Ocean wave measurement and wave energy calculation using overtopping power plant scheme

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Abstract. Indonesian seas have not been used as a source of electricity yet. One of the potential and abundant sources of energy from the sea is ocean waves. This study describes the measurement of the wave characteristics and calculates its spatial and temporal energy in Pari Island which can be utilized as electrical energy using overtopping ocean wave power plants scheme. The energy that can be harvested from ocean waves is calculated by wave energy converter using the Wave Dragon WEC. This converter is the terminator type. Sea waves on the Pari Island are classified as the smooth sea with 0.16-0.51 meters significant wave height and 2–4 seconds period. The calculated WEC can produce energy up to 28 Mega Joules and power up to 6 Mega Watts. Based on this calculation, Wave Dragon which is an overtopping WEC is able to meet the electricity needs on Pari Island with two options, The first one is using 35 units of WD 1 on the Pari Island Coast with a 500 m distance from the settlement, or the second one is using 6 units of WD 2 which is located in the northeast region of Pari Island waters with 18 Km distance from the settlement of Pari Island.

1. Introduction
Indonesia has more than 17,500 islands which are dominated by small islands [1]. Productive natural resources such as seagrass, mangroves, coral reefs are generally available in small islands, makes them suitable for conservation. Small islands also have large environmental services because they attract tourists by their marine potential. However, the utilization of small islands is not optimal [2], one of the reason is there are many small islands still need the electricity supply from the big island.

Indonesia is a maritime country with a huge sea. The proportion of Indonesia’s sea is about 76.94% of the country's area [3], but it has not been used as a source of electricity yet. There are some sources of energy from the ocean such as wave, current, tide, temperature gradient, and salinity gradient [4]. Marine energy in Indonesia can produce more than two Tera Watts electrical power if it were harvested optimally [5]. Marine energy is also clean energy and suitable for use on the coastal area and small island.

One of the potential and abundant energy sources from the ocean is waves. Ocean waves are water movement that goes up and down continuously. Ocean waves are generally caused by the wind and a small part is caused by other factors such as seismic activity, volcanic activity, the gravity of space objects, or human activities, for example, the motion of ships [6]. The one that has a great effect to makes wave variations in Indonesian waters is monsoon [7].

There are three types of ocean wave energy converters (WEC), those are point absorber which absorbs energy at one point of rising and falling sea levels, attenuator that absorbs energy linearly in the direction of the wave movement, and terminator that traps and absorbs the coming wave energy by its spatial movements [8]. There are two energy sources that can be harvested from ocean waves. The first
one is using the waves to drive the object directly, the second one is using the variations of air pressure that was caused by the waves [9].

Terminator type has the opportunity to harvest more energy than the other types because it absorbs wave energy from its spatial movements. There are two kinds of terminator WEC, the first one is oscillating water column (OWC) that utilizes variations of air pressure due to ocean waves [10], and the second one is overtopping that utilizes water runoff due to ocean waves [11]. The oscillation of water column oscillations in OWC causes it requires two turbines to harvest energy optimally when the water goes up or down. Another way is using the valve system that allows the air goes in and out by keeping the turbine rotate in one direction [12]. The overtopping system has a simpler concept because it works by utilizing runoff water that goes up to the top of the converter, then goes back to the ocean by drives the turbine with a fixed rotation direction.

Pari Island is a small island that has a high potential for marine tourism and requires electricity supply for tourism industry activities. Pari Island has a declivous topography, small tidal range, and constant wave [13]. This island is suitable to be the location of the overtopping power plant that is expected to support the electricity needs of the Pari Island community. This study describes the measurement of the wave characteristics and calculates its spatial and temporal energy in Pari Island Waters which can be utilized as electrical energy using overtopping ocean wave power plants.

2. Method

2.1. Tools and data sources

The tool that used in this research is a laptop with multiple operating systems, the first one is Linux with PyFerret 7.4.4 for data extraction and time series analysis, the second one is Windows with Excel 2019 for data processing, Ocean Data View 4.7 for wave data visualization, and Lakes Environmental WRPLOT 8.02 for wind data visualization. The data which are used in this research are the wave model, wave buoy movements, wind speed, and wind direction.

The ocean wave model in this study was downloaded from the Copernicus Marine Environmental Monitoring Service (CMEMS). The model data were generated from the Météo-France forecast system based on the MFWAM model which is a third-generation wave model with ECWAM-IFS-38R2 computational code [14]. The model has a 1/12 degree of spatial resolution and produces data every three hours. The downloaded data has an area in 106.4–106.8 °E and 5.7–6.1 °S with a period from March 1, 2018, to February 28, 2019.

Data from the model must be validated by primary data. Primary wave data was measured by wave buoy from Panrita Indonesia. Wave buoy that used was moored on the coast of Pari Island (106.62 °E, 5.86 °S). The data were generated by wave buoy is a displacement of the buoy that caused by waves.

Wind data is needed to determine the speed and direction of the wind that can be used as a reference to predict the direction of the coming waves. Wind data were obtained from Panrita Indonesia’s Automatic Coastal Weather Station (ACWS) located on Pari Island (106.52 °E, 5.81 °S). The wind data used has a period between 2 August 2018 - 10 July 2019.

2.2. Equations

2.2.1. Model validation. Model validation is needed to get the accuracy of the model data to field data. The model is validated by wave height from wave buoy. The validation method used is the root mean square error (RMSE) [15]. The RMSE value is an error that can be generated by the model. The lower error indicates the better model. RMSE values can be obtained by equation 1 which D is primary data, M is model data, and n is the number of data [15].

\[
\text{RMSE} = \sqrt{\frac{\sum(D-M)^2}{n}}
\] (1)
2.2.2. Wave dimensions. This research uses wave model data from CMEMS and primary data from wave buoy. Wave models from CMEMS are significant wave heights and wave periods. The data which downloaded from wave buoy is wave buoy movements on the Z-axis. The wave height of the wave buoy can be obtained by measuring the difference between the crest and the trough of the wave. Calculation of significant wave height (Hs) can be generated by averaging the 30% highest wave from all of the data that was shown by equation 2 which h is 30% highest wave heights and n is 30% of the number of data [16].

\[
H_s = \frac{h_1 + h_2 + h_3 + \cdots + h_n}{n} \text{ (m)}
\] (2)

Wave period (T) can be generated by using equation 3 [17]:

\[
T = \frac{3.55}{\sqrt{h}} \text{ (s)}
\] (3)

Wavelength (\(\lambda\)) can be generated by using equation 4 [18]:

\[
\lambda = 5.12T^2 \text{ (m)}
\] (4)

2.2.3. Energy calculation. Wave energy calculation based on the use of overtopping WEC. Overtopping WEC is a terminator type wave energy converter that harvests wave energy in from its spatial movements. Overtopping WEC utilizes water runoff that was caused by waves (Figure 1). The waves will be facing the reflector and will be directed to the center, then goes to the top and fill the reservoir, then the water will go back to the ocean by drives the turbine [8].

![Figure 1. Overtopping scheme.](image)

Calculation of energy, power, energy density, and power density of waves using the equation 5 [12], which Ew is wave energy, w is wave reflector length, \(\rho\) is water density, g is gravity, and a is wave amplitude.

\[
E_w = \frac{1}{2} \rho w g a^2 \lambda
\] (5)

Wave energy density (Ewd) is energy that can be harvested per area of the wave that can be measured by equation 6.

\[
E_{wd} = \frac{1}{2} \rho g a^2 \text{ (J/m}^2)\]
(6)

Power (Pw) that can be produced by ocean waves can be generated by calculating the energy of waves per time unit.

\[
P_w = \frac{E_w}{T} \text{ (Watt)}
\] (7)
Power density (P_{wd}) is the power that can be harvested per area of the wave that can be measured by equation 8.

\[ P_{wd} = \frac{E_{wd}}{T} \text{ (Watt/m}^2\text{)} \]  \hspace{1cm} (8)

3. Results

3.1. Model validation
Wave height model is validated by wave height from the conversion of wind data and wave height from wave buoy. The validation was conducted at the south of Pari Island (106.62 °E, 5.86 °S). Model validation is carried out on 3-13 June 2018 using wave buoy data and 2 August 2018 - 28 February 2019 using wind data.

The result of the model validation is shown in Figure 2 that shows the similar fluctuations wave height from the model, wind data, and wave buoy data. A high difference occurs in December-January, the wave height shown by the wind data was very high beyond the model data. That can be caused by the presence of tropical cyclones in the south and southwest of Indonesia which is coming in December-January [19]. It was causing wind speed escalation on Pari Island. RMSE calculation of the wave height from the model is conducted by using 37 data from wave buoy data. The error value of the model's wave height generated by RMSE calculation is about 0.13 m. This error is low enough, so the model data can be used to measure the energy and power on Pari Island waters.

3.2. Wave characteristics
The wave heights on Pari Island is about 0.16–0.51 m, and the wave period is about 2-4 seconds (Figure 3a). The Ocean wave on Pari Island Waters is categorized as the smooth sea with the second Douglas sea scale [20]. The high waves occur in the east monsoon (June–August) and west monsoon (December–February), whereas in the transition monsoon the wave heights tend to below. That indicates the seasonal wind patterns have an impact on Pari Island waves [13]. Ocean waves on Pari Island are also measured by wave buoy on 3-13 June 2018, these measurement data show the wave heights are about 0.3 m and the wave period are about 2 s (Figure 3b).
Figure 3. Wave Characteristics, (a) data model, (b) wave buoy, (■) significant wave height, (—) wave period.

3.3. Wave energy and power density
Energy density is the energy that can be harvested per wave area. The wave energy density which is presented in Figure 4 is conducted to determine the area that has rich wave energy. Wave energy density on the Pari Island waters ranges from 100–325 J/m². The highly wave energy density occurs in the east monsoon with 275–325 J/m² energy density, whereas in the west monsoon, the first transitional monsoon, and the second transitional monsoon, the energy density is about 150–200 J/m², 150–200 J/m², and 100–150 J/m². Higher density in the observation area occurs in the northeast region of Pari Island, which reaches 550 J/m².

Figure 4. Wave energy density, (a) first transitional monsoon, (b) west monsoon, (c) second transitional monsoon, (d) west monsoon, (J) Pari Island.
Power density is the wave power that can be harvested per wave propagation area. The power density which is presented in Figure 5 is used to determine the area that has a rich wave power. Wave power density in Pari Island is in the range of 30-80 W/m². The highly wave power density occurs in the east and west monsoons with the wave power density are about 70-80 W/m² and 60-70 W/m², whereas in the first transition power plant and second transition power plant the wave power density is about 50-60 W/m² and 30-40 W/m². Similar to the wave energy density, the higher wave power density occurs in the northeast region of Pari Island which reaches 130 W/m².

![Figure 5. Wave power density, (a) first transitional monsoon, (b) west monsoon, (c) second transitional monsoon, (d) west monsoon, (5) Pari Island.](image)

### 3.4. Wave energy and power

#### 3.4.1. The scenario of energy harvesting

The results of the wave power density calculation show that the wave power density on Pari Island tends to below, while the wave power density is high in the northeast region of Pari Island. Based on that result, this research using two scenarios of the way to harvesting the energy and power, the first one is using nearshore power plant and the second one is using offshore power plant. Both scenarios have their each advantage and disadvantages, the use of offshore power plant has considerable wave power, but it requires the underwater cable installation that requires more study and more cost [21], whereas nearshore powerplant has closer distance close to the settlement, but the potential wave power that can be generated tends to below.

WEC that used in the wave energy and power calculation is Wave Dragon (WD) which is an overtopping WEC [8]. Wave Dragon has two wave reflectors which are used to focus the wave moving towards the sloped middle part (ramp), the wave will move up and spill water into the reservoir, then the water will move down, drive the turbine, and return to the ocean as presented in Figure 6 [22].
Two locations of both of power plants are Pari Island's south coast (106.62 °E, 5.86 °S) for near coast powerplant and the northeast region of Pari Island waters (106.75 °E, 5.75 °S) for offshore powerplant (Figure 7). The nearshore powerplant has a 0.5 Km distance to the settlement and the offshore powerplant has 18 Km. Wave Dragon provides four types of wave energy converters with each specification (Table 1). The wave energy converter that was used in the calculation is WD 1 as a nearshore power plant and WD 2 as an offshore power plant. The use of them based on energy density and bathymetry in each region.

Table 1. Specification of wave dragon.

| Wave Dragon dimensions | WD 1 | WD 2 | WD 3 | WD 4 |
|------------------------|------|------|------|------|
| Power density (KW/m)   | 4    | 24   | 36   | 48   |
| Weight (ton)           | 237  | 22,000| 33,000| 54,000|
| Wide (m)               | 58   | 260  | 300  | 390  |
| Length (m)             | 33   | 150  | 170  | 220  |
| Wave reflector length (m) | 28  | 126  | 145  | 190  |
| Height (m)             | 3.6  | 16   | 17.5 | 19   |
| Reservoir volume (m³)  | 55   | 5,000| 8,000| 14,000|
| Number of turbines     | 7    | 16   | 16–20| 16–24|
| Power per unit (kW)    | 20   | 4    | 7    | 1    |
| Annual power (GWh/y)   | -    | 12   | 20   | 35   |
| Water depth (m)        | 6    | > 20 | > 25 | > 30 |
3.4.2. Wave energy. The wave energy that calculated by the scenario of using WD 1 with a 28 m wave reflector for nearshore power plant and WD 2 with a 126 m wave reflector for offshore power plant (Table 1). The result of the energy calculation is presented in Figure 8 that shows that the energy produced by the nearshore power plant reaches 4 MJ, while the offshore power plant produces more energy which reaches 28 MJ. That was conducted because the offshore power plant has more energy density and longer wave reflector.

![Wave Energy Graph](image1)

**Figure 8.** Wave energy calculated, (—) nearshore power plant, (—) offshore power plant.

3.4.3. Wave power. Wave power Fluctuation on Pari Island is presented in Figure 9 that shows a pattern similar to wave energy (Figure 8). That was conducted because of the thing that most influences power is energy. The maximum power that can be generated by the nearshore power plant is 1 MW, while the maximum power that can be produced by the offshore power plant is 6 MW that occurs in June, end of December and the end of January. The minimum power occurs in April and October to the beginning December, in which the power that was generated by the near coast power plant reaches only 0.25 MW and the offshore power plant only produces a 3 MW maximum power.

![Wave Power Graph](image2)

**Figure 9.** Wave power calculated, (—) nearshore power plant, (—) offshore power plant.

The Statistics Indonesia recorded that there were 395 customers of State Electricity Enterprise of Indonesia in 2016 on Pari Island [23]. If all of them use 450 W electricity, the power which is required
by Pari Island is 0.18 MW. If all customers use 900 W electricity, the power which is required by Pari Island is 0.36 MW.

Generally, power plants are not able to convert all energy sources into electrical energy, in this case, Wave Dragon has an efficiency value (e) from waves to transmission is about 18% [22]. Based on that information, nearshore or offshore power plant cannot meet the electricity needs of Pari Island. The electric power that can be generated is only 0.03 MW using a nearshore power plant, and 0.19 MW using an offshore POWER PLANT, both of which occur in the east season (Figure 10a). The power requirements that can be met by power plant only during the east monsoon using offshore power plant, even then with the scenario of 450 W power usage by all customers which tend to be small. Electricity needs on Pari Island can be met by using 35 offshore power plant units or 6 offshore power plant units (Figure 10b), but still aneed a power storage mechanism to store excess power especially in the east season to be used when electricity power tends to be low in the western season, so that all customers can use 900 W of power throughout the year.

Offshore power plant can produce more energy and power compared to power plant near the coast, so it can meet the electricity needs on Pari Island with a smaller number of units. What also needs to be taken into account in determining the use of power plant is the distance from the generator to the user. Offshore power plant requires a long transmission cable which is around 18 Km to reach the user and costs more underwater cable installation than power plant near the beach which is only 0.5 Km from the user. Another option that can be taken to avoid energy loss in the transmission process from the generator to the user and also the cost of expensive underwater cable installation is to use an electric energy storage mechanism in the form of a battery.

Figure 10. Average of wave power per season, (a) using 1 nearshore power plant and 1 offshore power plant, (b) using 35 nearshore power plants and 6 offshore power plants (■) nearshore power plant, (▲) offshore power plant, (——) power requirements using 900 W of power, (-----) power requirements using 450 W of power.

3.4.4. Wind condition. Ocean waves are generally formed by the wind, so that to harvest wave energy more optimal the reflector of overtopping WEC must be facing the coming wave that moves parallel
with the wind. The characteristics of Pari Island and the other island in Seribu Islands waters are strongly influenced by monsoon winds [13]. This is proved by the results of wind measurements on Pari Island which shows the difference in wind direction each monsoon. Wind roses on Pari Island (Figure 11) show that in the first transition monsoon the dominant direction of coming wind is from the northeast and southwest, in the east monsoon the dominant wind comes from the southwest, in the second transition monsoon the dominant wind comes from the northwest and tends to be calm while in the west monsoon the dominant wind comes from the northeast and the speed tends to be high. The direction of the coming wind can be used to determine the direction of where the wave reflector must be directed in each season. The displacement of the wave reflector is possible because the Wave Dragon is designed to be floating and semi moored [23].

![Wind Rose](image)

**Figure 11.** Wind rose, (a) first transition, (b) east monsoon, (c) second transition, (d) west monsoon.

### 4. Conclusion

Ocean waves on the Pari Island are classified as the smooth sea with 0.16-0.51 m significant wave height and 2-4 seconds period. The calculated WEC can produce energy up to 28 MJ and power up to 6 MW. Based on this calculation, Wave Dragon able to meet the electricity needs on Pari Island with two options. The first one is using 35 units of WD 1 on the Pari Island Coast with a 500 m distance from the settlement, or the second one is using 6 units of WD 2 which is located in the northeast region of Pari Island waters with 18 Km distance from the settlement of Pari Island.

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