Estimation of the potential utilization of wave power surrounding Bali beach using CSP-MS

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Abstract. A series of studies have been and are being carried out to get an innovative engineering-based method of changing the paradigm of a breakwater as a dissipate wave energy structures into a coastal structure that protects the coast by capturing wave energy (Catchwater Shore Protection-CSP) to turn generator turbines. This work estimates the potential utilization of wave energy around the South Coast of Bali Island to be used as electric power with a multi slope CSP structure (CSP-MS). Wave data for 15 years (2005-2019) at 4 observation points were gathered up from the European Center for Medium-Range Weather Forecasts (ECMWF). The representative wave analysis (Hn, where n is the return period year) yields a base value of H₁₀ = 2.79 m with T₁₀ = 13.36 s; Hₛ = 2.40 m with Tₛ = 12.33 s; H₅₀ = 2.24 m with T₅₀ = 11.89 s and H₅₀0 = 1.87 m with T₁₀₀ = 10.75 s. The empirical analysis results indicate that the efficiency of capturing wave energy is ranging from 34.8% to 43.3% using CSP-MS.

1. Introduction

As a maritime country, Indonesia has sufficient potential for energy from the sea, especially waves, which unfortunately has not been explored at all. Research on the conversion of wave energy to electric power has been widely carried out and found various technically feasible conversion methods. The obstacle that hinders so that it cannot be applied is its unfulfilled financial viability. The investment cost of building a wave power plant is very expensive because it is located in quite deep waters. Therefore, the selling value of electricity is difficult to compete with other power plants. If we look at other situations related to wave power which can damage the coast and even cause disasters on the coast, the Indonesian Government has allocated a large enough budget to build coastal protection structures such as breakwaters, sea walls, and others just to destroy wave energy so that the land the coast is protected from damage and disaster from the onslaught of wave energy. This proposed research aims to change the paradigm of coastal protection structures (breakwater/seawall/revetment) into a double function catcher building to protect the beach and capture wave energy. The breakwater that is built at a high cost to protect a coastal area by destroying wave energy will be converted into buildings that protect the coast by capturing wave energy to be used to rotate power generation turbines. With a conversion model like this, the practicality of financing will be lighter and even cost-less is needed, even if there is even efficiency due to reduced use of materials. Thus the selling price of electricity is very feasible.
This research is applied research to estimate the potential of electrical energy at the location of the South Coast Bali Island by using the results of the latest research with the topic of the Study of the Effect of Wave Deformation on Overtopping Discharge OWEC Breakwater or CSP-MS simulation of 2D models in wave channels [1]. This latest research is a series of long studies from the proposing team from 2015 to 2020. Previous studies that have become references include those conducted by [2-5]. This latest research gets the best geometric model results and is equipped with empirical equations that can be used to estimate the wave energy that can be mobilized to become electrical energy under prototype conditions.

2. Literature review & theory

2.1. Energy & wave power

In addition to moving particles, moving waves can also provide wave energy. Wave energy consists of two types, namely kinetic energy and wave potential energy. Kinetic energy occurs due to the velocity of particles due to wave motion. Meanwhile, the potential energy occurs due to the displacement of the water level due to wave motion. For the small-amplitude wave theory, if the energy of the wave is fixed relative to the water level at rest, and all the waves travel in the same direction, then the components of potential energy and kinetic energy are the same. For Airy’s wave theory, solving the next equation yields the respective wave energies as shown in equations 1 and 2.

\[
Ek = \frac{\rho g H^2 L}{16}
\]

\[
Ep = \frac{\rho g H^2 L}{16}
\]

Thus the total energy in one wavelength of the unity of the wave width is shown in equation 3

\[
Et = Ek + Ep = \frac{\rho g H^2 L}{8}
\]

While the energy of the average area of unity is shown in equation 4.

\[
E = \frac{Et}{L} = \frac{\rho g H^2}{8}
\]

with:
- \(Ek\) : kinetic energy unity of wavelength (joules/m)
- \(Ep\) : potential energy per unit width of wavelength (joules/m)
- \(Et\) : total energy unit width of wavelength (joules/m)
- \(E\) : average energy of the unit area wave (joules/m2)
- \(H\) : wave height (m)
- \(\rho\) : density of water mass (kg/m3)
- \(g\) : acceleration due to gravity (m/s2)

Wave power \((P)\) is the energy of the wave per unit time in the direction of the wave propagation, as shown in equations 5 [6].

\[
P = \frac{nE}{T}
\]

Where \(n\) is a factor of wave energy which is valued by equation 6.

\[
n = \frac{1}{2} \left(1 + \frac{2kd}{\sinh 2kd}\right)
\]

The power available in the reservoir is shown in equation 7.

\[
D = Qhy
\]

2.2. Wave deformation
Wave deformation is a change in wave characteristics due to the influence of depth and / or the presence of an obstacle medium that the wave passes through in its propagation. Wave deformation can be in the form of refraction, shoaling, diffraction, reflection, and breaking waves. Wave refraction is the process of bending the waves due to the influence of the contours of the bottom of the water, shoaling is the deformation of waves caused by the influence of the shallowness of the water bed, diffraction is the process of turning waves due to structural obstacles or islands that the waves pass through, reflection is the reflection of waves hitting obstacles in their propagation and breaking wave is the process of breaking a wave due to the influence of the depth or obstacle. All types of deformation cause changes in wave characteristics, especially wave height, period, and direction. The types of deformation associated with this research are shoaling and wave breaking.

2.3. **OWEC (Overtopping Wave Energy Converter)**

Overtopping Wave Energy Converter (OWEC) is one of Wave Energy Converter (WEC) technology with wave overtopping types from several known types. Figure 1 shows the available WEC types.

![Figure 1. Types of Wave Energy Converter (WEC)](image)

- **a)** Wave Activated Body Type
- **b)** Point Absorber Type
- **c)** Oscillating Water Column Type
- **d)** Overtopping Type

The concept used in the overtopping wave energy converter as shown in figure 1 is to bring the wave up into the reservoir through the wave runup & overtopping mechanism, wherefrom the reservoir located at the top of the converter which is located higher than sea level, potential energy is converted into energy. mechanics through the turbines.

The use of the WEC overtopping concept on a breakwater has been initiated by the discovery of the Sea Slot-Cone Generator (SSG) in 2002 and OBREC in 2013. In 2015 the only prototype that has been developed of this type is OBREC. The OBREC prototype unit has been applied to a rubble mount type breakwater at the port of Naples, Italy. The reason for using this concept (WEC-breakwater integration) is triggered by the suitability of the aspect which matches the design of the horizontal concrete caisson breakwater at the port. The slope of the slope at the front of the breakwater is designed to destroy the waves by reducing the depth of the sea. When the depth of the sea decreases, the waves will begin to...
break in the form of breaking waves. It can be spilling, collapsing, plunging, or surging, depending on
the angle of the shoreline area.

In the combined concept of WEC-breakwater overtopping, a surging type of breaking wave will be
utilized. The waves will rise and overtopping then collected in the reservoir and used again to generate
electricity using low head hydro-turbines. In other words, the concept of this incorporation can optimally
improve the ability of conventional breakwaters with one function into dual functions, namely, as coastal
protection and wave energy converter technology.

Overtopping of a wave is a function of hydraulic parameters such as wave height, wave period,
wavelength, and water level as well as a function of structural parameters such as geometric, layout, and
structural material properties. Wave overtopping is a very dynamic and irregular process. This process
can be characterized by wave overtopping discharge. In reality, there is no constant discharge
overtopping the top of the structure during overtopping. The process of overtopping a wave is very
random in time, space, and volume. The highest waves will push large volumes of water above the crest
for a short period, while the lower waves may not produce any overtopping.

Physical modeling is generally used to study wave overtopping and develop an empirical formula to
predict it. The large number of relevant parameters affecting this phenomenon makes it difficult to
develop theoretical or numerical approaches that properly represent the nature of overtopping. In
contrast, experimental tests are a well-established and reliable method of determining the mean
overtopping waves for coastal structures [7].

Puspita examined the effect of wave deformation on overtopping discharge in OWEC breakwaters,
finding that the best geometric model of the OWEC breakwater front wall in producing large discharge
is a wall with a combination slope of 90° and 45° slope and relative wall height \( s/d \) = 1 or the water
depth is at the level of the upper edge of the vertical wall. The resulting empirical equation as shown in
equation 8 can be used to estimate the amount of potential energy that can be utilized in the field.

\[
q = \sqrt{g \cdot H_i \cdot \left(0.0103 \cdot \frac{Ru}{Rc} - 0.0103\right)} \tag{8}
\]

Where the wave runup (Ru) is determined using the empiric equation 9.

\[
Ru = Hi \left(0.3452 \cdot \frac{\xi s}{d}\right) \tag{9}
\]

With
- \( g \) = acceleration due to gravity (m / s2)
- \( Hi \) = incident wave height (m)
- \( Ru \) = wave run-up height (m)
- \( Rc \) = freeboard height (m)
- \( \xi \) = parameter breaker
- \( s \) = sub-slope height (m)
- \( d \) = water depth (m)

Equation 8 applies to the maximum value of \( Ru/Rc \) ranging from 1 to 2.5 and equation 9 applies to
the range \( \xi \) to 4 to 14.

3. Research location
The research location was determined by the South Coast of Bali Island which is part of the Indian
Ocean. This location was chosen because it is one of the locations that have sufficient potential for wave
ergy. The generation of waves by the wind occurs in the middle of the Indian Ocean and the waves
that form spread towards Indonesian waters, especially to the South Coast of Java Island, the West Coast
of Sumatra Island, and the South Coast of Bali & Nusa Tenggara Islands. The research location is shown
in figure 2. Table 1 shown an example of deep-sea wave characteristics data at location 1 January 1,
2005.
Table 1. Example of deep-sea wave characteristics data at location 1 January 1, 2005

| Longitude [Degrees East] | Latitude [Degrees north] | Time_ISO8601 | Mean wave direction [Degree] | Mean Wave Period [sec] | Significant Height of Combined Wind Waves and Swell [m] |
|--------------------------|--------------------------|--------------|-------------------------------|------------------------|-------------------------------------------------------|
| 114.75 E                 | -9                       | 2005-01-01T00:00:00 | 221.700                      | 7.262                  | 1.380                                                 |
|                          |                          | 2005-01-01T06:00:00 | 221.876                      | 7.161                  | 1.513                                                 |
|                          |                          | 2005-01-01T12:00:00 | 218.97                       | 7.587                  | 1.571                                                 |
|                          |                          | 2005-01-01T18:00:00 | 218.799                      | 7.958                  | 1.689                                                 |
|                          |                          | 2005-01-02T00:00:00 | 219.651                      | 8.202                  | 1.830                                                 |

Source: https://www.ecmwf.int/

4. Result and discussion

From the obtained wave data, then statistical analysis is carried out related to the percentage of incidents and is presented in the form of a graphic image of a wave rose based on the direction of propagation at four review locations. The wave roses at four locations can be seen in figure 3.
Figure 3. Wave roses at 4 locations

Figure 3 shown that the dominant waves in the season period at all locations are the same, namely from the Southwest direction or at 225 ° N, which is around an average of 61.29% of events, following from the South or at 180 ° N with an average range of 36.33% incidence. The subsequent analysis aimed at the percentage of incidents based on the height interval and wave period. Table 2 presents the percentage of incidence based on wave height at the 4 locations reviewed.

Table 2. Percentage of wave events based on the wave height interval

| Wave Height Interval (m) | Middle value (m) | Location of data collection | Average   |
|--------------------------|------------------|-----------------------------|-----------|
|                          |                  | Location 1 | Location 2 | Location 3 | Location 4 |         |
| 0.0 - 1.0                | 0.5              | 0.58%      | 1.18%      | 0.38%      | 0.52%      | 0.67%   |
| 1.0 - 2.0                | 1.5              | 66.98%     | 72.49%     | 57.46%     | 61.08%     | 64.50%  |
| 2.0 - 3.0                | 2.5              | 31.04%     | 25.47%     | 39.10%     | 36.00%     | 32.90%  |
| 3.0 - 4.0                | 3.5              | 1.37%      | 0.84%      | 3.00%      | 2.35%      | 1.89%   |
| 4.0 - 5.0                | 4.5              | 0.03%      | 0.02%      | 0.06%      | 0.05%      | 0.04%   |
| **Amount**               |                  | 100.00%    | 100.00%    | 100.00%    | 100.00%    | 100.00% |

Table 2 shows that on average from the 4 data collection locations, the most frequent wave heights that occur in the southern waters of the island of Bali are waves with a height ranging from 1-2 m or an average of 1.5 m with a percentage range. 64.50%, following waves with a height of 2-3 m or an average of 2.5 m with a percentage of around 32.90%. There is a wave height of 3-4 m with an average percentage of incidence around 2%. Meanwhile, the percentage of wave events based on the wave period interval is presented in table 3.

Table 3. Percentage of wave events based on the interval of the wave period

| Wave Period Interval (second) | Period middle value (second) | Location of data collection | Average |
|------------------------------|------------------------------|----------------------------|---------|
|                              |                              | Loc 1 | Loc 2 | Loc 3 | Loc 4 |         |
| 5.0 - 7.5                    | 6.25                         | 0.58% | 0.75% | 0.76% | 0.92% | 0.75%   |
| 7.5 - 10.0                   | 8.75                         | 66.98%| 27.79%| 31.87%| 32.95%| 3.90%   |
| 10.0 - 12.5                  | 11.25                        | 31.04%| 59.92%| 57.00%| 56.26%| 51.05%  |
| 12.5 - 15.0                  | 13.75                        | 1.37% | 11.17%| 9.97% | 9.50% | 8.00%   |
| 15.0 - 17.5                  | 16.25                        | 0.03% | 0.37% | 0.39% | 0.37% | 0.29%   |
| **Amount**                   |                              | 100%  | 100%  | 100%  | 100%  | 100%    |
On average, the waves with the most frequent occurrences were waves with period intervals of 10.00 to 12.5 seconds (51.08%) followed by waves with intervals of 1.5 to 10.0 seconds (39.90%). For other periods it is relatively small and the incidence is negligible.

The data described in the four locations above are only the wave characteristics data in the deep-sea because it is necessary to analyze the wave deformation in its propagation from the four data collection locations towards the coast of Bali Island. Then wave transformation analysis is needed. Table 4 shows the deep ocean wave height and period from four locations.

**Table 4. Deep ocean wave height and period from four locations**

| Location | Wave Height | Wave Period |
|----------|-------------|-------------|
|          | H10% | H33% | H50% | H100% | T10% | T33% | T50% | T100% |
| 1        | 2.74  | 2.36 | 2.20 | 1.84  | 13.47| 12.45| 12.01| 10.89 |
| 2        | 2.63  | 2.26 | 2.10 | 1.76  | 13.39| 12.37| 11.93| 10.81 |
| 3        | 2.93  | 2.52 | 2.35 | 1.96  | 13.32| 12.28| 11.83| 10.68 |
| 4        | 2.87  | 2.46 | 2.29 | 1.91  | 13.28| 12.23| 11.78| 10.63 |
| **Average** | **2.79** | **2.40** | **2.24** | **1.87** | **13.36** | **12.33** | **11.89** | **10.75** |

**4.1. Wave deformation analysis**

The wave data described at the four location points above are data on the height and period of deep-sea waves. For this reason, it is necessary to study changes in wave characteristics or wave deformations that propagate towards shallower coastal waters. Figure 4 shows the wave deformation curves for 4 wave representations, namely H100, H50, H33, and H10.
From Figure 4, it can be seen that the breaking waves for the H100 mean height (Hb) ranging from 2.40 m occur at a depth (d) ranging from 3 m. For H50 the mean height (Hb) is around 2.85 m, occurs at d ranges from 3.70 m; H33 with Hb as high as 3.60 m occurs at d ranges from 4.5 m. Depth (d) is the depth based on the chart datum which is determined at low tide. From figure 4, it can be determined the location of the placement of the CSP-MS structure, namely the location of the wave that has not yet broken but is as close as possible to the location of the breaking wave, therefore the structure will be placed at a depth of 5 m.

4.2. Estimation of wave power that can be captured & utilized

Based on statistical analysis and wave deformation as presented in table 4 and figure 4, then the calculation or estimation of the amount of wave power that can be captured and utilized to generate electric power is carried out using equation 8 and equation 9. The analysis results are presented in table 5 and table 6.

**Table 5. The results of wave run-up analysis on the CSP-MS structure**

| H   | Ho (m) | Hi at d=5m (m) | T (s) | Lo (m) | L (m) | tan θ | s (m) | d (m) | s/d | ξ  | Ru (m) |
|-----|--------|----------------|-------|--------|-------|-------|-------|-------|-----|-----|--------|
| H100| 1.87   | 2.15           | 10.75 | 180.28 | 63.10 | 1.00  | 5.00  | 5.00  | 1.00| 9.15696 | 6.80   |
| H50 | 2.24   | 2.67           | 11.89 | 220.54 | 77.19 | 1.00  | 5.00  | 5.00  | 1.00| 9.08842 | 8.38   |
| H33 | 2.40   | 2.91           | 12.33 | 237.17 | 83.01 | 1.00  | 5.00  | 5.00  | 1.00| 9.02774 | 9.07   |
| H10 | 2.79   | 3.90           | 13.36 | 278.44 | 97.46 | 1.00  | 5.00  | 5.00  | 1.00| 8.44961 | 11.38  |

**Table 6. The results of the analysis of the efficiency of the use of wave power that can be captured by the CSP-MS structure**

| H | Ho (m) | Hi at d=5m (m) | T (s) | Rc (m) | g (m/s^2) | Ru (m) | q / (m^2.s) | Q (m^3/s) | d (m) | s/d | q / (m^2.s) | F (Nm) | P wave (Nm/s) | P occupied (Nm/s) | P occupied (%) |
|---|--------|----------------|-------|--------|-----------|--------|-------------|------------|-------|-----|-------------|---------|--------------|------------------|---------------|
| H100| 1.87   | 2.15           | 10.75 | 2.27   | 9.81      | 6.89   | 0.2034      | 0.0630     | 357656.00 | 16335.16 | 1439.45 | 8.65 |
| H50 | 2.24   | 2.67           | 11.89 | 2.79   | 9.81      | 8.38   | 0.2815      | 0.8788     | 693666.96 | 29170.18 | 2219.95 | 7.61 |
| H33 | 2.40   | 2.91           | 12.33 | 3.02   | 9.81      | 9.07   | 0.3203      | 0.9865     | 816088.11 | 35932.20 | 2634.97 | 7.34 |
| H10 | 2.79   | 3.90           | 13.36 | 3.79   | 9.81      | 11.38  | 0.4969      | 1.1239     | 1180559.00 | 69931.12 | 4736.41 | 6.77 |

From table 5 and table 6, it is obtained the amount of Run-Up (Ru) that occurs, overtopping discharge (Q), wave power both available in the waters (P), and those that can be captured for use (P occupied). For the average wave height H100 with Hi = 2.15 m at a depth of d = 5 m, then the P-occupied is 1439.45 Nm / s per wave width or around 8.65%. So for 100 m long, the CSP-MS structure will be able to produce 143945 Nm / s or around 144 kW. The value of the resulting wave power is relatively small. This is because the wave height data obtained at the 4 review locations are relatively small (H100 only ranges from 1.87 m in the deep sea or ranges from 2.15 m at a depth of 5 m). However, the construction of a coast protection breakwater that also captures wave energy with CSP-MS, it will produce a wave power of 143,945 Nm / s or 144kW of electric power per 100 m of building length.

5. Conclusions

1. Wave data on the South Coast of Bali Island for 15 years (2005-2019) shows that the average wave height (H100) is relatively small, namely around 1.87 m in deep-sea and around 2.15 m at a depth of 5 m.
2. The results of the analysis of the average wave height show the estimated amount of wave power (P) that can be captured and converted into electric power is 1439.45 Mn / s per wave width or only around 8.65% of the available wave energy.

3. If a coastal protection breakwater is built which also captures wave energy with CSP-MS at the location, it will produce a wave power of 143,945 Nm / s or 144kW of electric power per 100 m of building length.

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