Identification of wave energy potential with floating oscillating water column technology in Pulau Baai Beach, Bengkulu

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Abstract. Pulau Baai is a beach, which is located in Bengkulu, Indonesia. This location has swell waves, which is beneficial for wave energy, because it directly faces the Indian Ocean. Floating Oscillating Water Column (OWC) is a prototype used to generate electricity from wave energy. The objective of this research is to identify how much electricity can be generated from floating OWC. This research used a quantitative method by processing wind data (speed and direction) from ogimet.com in 2000-2016. The wind speed rate for wave energy potential of this location is above 5.14 m/s. Wind data is converted to significant wave height and periods data by Sverdrup, Munk, and Bretschneider (SMB) method. Significant wave height rate of this location is 0.06 – 5.33 meters. Assuming that this power plant uses 3 chambers of floating OWC, the power output of OWC is 1.9 GW/year. Thus, suppose each residents’ house uses 1300 watt, this power plant can be used for 1,461,538 residents per year.

Keywords: Wave Energy, Electricity, Floating OWC, Pulau Baai Beach, Bengkulu.

1. Introduction

The demand for energy in Indonesia increases every year. The energy crisis also has been a crucial issue in recent years. This energy crisis occurs due to the depletion of fossil fuel reserves. Because of the excessive human consumption and dependency towards fossil fuels, the fuel reserves become depleted, while it takes thousands and even millions of years for its renewal. [1]. Total energy needs final in Sumatra from 2013 to 2050 is estimated to grow at a rate of average growth 5% each year from 35 million TOE in 2013 increased to 68 million TOE in 2025 and to 212 million TOE in 2050 [2]. Indonesia will certainly meet an energy crisis if only rely on energy from fossil (non-renewable energy). Therefore, we can do the mitigation energy crisis by using the potential of wave energy as a renewable energy.

Amongst the numerous devices that have been suggested for wave energy conversion, the oscillating water column (OWC) wave energy device is probably the most extensively studied type [3]. The oscillating water column (OWC) is a type of wave energy converter (WEC) that has been object of study since the 1940s, when Yoshio Masuda started developing a navigation buoy powered by this device. It consists of a pneumatic chamber open at the bottom to the sea water and at the top to the atmosphere through an air turbine [4].
An Oscillating Water Column (OWC) is basically a device that transforms the mechanical energy of the waves into electric power. The waves entering the chamber to compress and decompress the air around this SWL so that an oscillating airflow is created. This airflow is passed through a power take-off (PTO) system consisting of a turbine and an induction generator that transforms this motion into electrical power [5]. The oscillating motion of the water column acted upon by waves produces a bidirectional flow through the turbine that drives an electrical generator [4]. An offshore OWC will have to float, which uniquely requires that both the wave activated body and the OWC are modeled in a coupled fashion as each absorbs power from the waves [6].

Floating Oscillating Water Column is a particular type of OWC device known as the backward bent duct buoy (BBDB) first proposed by Masuda [7]. It has a submerged opening aligned downstream of the incident wave propagation direction. It has a single air chamber and is free to move in six degrees of freedom. The device is constructed of thin walls enclosing the water column. The PTO system is provided by means of an air turbine connected to an electric generator. The motion of the water column relative to the OWC body creates oscillating pressure in the chamber and air flow through the turbine. A relief valve provides a way to keep the pressure in the air chamber within acceptable limits to prevent the turbine from stalling [8].

Oscillating water column (OWC) wave energy conversion devices consist of a partially submerged chamber open to wave forces at the base as illustrated in Figure 1. The wave forces cause the water column within the chamber to rise and fall, driving the air in and out (inhalation and exhalation) of the chamber typically through a Wells or variable pitch type air turbine. An electrical generator is then utilized to convert the oscillatory airflow established into electrical energy. The pneumatic gearing provided by the air coupling facilitates the conversion of low frequency wave power into high frequency electrical power [9].

Figure 1. Floating Oscillating Water Column Wave energy device (air flow arrows indicate the exhalation phase) [9]

Pulau Baai is a beach which is located in Bengkulu, Indonesia which directly faces the Indian Ocean [10]. This location is very easy to access and some of its area is used for tourism and ports. Therefore, this location requires more source of electrical energy. The objective of this paper is calculating wave energy potential and converted to electrical energy in Pulau Baai Beach Bengkulu by using Floating Oscillating Water Column Technology.

2. Methodology

The study was conducted using a quantitative method. The data were collected from indirect observations. Based on its objectives, this study is categorized as an applied research methods [11].

2.1. Research Location

The study was conducted in the Pulau Baai Beach Bengkulu city with latitude coordinates 3 ° 48'38.31 "S to 4 ° 1'34.37" S and longitude 102 ° 2'35.36 "E to 102 ° 27'38.46" E. The identification of wave energy was done before the wave hit the coast.
2.2. Wave Forecasting

The data used in this study were the wind data from Ogimet (2000-2016). Then, the wind data were calculated using the SMB method for wave forecasting. Ocean winds were estimated using the wave height and period and Sverdrup-Munk-Bretschneider’s SMB method. Wind speed is estimated from the following equation (1).

\[
\frac{gH_{1/3}}{U_{10}^2} = 0.26 \tanh \left[ \frac{1}{f_m U_{10}} \right]^{3/2} \left( \frac{3.5g}{10^2} \right)^{3/2}
\]

where, \( g \): gravity (m/s²), \( H_{1/3} \): significant wave height (m), \( U_{10} \): wind speed at 10m above the ground (m/s), \( f_m \): peak frequency of ocean wave spectrum (1/s). However, the peak frequency of the ocean wave spectrum could not be taken; it was treated as \( f_m \) by taking the reciprocal of the observed significant wave period at this time.

Wind speed at 10 m above the ground was assumed in the equation (1), it was corrected using the power law from the following equation (2).

\[
U_Z = U_{10} \left( \frac{Z}{10} \right)^\alpha
\]

where, \( U_Z \): wind speed at measured station (m/s), \( U_{10} \): wind speed at 10 meter height (m/s), \( Z \): distance from the ground, \( \alpha \): power index (0.12) [12].

To determine the fetch length in the SMB method, cosine average method was used. Based on this method, 15 radials were extend in the upwind direction ± 45 degree (at 6 degree intervals). Then the fetch length (X) was calculated as:

\[
X = \frac{\sum \Xi_i \cos \alpha_i}{\sum \Xi_i \cos^2 \alpha_i}
\]

where, \( \Xi_i \): fetch length which measured from waves observation to the fetch ends. \( \alpha \): deviation on both sides of the wind direction, using a 6-degree increase, up to an angle of 42 degrees on either side of the wind direction (degrees).

According to this method, to accomplish the fetch-limited condition, the wind duration must be greater than \( t_{min} \) that is:
where \( U \): corrected wind speed (m/s)
In the fetch limited condition, the equation for predicting wave height (\( H_s \)) is:

\[
\frac{g H_s}{U^2} = 0.283 \tanh \left[ 0.0125 \left( \frac{g x}{U^2} \right)^{0.42} \right]
\]  

If the wind duration is smaller than \( t_{\text{min}} \), the condition is called duration limited. In this condition, equivalent fetch must be calculated by substituting the wind duration into the equation (4). Then, the wave heights are estimated by substituting the equivalent fetch into the equation (5) [13].

2.3. Energy and Power Calculation Analysis
The type of OWC used in this study was the floating type, which has mechanical oscillator model utilized in the present study, (Figure 3) was the fixed OWC model proposed by Szumko [9] with the inclusion of air compressibility. The lower-case variables \( k, m \) are the owe water plane stiffness, radiation damping and mass respectively. The corresponding upper-case parameters for the floating structure are \( K, B, M \). The mass terms include the hydrodynamic mass. It must be noted that for the floating structure, \( K \) also includes the mooring line stiffness. The turbine damping is modelled by the linear damping parameter \( A \) and the air compressibility by the linear stiffness /1. The \( x \) coordinate is the OWC mean free surface elevation and \( z \) is the floating structure displacement relative to the still-water level (see also Figure 1) [9].

**Figure 3.** Discrete mass-spring-damper model of the heave motions of a floating OWC WEC device [9]

The equations of motion of the system illustrated in Figure 2 are:

\[
m \frac{d^2 x}{dt^2} + B \frac{dx}{dt} + k x + \mu (x - y) = f_0
\]  

\[
\lambda \frac{d(y - z)}{dt} + \mu 9y = 0
\]  

\[
M \frac{d^2 z}{dt^2} + B \frac{dz}{dt} + \lambda \frac{d(x - y)}{dt} + Kz = f_s
\]  

The wave forces on the OWC, \( f_0 \), and the floating structure, \( f_s \), are assumed to be related via the parameter \( r \) (see Eq. 4). In general, \( r \) is complex, allowing both a magnitude and phase difference between the forces. In the present analysis, the floating owe is assumed to be axisymmetric. In the
limit of large wavelength, or small wave number, $r$ can also be shown to be equivalent to the area ratio of the OWC opening to the total base area of the floating wave energy converter \[9\].

\[
\begin{align*}
\hat{f}_0 &= r \hat{f}, \\
\hat{f}_r &= (1 - r) \hat{f}, \\
\hat{y} &= Y e^{i\omega t}, \\
\hat{z} &= Z e^{i\omega t}, \\
(k + \mu - m \omega^2 + i b \omega)X - \mu Y &= F_r \tag{11}
\end{align*}
\]

\[
\mu X - (\mu + i \lambda \omega)Y + i \lambda Z = 0 \tag{12}
\]

\[
(K - M \omega^2 + i \omega (B + \lambda))Z - i \lambda \omega Y = F(1 - r) \tag{13}
\]

Making the substitutions $\alpha = k - m \omega^2$, $\beta = b \omega$, $\gamma = K - M \omega^2$, $\delta = B \omega$ and $A = \lambda \omega$ and solving the set of simultaneous equations.

The fixed OWC solution \[9\] can be retrieved by setting $S \rightarrow \infty$ and $T \rightarrow \infty$ (i.e. $K \rightarrow \infty$);

\[
A_{\text{opr.f}} = \frac{(1+\Omega^2)R^2 \mu^2}{R^2 + \Omega^2 (1+R)^2}; \text{ and} \tag{14}
\]

\[
P_{\text{max.f}} = \frac{|Fr|^2 q^2 \omega}{4 \mu (QR + \sqrt{R^2 + \Omega^2 (1+R)^2}) \sqrt{(1+\Omega^2)R^2}} \tag{15}
\]

The forcing term $Fr$ is the force on the oscillating water column. The limiting case of incompressible air for a fixed OWC may be obtained by setting $R \rightarrow 0$ ($\mu \rightarrow \infty$).

\[
P_{\text{max.f}_{\text{incomp}}} = \frac{|Fr|^2}{4 b (1 + \sqrt{1+\Omega^2})} \tag{16}
\]

The ratio of maximum fixed OWC power capture ratio for the compressible and incompressible flow cases is then

\[
\frac{P_{\text{max.f}}}{P_{\text{max.f}_{\text{incomp}}}} = \frac{QR (1 + \sqrt{1+\Omega^2})}{QR + \sqrt{R^2 + \Omega^2 (1+R)^2} \sqrt{(1+\Omega^2)R^2}} \tag{17}
\]

In interpreting Eq. 23, the relationship between the expressions for $Q$ and $R$, stated previously, must be considered. Solving these equations yields

\[
Q = \frac{\mu}{\beta} R = \frac{\mu}{b \omega} R \tag{18}
\]

The parameters $Q$ and $R$ may be represented as a function of the ratio of the wave frequency to the incompressible system natural frequency, $Q_0$, as

\[
\left\{
\begin{align*}
Q &= \frac{\alpha}{\beta} = \frac{k - m \omega^2}{b \omega} = \frac{1}{2 \kappa_0} \left( \frac{1}{\Omega_0} - \Omega_0 \right), \\
R &= \frac{\alpha}{\mu} = \frac{k - m \omega^2}{\mu} = \kappa_0 (1 - \Omega_0^2)
\end{align*}
\right\} \tag{19}
\]

The air compressibility spring rate expression may be estimated assuming isentropic compression with only small changes in volume (relative to the total chamber volume). It is expressed in terms of the ratio of specific heats of air, $c_p/c_v$, atmospheric pressure, $p$, the oww water surface area, $A$, and the chamber height, $h$, as

\[
\mu = \frac{(c_p/c_v)pA}{h} \tag{20}
\]
The power capture presented is normalized as [9]:

\[ P = \frac{P_{\text{max}}}{\left( \frac{H}{H_{\infty}} \right)^b} \]  

where \( P_{\text{max}} \) is maximum power.

2.4. Data Analysis

Data analysis was conducted to identify the potential development of Floating OWC (Oscillating Water Column) in Pulau Baai Beach Bengkulu. It included the review of wave energy potential for electricity. Our study focused on calculating the electrical energy from wave using Floating OWC prototype to be used in Pulau Baai beach, and calculated the residents who could use this technology.

3. Results and Discussion

3.1. Forecasting Wave

Based on Sverdrup, Munk, and Bretschneider (SMB) method, the highest significant wave height in the period from 2000 to 2016, is 5.33 meters, with a period of 9.94 second. The minimal significant wave height is 0.062 meters with a period of 0.062 second. Meanwhile, the average significant wave height is 2.01 meters and the average significant wave period is 6.78 second. The data distribution is shown below in Figure 4 (a & b):

![Figure 4](image)

**Figure 4.** (a) Significant wave height and (b) Significant wave periods distribution (2000-2016)

Based on the Beaufort scale, the wind speed that has the potential to produce waves that can be used as an energy plant is 10 knots (equivalent to the wave height of 2 meters and above). Based on table 1 and 2, the significant wave height value is above 2 meters, there are as much as 53.8%.
Table 1. Significant waves height distribution (2000-2016).

| Range (m) | Frequency (amount of data) | Percentage (%) |
|-----------|----------------------------|----------------|
| 0-1       | 660                        | 12.34          |
| 1.1-2     | 1809                       | 33.84          |
| 2.1-3     | 2455                       | 45.93          |
| 3.1-4     | 394                        | 7.37           |
| 4.1-5     | 21                         | 0.39           |
| 5.1-6     | 6                          | 0.11           |

Table 2. Significant waves periods distribution (2000-2016).

| Range (s) | Frequency (amount of data) | Percentage (%) |
|-----------|----------------------------|----------------|
| 0-1       | 92                         | 1.72           |
| 1.1-2     | 50                         | 0.93           |
| 2.1-3     | 63                         | 1.18           |
| 3.1-4     | 148                        | 2.77           |
| 4.1-5     | 348                        | 6.52           |
| 5.1-6     | 191                        | 3.57           |
| 6.1-7     | 1352                       | 25.32          |
| 7.1-8     | 2308                       | 43.22          |
| 8.1-9     | 754                        | 14.11          |
| 9.1-10    | 34                         | 0.64           |

In addition, this research analyzed the daily height and period of significant wave as shown in Figure 5 (a & b):

Figure 5. (a) Daily significant wave height and (b) Daily significant wave period distribution

The data of daily significant wave height and daily significant wave period distribution is presented on table 4 and 5, the significant wave height values above 2 meters are 52.65%. Therefore, Pulau Baai Beach is suitable for developing renewable energy from ocean waves.
Table 3. Daily significant wave height

| Range (m) | Frequency | Percentage (%) |
|-----------|-----------|----------------|
| 0-1       | 247       | 8.11           |
| 1.1-2     | 1195      | 39.23          |
| 2.1-3     | 1411      | 46.32          |
| 3.1-4     | 173       | 5.68           |
| 4.1-5     | 14        | 0.46           |
| 5.1-6     | 6         | 0.19           |

Table 4. Daily significant wave periods

| Range (s) | Frequency | Percentage (%) |
|-----------|-----------|----------------|
| 0-1       | 18        | 0.59           |
| 1.1-2     | 56        | 1.84           |
| 2.1-3     | 110       | 3.61           |
| 3.1-4     | 301       | 9.89           |
| 4.1-5     | 356       | 11.70          |
| 5.1-6     | 367       | 12.06          |
| 6.1-7     | 608       | 19.98          |
| 7.1-8     | 1000      | 32.87          |
| 8.1-9     | 212       | 6.96           |
| 9.1-10    | 14        | 0.46           |

Table 5. Maximum power

| Parameters                                           | Symbol    | Value       | Unit    |
|------------------------------------------------------|-----------|-------------|---------|
| Wave force                                           | $f_0$     | $1.42 \times 10^4$ | N       |
| Floating stucture force                              | $f_s$     | $3.57 \times 10^3$ | N       |
| Total area of OWC                                     | $A$       | 76.18       | m²      |
| Optimal Damping                                      | $A_{opt-f}^2$ | $9.22 \times 10^8$ | m²      |
| Maximal Power                                        | $P_{max-f}$ | 4.28       | J/s     |
| Power incompressible air in OWC (R=0)                | $P_{max-f,\text{incomp}}$ | 0.04   | J/s     |
| Time duration each year                              | $t$       | $3.15 \times 10^7$ | s       |
| The Power                                            | $P$       | 0.04        | J/s     |
| The Energy Working                                   | $E_{\text{sw}}$ | $1.16 \times 10^6$ | watt |

3.2. Energy and Power Generating

Generating energy and power from wave energy have been calculated based on the methods in section (2.3) before. Some parameters of this calculation were assumed in some sizes. Cross-sectional area of OWC were assumed 100 m², height of OWC’s chamber to be 25 meters, and OWC operated to be 15 meters depth. The results are as follows:
3.2.1. Maximum Power

Maximum power was assumed as the power which can be generated by maximum wave height and period, maximum Sea Surface Temperature (SST), and maximum wave force. The maximum significant wave height value is 5.33 meters, the maximum significant wave period value is 9.95 second, the maximum Sea Surface Temperature (SST) value is 31 degrees, and the maximum of wave force is 17858.41 N. The power calculation in maximum condition are presented in the Table 5.

3.2.2. Minimum Power

Minimum power is assumed as the power which can be generated by the minimum wave height and period, the minimum Sea Surface Temperature (SST), and the minimum of wave force. The minimum significant wave height value is 0.062 meters, the minimum significant wave period value is 0.062 second, the minimum Sea Surface Temperature (SST) value is 29 degrees, and the minimum of wave force is 2.44 N. The power calculation in minimum condition are presented in the Table 6 below:

| Parameters                        | Symbol | Value  | Unit   |
|-----------------------------------|--------|--------|--------|
| Wave force                        | $f_0$  | 1.95   | N      |
| Floating stucture force           | $f_s$  | 0.49   | N      |
| Total area of OWC                 | $A$    | 76.18  | m$^2$  |
| Optimal Damping                   | $A_{opt}$ | 8.06 x 10$^8$ | m$^2$ |
| Maximal Power                     | $P_{max_f}$ | 4.27 | J/s    |
| Power in compressible air in OWC  | $P_{max_f, incomp}$ | 0.69 | J/s    |
| Time duration each year           | $t$    | 3.15 x 10$^7$ | s    |
| The Power                         | $P$    | 0.002  | J/s    |
| The Energy Working                | $E_w$  | 6.83 x 10$^4$ | watt |

3.2.3. Average power

Average power is assumed as the power which can be generated by the average wave height and period, the average Sea Surface Temperature (SST), and the average of wave force. The average significant wave height value is 2.01 meters, the average significant wave period value is 6.78 second, the average Sea Surface Temperature (SST) value is 29.5 degrees, and the average of wave force is 2956.33 N. The power calculation in average condition are presented in the Table 7 below:

| Parameters                        | Symbol | Value   | Unit   |
|-----------------------------------|--------|---------|--------|
| Wave force                        | $f_0$  | 2,365.55 | N      |
| Floating structure force           | $f_s$  | 591.39  | N      |
| Total area of OWC                 | $A$    | 76.18   | m$^2$  |
| Optimal Damping                   | $A_{opt,f}$ | 8.35 x 10$^4$ | m$^2$ |
| Maximal Power                     | $P_{max_f}$ | 4.28 | J/s    |
| Power in compressible air in OWC  | $P_{max_f, incomp}$ | 0.05 | J/s    |
| Time duration each year           | $t$    | 3.15 x 10$^7$ | s    |
| The Power                         | $P$    | 0.02   | J/s    |
| The Energy Working                | $E_w$  | 7.53 x 10$^5$ | watt |
3.3. Recommendations Based on Power Output

The results of the calculation in section (3.2.1), (3.2.2) and (3.2.3), are summarized in Table 8. From the table, the average power output of floating OWC (one chamber) is $6.60 \times 10^5$ watt. The power plant generates at least 1 GW as a standard. So, to implement this power plant in Pulau Baai beach, at least 3 chambers of floating OWC are needed. The total energy of 3 chambers of OWC is 1.9 GW per year. If we assume each residents’ house used 1300 watt, this power plant can be used for 1,461,538 residents per year.

Table 8. Summary of power output

| Energy of OWC | Average Energy Calculation Each Year | Unit |
|---------------|-------------------------------------|------|
|               | Average                            | 7.53 $\times 10^5$ Watt |
|               | Minimal                             | 6.83 $\times 10^4$ Watt |
|               | Maximal                             | 1.16 $\times 10^6$ Watt |
| Average       |                                     | 6.60 $\times 10^5$ Watt |

4. Conclusion

In this study, we overview the identification of wave energy potential in Pulau Baai beach, Bengkulu. Based on the results of the study, this power plant has a great potential to be implemented and developed, although its establishment will cost a larger amount of money. However, we still have to develop renewable energy before we run out of fossil energy in the future.

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