other inner sea are not included in the potential category because of their discontinuity. The PE value, in general, is more than 2.5%, so we eliminate this area. This condition is in line with Koto, et.al., 2014 [20]. Their research shows that WEC installed on the Malaysian coast does not work throughout the year due to wave height fluctuations.

The high average wave power density distributed throughout western Sumatra, Southern Java, until East Nusa Tenggara diverges from 15-30 kW/m. In general, the energy flux in western Sumatra is higher on the outer island, such as Simeulue, Nias, Siberut, Sipura, Pagai, and Enggano, compared with the coastline of Sumatra Island. The Bengkulu and western part of Lampung location is relatively high on energy flux in western Sumatra coastal because of their open area. However, in another area with no border island in front of their coastal such as Nangro Aceh Darussalam (NAD), Talauld Island, Morotai, and northern Papua coastal, their power density is low diverged from 2-15 kW/m as shown in Figure 1.

![Figure 1. Wave energy flux climate in Indonesia (1991-2015).](image-url)
We evaluate 21 sample location in this research to analyze the spatial and temporal variation of energy density and their stability; they are Nangro Aceh Darussalam (NAD), Simeulue (SIM), Nias, Siberut (SIB), Pagai, Bengkulu (BKL), Enggano Island (ENG), Lampung (LPG), Banten (BNT), West Java (JABAR), Central Java (JATENG), Yogyakarta Special Region (DIY), East Java (JATIM), Bali, Sumbawa (SMB), Sumba, Kupang (KPG), Talaud (TLD), Morotai (MRT), Biak and Papua. The monthly power density and coefficient of variation shown in Fig 2. We clustered 21 locations into four graphics for easier to evaluate. In cluster 1, NAD and Nias energy density are insufficient compared with Pagai, Simeuleu, and Siberut. Their power density only 5-10 kW/m compared with 8-28 kW/m in the other area. The peak of power density in these areas is coherent with Australian monsoon June-July-August (JJA), and the lowest is in December-January-February (DJF) eventuate with the Asian monsoon. The coefficient of variation index, which represents the stability level in cluster 1 indicates that their index is lowest in JJA and highest in May coherent with the transition period. This condition determines that in Australian monsoon, the power density is more stable than in the transition period. Spatial

Cluster 2 consists of five locations, Bengkulu, Enggano Island, Lampung, Banten, and West Java. The power density is highest in July-August-September with 25-35 kW/m, and contrary, the lowest is in DJF with 6-13 kW/m. The coefficient of variation index in this cluster commonly at a low level whose indicates this area is stable. The index has seen higher in the transition period than the monsoon onset. This condition presented the power density are more stable in onset monsoon (DJF and JJA) than the transition period (MAM and SON). The condition in cluster 2, also seen in cluster 3, consist of Central Java, DIY, East Java, Bali, Sumbawa, and Kupang. The highest power density eventuates with Australian monsoon onset with 21-37 kW/m. Cluster 4 consists of Talaud, Morotai, Papua, and Biak. Unlike another cluster, this cluster reaches a maximum power density in DJF coherent with Asian monsoon and minimum in JJA. Their coefficient of variation tends a similar pattern, more stable in DJF and unstable in the transition period.

Wave power density in the research area influenced by the monsoonal cycle. In the monsoon onset, their energy flux increases. The coastal area bounded with the Indian Ocean commonly reaches the maximum power density coherent with the Australian monsoon. Contrary to the research area bounded with the Pacific Ocean, are in maximum when Asian monsoon is onset. The wind field in monsoon onset is more persistent than the transition period. This condition is similar to Kurniawan et al., 2011 [21] declares that the monsoon cycle has a direct implication on wave heigh in Indonesia waters.
3.1. Monthly variability index

The Monthly Variability Index is a method for assessing the stability level of the data based on its monthly data average. The lower index value indicates, the more stable the data. Figure 3. shows the spatial distribution of monthly variability indices in the research area. According to this index, the most stable regions are in open waters such as the Indian Ocean along Sumatra to Kupang, Arafura Sea, Banda Sea, parts of the Java Sea, and the Pacific Ocean along Papua to the Sulawesi Sea. It means that the power density in this area tends to be stable. However, these indices only assessing the data stability based on their variation, without their quantity of the power density itself. The unstable areas marked by high variability index, they are Tomini Bay, Seram Sea, Flores Sea, part of the Makassar Strait, Cenderawasih Bay, southern Java Sea, Malacca Strait, Karimata Strait and most of the South China Sea. These data show that there is a higher monthly variability on those than other regions. The unstable condition caused by inconsistencies in energy density in this area. In certain months the power density is high and decreases in other months, so the monthly fluctuations are high. This condition is represented by monthly index value at a high level.

Figure 3. Monthly Variability Index of wave power density over the Indonesia

3.2. Seasonal variability index

The seasonal variability index is a similar concept with a monthly variability index, except the average seasonal data used in this method. These indices represent the seasonal stability of energy flux in the research area. The spatial distribution of this index shown in Figure 4.
Figure 4. Seasonal Variability Index of wave power density over the Indonesia

The location bounded with the Indian Ocean, and the Pacific Ocean commonly has a low seasonal variability index. In the inner sea, generally have a higher variability index. The highest index found in Tomini Bay that indicates there are high seasonal variations. This index shows that the monsoon cycle influences this area, so seasonal variations clearly seen. In general, the seasonal variation index has a lower range than the month index. The monthly index of energy flux in this study area is between 0-32.5, while the seasonal index is only in the range 0-14. This result is similar with Habibie et al., 2019 [22] that significant wave height are more stable in open-sea than inner sea. According to López-Ruiz et al., 2016 [3], there are similarities; the seasonal variability index spatially shows that in the inner sea and the South China Sea, very influenced by the monsoon season.

Wave power density in Indonesia waters is varies spatially and temporally. Spatial distribution of wave power density conjunct with wave height distribution. The wave power density with high category distributes along western Sumatra, southern Java, until West Nusa Tenggara. The outer island of western Sumatra waters commonly has higher wave power density than the coastal area. The wave energy flux in the open sea is higher compared with the inner sea and coastal area. Commonly their category is high in the ocean and decreases when entering the coastal area. Another research shows similarities with our research; wave power density decreases when entering the coastal because of the bathymetry changing and the barrier of islands group [23]. The group of islands in the western of Sumatra clearly shows that their existence directly influences the decreasing wave power density in their backyard.

The coefficient of variation, monthly variability index, and seasonal variability index analysis simultaneously shows the high level on stability area are along western Sumatra, especially in Bengkulu and Enggano, southern Java, until West Nusa Tenggara. Eventually, this area also has a high category in wave power density. So this area has an excellent prospect to wave power plant development. The stability of wave power density indicates the continuity of the electrical energy will be produced. The high wave power density will be useless if his stability level is low because the electricity produced is unstable. According with Habibie et al., 2019 [22] the most stable area based on significant wave height are in open-sea. The Red Sea, for example, there is a high fluctuation in monthly wave power density. November-April is producing the highest energy, but in another month, their energy decreases significantly. This study concluded that the Red Sea is relatively abundant for wind and wave energy. However, seasonal fluctuations are a limiting factor that must be considered if harvesting will be done [17].

In this research, the temporal distribution analysis of wave power density based on the seasonal pattern. Indonesia's territory is affected by the monsoon. It directly implicated on wave power density, which is in the onset monsoon they tend to increase and contrary, decrease in the transition period. This
fluctuation clearly is seen; in Australian monsoon (JJA), their density on the Indian Ocean is more than 30 kW/m, while in DJF, it drops to 6-15 kW/m. The condition in the Pacific Ocean is opposite with the Indian Ocean; the maximum wave power density is in DJF with 15-30 kW/m and drops into 6-15 kW/m in JJA. This result is similar to Mirzaei et al., (2014) [23]; their research shows a seasonal variation on power density in the South China Sea caused by the monsoon cycle. The highest power density occurs in the DJF with 12 kW/m in open water, whereas the coastal area is only 5 kW/m. In MAM and SON, the power density is 1-3 kW/m and 0.5 kW/m and 2 kW/m in JJA. Their research also shows which the inter-annual variability such as El Nino Southern Oscillation (ENSO) influences wave power density in Malaysia. The maximum occurs in the La Nina event [23]. Seasonal fluctuations also occur in other regions such as Canada, the wave power density reaches 50 kW/m in winter and changes dramatically to 6.5 kW/m in the summer [24]. They analyze monthly and yearly variations; the result shows there is no significant annual variation, but the seasonal variation is clearly seen, especially in winter and summer.

Some researcher requires the wave power density of at least 10 kW/m to develop power plant reliability [25]). Considering their stability and wave power density throughout the year, there are six potential areas to develop into a power plant. This area has a power density of more than 10 kW/m throughout a year and high stability. This area is Enggano, Lampung, West Java, DIY, East Java, and Bali.

4. Conclusion
The monsoon cycle is the leading player to control the variability of wave power density and their stability level in the research area. The power density in the Indian Ocean is at the highest level, eventuating with Australian monsoon and lowest in Asian monsoon onset, but in the Pacific Ocean are the opposite, their maximum power density is coherent with the Asian monsoon. Based on the wave power resources represented by 21 sample locations, considering PE value, C, MV, and SV, the potential area to develop wave power plants are Enggano, Lampung, West Java, DIY, East Java, and Bali.

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