

ASSESSMENT OF WAVE ENERGY RESOURCES IN THE VICINITY OF NATUNA ISLANDS

*Krisnaldi Idris¹, Desmira Anindya Gammaranti²

^{1,2}Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Indonesia

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ABSTRACT: The objective of this work is to study the wave energy resources and selection of conversion technologies options in the vicinity of the Natuna Islands. This study involves analyzing the wave characteristics of the area and the theoretical wave energy resources currently available and estimating the electricity production of three types of wave energy converters (attenuator, terminator, and point absorber). The 59-year wave data were obtained from the SEAMOS-South Fine Grid Hindcast (SEAFINE) and statistical analysis was performed to obtain probability of occurrence of the wave height and wave period, which describe the sea states. The seasonal variations of the wave characteristics were identified. The wave statistical analysis and estimation of energy production were analyzed on a monthly basis. The performance characteristics are provided for selected wave energy converter types, where the performance is a function of the sea state conditions. The incorporation of the probability of occurrence of sea states and performance of the wave energy converter show the highest estimation of electricity production occur during North East Monsoon season, and the lowest one during South West Monsoon season.

Keywords: Renewable energy, Wave energy resource, Wave power, Indonesia

1. INTRODUCTION

Being an archipelagic country, Indonesia mostly consists of approximately 17,504 islands, ~108,000 km long coastline and a total sea water area of 6.400.000 km² [1]. Thus, it is crucial to explore the possibility of extracting energy from the ocean and one of them is wave energy. To ensure a sustainable supply of energy and a balanced mixture of various energy resources, the Indonesian National Energy Council (Dewan Energi Nasional) [2] in Indonesia targeted that renewable energy will contribute 23% of the national energy resource mix by 2025, in which 3,100 MW is generated from the ocean.

Indonesian waters were included in Cornett's assessment of global wave energy resources [3], which was based on 10-year wave data generated by the WAVEWATCH-III (NWW3) wind-wave model. Cornett [3] presented the spatial and temporal variations of the global wave energy resources, in which Indonesian waters were classified as an area with an available average power of less than 10 kW/m and characterized by relatively high Seasonal and Monthly Variability Indexes. The Indonesian Ocean Energy Association (Asosiasi Energi Laut Indonesia, ASELI) [4] performed a preliminary analysis on the wave energy resources in Indonesian waters based on the wave data collected from various sources and recommended several potential areas for wave energy extraction in Indonesia, as shown in Fig.1. The waters in the vicinity of the Natuna

Islands were identified as potential areas for wave energy extraction. Incorporation of probability of occurrence of seastates and performance characteristics of wave energy converters (WECs) may provide a better understanding of wave energy harvesting method.

Dunnet and Wallace [5] evaluated the wave power and electricity production at hundreds of locations in Canadian waters using the available wave data and performance characteristics of different types of WECs. The performance characteristics of a WEC were presented as a function of seastate and therefore, can be linked to the occurrence of a certain sea state. In this manner, the electricity production of a WEC over a certain period can be estimated.

The objectives of this study are to estimate the gross energy content of wave energy based on available theoretical methods and estimate the electricity production of three types of WEC (attenuator, terminator, and point absorber). This study is focused on a limited zone in the Natuna Islands and the evaluation includes the temporal and spatial characteristics of the ocean waves.



Fig.1 Potential areas for wave energy extraction in Indonesia (ASELI) [4].

2. QUANTIFICATION OF WAVE ENERGY

Ocean waves are considered to be a random phenomenon, where ocean waves can be described as the superposition of numerous regular waves with different wave heights, frequencies, and phases. A sea state can be defined as a pair of significant wave heights and corresponding wave peak periods. The various combinations of sea states can be presented in the form of a scatter diagram. A scatter diagram shows the frequency of occurrence (expressed as the number or percentage of occurrence) of numerous sea-states over a specific period such as monthly or seasonal period. Therefore, a scatter diagram can be used as a basis to estimate electricity production of a WEC [5, 6 and 7].

The wave energy flux per unit crest width (W/m) for each sea state in a scatter diagram can be approximated as:

$$P \approx \frac{\rho g^2}{64\pi} H_s^2 T_e \quad (1)$$

Where ρ is the sea water density (kg/m^3), g is the acceleration due to gravity (m/s^2), H_s is the significant wave height (m), and T_e is the wave energy period (s), which is defined as the period of a sinusoidal wave that has the same energy as the sea state. The wave energy period can be derived from the wave energy density spectrum as follows:

$$T_e = 2\pi \frac{m_{-1}}{m_0} = 2\pi \frac{\int_0^{2\pi} \int_0^\infty \omega^{-1} \cdot S(\omega) \cdot d\omega d\theta}{\int_0^{2\pi} \int_0^\infty S(\omega) \cdot d\omega d\theta} \quad (2)$$

The value of T_e is dependent on the selected wave energy density spectrum, which can be related to other important wave periods such as the peak period (T_p) or zero crossing period (T_z or T_{02}). It is important to select the appropriate value of T_e in order to obtain accurate estimates of the wave energy resources. Cornett [3] used $T_e = 0.9T_p$, which corresponds to the JONSWAP theoretical energy spectrum with a peak enhancement factor of $\gamma = 3.3$. Cahill and Lewis [8] studied the ratio between T_e and the average zero crossing period (T_{02}) in calculating the wave power and then proposed a relationship between T_e with m_0 and m_2 , as:

$$T_e = 2\pi \frac{m_{-1}}{m_0} = 1.2 \cdot \left(2\pi \sqrt{\frac{m_0}{m_2}} \right) \quad (3)$$

In this work, due to the availability of data, the T_e values will be calculated using the method proposed by Cahill and Lewis [8].

3. WAVE ENERGY RESOURCES

In this study, the wave data of Natuna waters were obtained through PT Bina Rekacipta Utama, an engineering company [9], who's acquired SEAMOS-South Fine Grid Hindcast (SEAFINE) wave data, collected by the Oceanweather Inc [10] through a joint industry project. The goal of the project was to obtain wind and wave hindcast data in a fine grid of the southern region of the South China Sea. The SEAFINE data consist of hourly wave data on a 25-km selected uniform grid over a 59-year period (July 1956 to June 2015) and reveal important wave parameters such as the significant wave height, wave spectrum peak period, spectral moments (m_0 , m_1 , and m_2), and wave direction. The wave hindcasting and data processing methods used by SEAFINE are beyond the scope of this paper.



Fig.2 Stations around the Natuna Islands from which the wave parameters were extracted

The wave parameters were extracted for 26 stations in the vicinity of Natuna Islands, especially around the big island, Bunguran Island, as shown in Fig.2. The 59-year wave data were analyzed based on local seasonal variations and long-term occurrence data. Raghupathi et al. [11], classified wave temporal variation at South China Sea as North East Monsoon Season, South West Monsoon Season, and two in between transitional season. Similar seasonal classification is adopted with a slightly different time period. The seasonal or temporal variations of the waves are classified as: (1) North East Monsoon Season (December to February), (2) Transitional Season 1 (i.e., transition from the North East Monsoon Season to the South West Monsoon Season, March to May), (3) South West Monsoon Season (June to August),

and (4) Transitional Season 2 (transition from the South West Monsoon Season to the North East Monsoon Season, September-November).

A sea state is defined as a combination of the significant wave height (H_s) and its corresponding peak period (T_p). Based on the wave data, the frequency of occurrence of a sea state can be generated and presented in a scatter diagram. The scatter diagram shows the frequency of occurrence of a sea state in terms of the number or percentage of occurrence. The scatter diagram can be plotted for yearly, monthly, or seasonal periods. The wave characteristics at Station 7 (3.75°N, 108.75°E), represent the statistical characteristics of the waters east of the Bunguran Island. Fig.3 shows the scatter diagrams of the sea states at Station 7 in the North East Monsoon Season, Transitional Season 1, South West Monsoon Season, and Transitional Season 2. The scatter diagrams show the contours of the frequency of occurrence of the sea states.

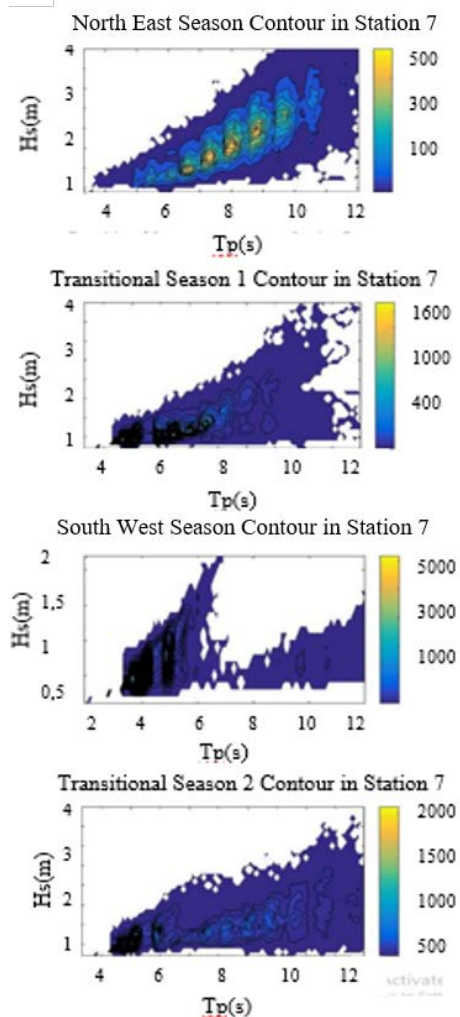


Fig.3 Seasonal frequency of occurrence of sea states at Station 7.

The four scatter diagrams for Station 7

indicate the temporal variations of sea state occurrences. It is evident that the North East Monsoon Season is characterized by waves with higher wave heights and longer periods compared to other seasons. Based on the data, waves with a height of 1.5–2.0 m and period of 8–10 s are mostly likely to occur in this season. The probability of occurrence for waves with a height greater than or equal to 2.5 m and period of more than 5 s is ~16%. However, the waves may reach a height of 3.5–4.0 m with a period of 10–12 s despite the low frequency of occurrence. In contrast, during the South West Monsoon Season, a calm sea condition is expected most of the time, where the wave height is within the range of 0.5–1 m. The maximum wave height is 2 m and the corresponding peak period is 5 s. However, waves with similar heights and longer periods (up to 15 s) also frequently occur in this season. During the transition seasons, waves with a height of 0.5–1.0 m and period of 5–6 s are most likely to occur. The probability of occurrence for waves with a height greater than or equal to 2.5 m and period of more than 5 s is ~1%. The waves may reach a height of 3.0–3.5 m with a period of 10–12 s in these seasons. The scatter diagrams for other stations located east of the Bunguran Island appear to have similar sea state occurrences as those for Station 7 whereas stations located west of the Bunguran Island appear to experience waves with smaller wave heights and shorter periods.

Station 25, located west of the Bunguran Island, represents the statistical characteristics of the waves in this area. Fig. 4 shows the scatter diagrams of the sea states at Station 25 for the four monsoon seasons. Similar to the scatter diagrams for Station 7, the scatter diagrams for Station 25 show the temporal variations of sea state occurrences. The North East Monsoon Season is a period in which waves with a wave height of 1.0–1.5 m and period of 9 s will mostly likely occur. The waves may reach a wave height of 2.5–3.0 m and period of 9–11 s. The probability of occurrence for waves with a height greater than or equal to 2.5 m with wave period of more than 5 s is ~6%. During the South West Monsoon Season, a calm sea condition is expected most of the time, where waves with a height of 0.5–1.0 m and corresponding peak period of 5 s will most likely occur. Waves with a similar height of 0.5–1.0 m and longer periods (up to 15 s) also frequently occur east of the Bunguran Island. The maximum wave height is 2 m in the South West Monsoon Season. During the transition seasons, waves with a height of 0.0–1.0 m and period of 4–5 s will most likely occur. The probability of occurrence for waves with a height greater than or equal to 2.5 m with a wave period

of more than 5 s is less than 1%. However, the waves may reach a wave height of 2.0-2.5 m with a period of 10–11 s.

The SEAFINE uniform grid of 25-km and documented wave data from 26 stations within vicinity of the Natuna Islands, enables one to analyze the spatial variations of waves. The average significant wave height and average wave peak period were calculated and presented in the form of wave height contour map or wave period map.

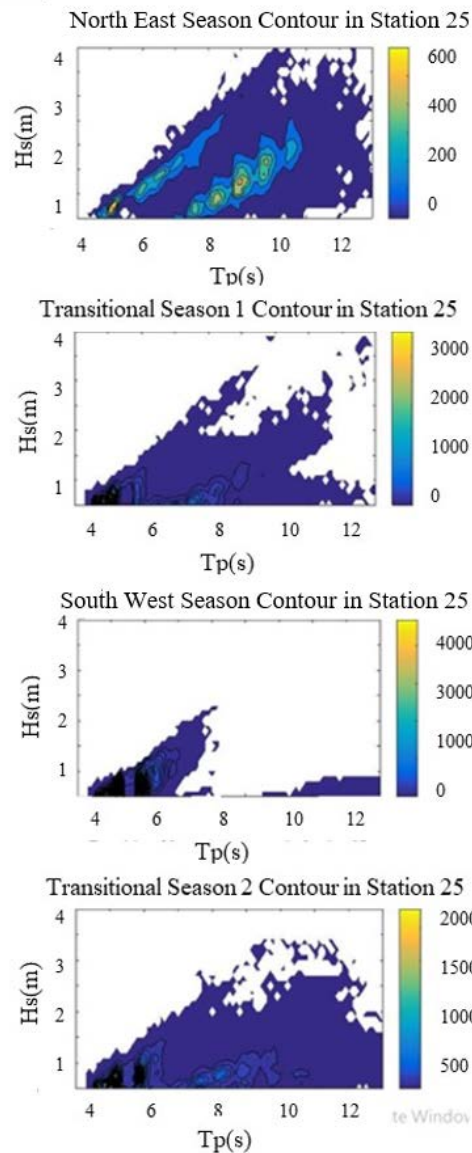


Fig.4 Seasonal frequency of occurrence of sea states at Station 25

Fig.5 shows the spatial distributions of the average significant wave height for the four monsoon seasons while Fig.6 shows the corresponding spatial distributions of the average peak wave period. As shown in Figs.5 and 6, the

eastern region of the Bunguran Island experiences higher waves with longer wave periods compared to the western region, which conforms well to the sea states scatter diagrams plotted for the eastern and western regions of the Bunguran Island. During the North East Monsoon Season, the average significant wave height is ~1.5 m and the corresponding average wave peak period is 7–8 s. The western region experiences waves with a smaller height of 0.5–1.0 m with an average period 4–5 s. Figs.5 and 6 also show that the average significant wave height is less than or equal to 1.0 m and the average peak period is shorter (2–4 s) during the South West Monsoon Season and both transitional seasons in this region.

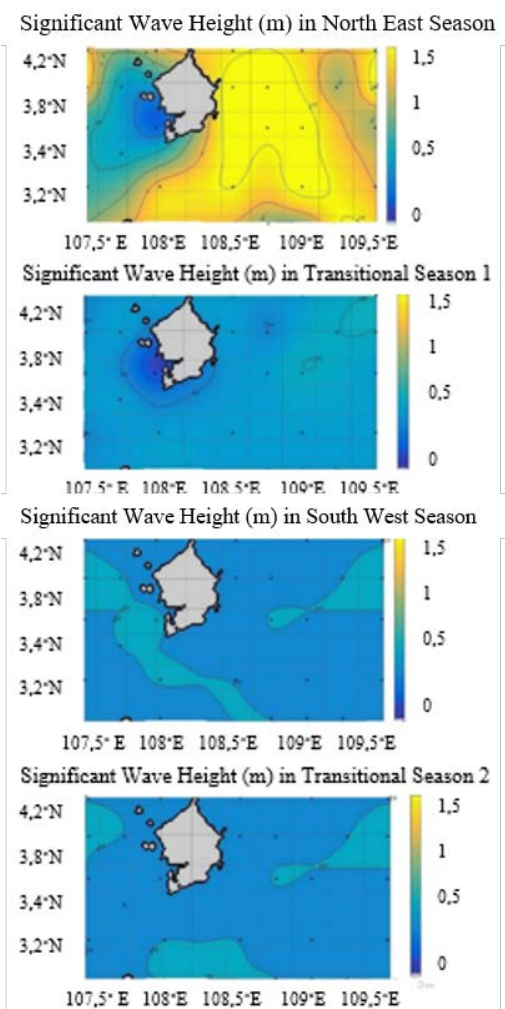


Fig.5 Spatial distributions of the average significant wave height.

Based on the spatial distributions of the average significant wave height and average peak period (Figs.5 and 6), the theoretical energy resource potential was estimated using Eq (1), in

which the energy period (T_e) was determined using Eq (3) and the occurrence of each sea state was determined from the respective scatter diagrams. The energy flux was estimated for each station and the spatial contours of the theoretical energy resources were generated. Fig.7 shows the spatial distributions of energy flux for the North East Monsoon Season, South West Monsoon Season, Transitional Season 1, and Transitional Season 2. The energy flux may reach 1.4–1.6 kW/m in the east of the Bunguran Island during the North East Monsoon Season while the energy flux is only 0.0–0.2 kW/m during the South West Monsoon Season and transition seasons. The energy flux during the North East Monsoon Season is 0.2–0.4 kW/m in the west of the Bunguran Islands whereas the energy flux is 0.0–0.2 kW/m during the South West Monsoon Season and two transition seasons. It is evident from Fig.7 that there are temporal and spatial variations of the energy flux in the waters surrounding Natuna Islands.

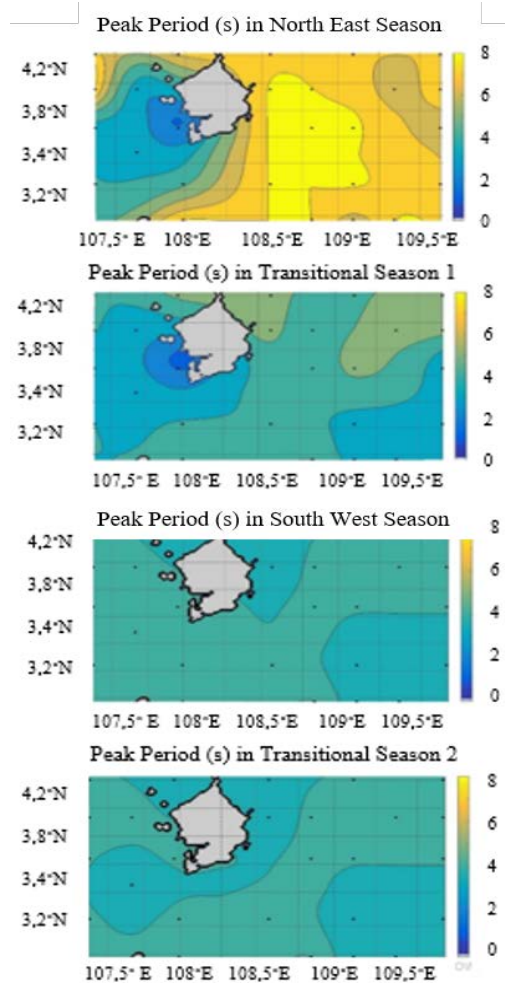


Fig.6 Spatial distributions of the average wave peak period.

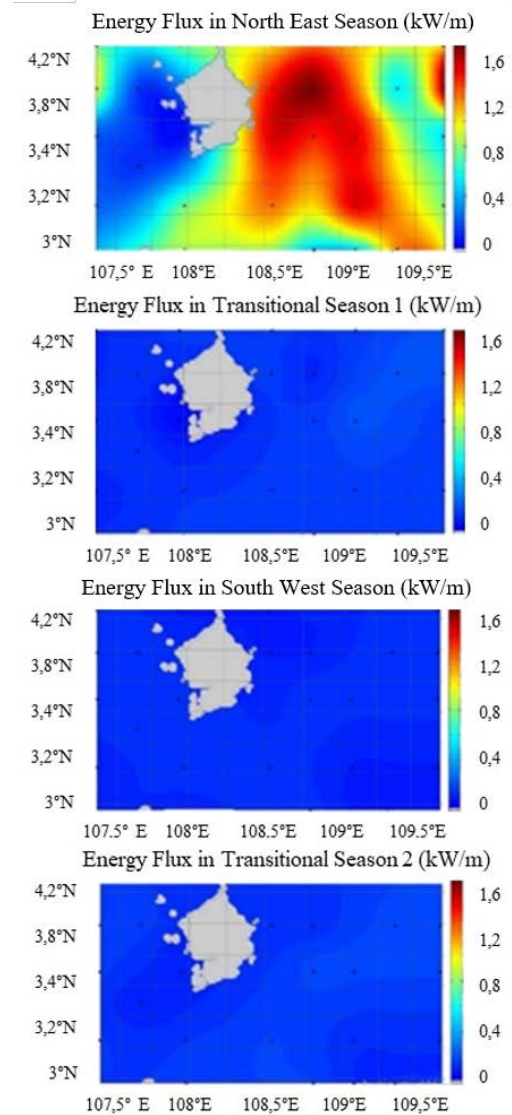


Fig.7 Spatial distributions of the wave energy flux.

4. PERFORMANCE OF WECs

WECs are used to transform wave energy into mechanical energy, which in turn, drives the electric generator and produces electricity. Because wave motions are mostly concentrated on the free surface, the WECs are usually installed on the ocean surface or close to the free surface. The wave energy conversion method varies from one WEC to another; the method can be based on variations in the wave particle motions, vertical motions of the water surface, wave slope/steepness, or dynamic pressure. Various WECs have been developed over the years and these devices can be classified as attenuators, terminators, and point absorbers. WECs can also be classified as onshore and offshore devices based on their installation site.

The different types of WECs are briefly described as follows.

Point absorber devices can either be floating or submerged devices. The wave energy is converted through several motions such as vertical motion (heaving device), surface gradient (pitching device), or a combination of both motions (heaving and pitching device). Point absorber devices can also convert wave energy into mechanical energy based on variations in the dynamic pressure. The performance of point absorber devices is not influenced by the incident wave direction.

Attenuator devices (also known as linear absorber devices) are designed to be positioned parallel to the incident wave direction. These devices are able to adjust their orientation in line with the incoming wave direction. The wave energy is converted into mechanical energy based on variations of the water surface gradient or steepness.

Terminator devices are designed to be directed to the dominant incident wave direction in order to achieve the best performance. These devices may be equipped with a wave directing/collecting device, which focuses the incident wave to a certain point in order to extract wave energy and these devices are connected to an electric generator. These devices convert wave energy into mechanical energy based on the variations of the wave dynamic pressure or differences in the water elevation through wave overtopping.

Lehmanna et al. [12] studied the development of WECs and they reported that there were 256 wave energy developers worldwide from which 38% were located in the United States of America. They also reported that 64% of the WECs were designed to be installed on offshore sites. Based on the types of WECs developed, they reported that 40% are point absorber devices whereas 23% were attenuator devices.

The performance of a particular WEC is determined by the wave energy conversion method. The performance of each WEC varies in response to the incoming waves as well as significant wave height and peak period (i.e., sea state). Therefore, information on WEC performance is always related to a particular sea state. For this reason, the frequency of occurrence of sea states can be linked to the performance of WECs used to estimate the electricity production at a selected location. Silva et al. [13] and Dunnet and Wallace [5] provided information on the performance characteristics of several WECs, specifically the power produced by each device as a function of a sea state. Figs.8, 9, and 10 show the performance contours of three different types of WECs (named WEC-1, WEC-2, and WEC-3).

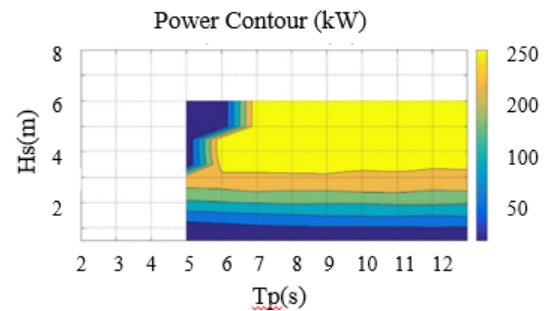


Fig.8 Performance of the WEC-1 device

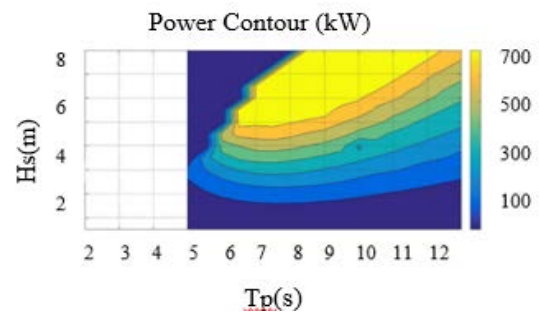


Fig.9 Performance of the WEC-2 device

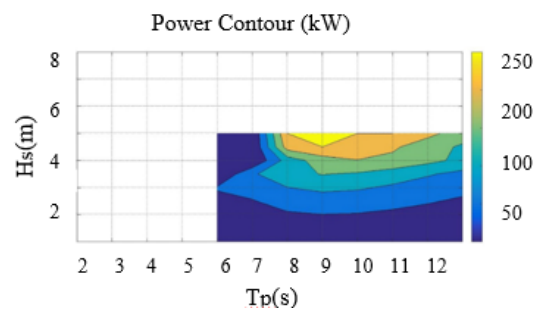


Fig.10 Performance of the WEC-3 device

It can be seen that there is a similar trend in the performance contours for all three WECs, where the maximum performance of the WEC occurs within a wave height of 5–6 m and period of 6–12 s, except for the WEC-1 device, where its maximum performance occurs at a wave height of 3 m and period of 6 s.

Based on the sea state data, the WEC-1 device may be suitable for waters in the east of the Bunguran Island due to its ability to produce electricity for waves with smaller wave heights and shorter periods. The WEC-3 device may produce less electricity in this region because it requires higher wave heights and longer periods. However, variations in the monthly (temporal) wave conditions may affect the electricity production for all three WECs.

5. ESTIMATION OF ELECTRICITY PRODUCTION

The performance characteristics of a particular WEC (Fig.10) indicated the expected power output for a sea state while the scatter diagrams (Figs.3 and 4) show the frequency of occurrence of each sea state at a selected location. Since the scatter diagrams can be easily converted into the number of hours where each sea state occurs, the incorporation of the WEC performance data and frequency of occurrence for each sea state (in h) enable one to estimate the electricity production for a certain period (e.g., 1 year or 1 month). Knowing the expected number of sea state occurrences (in hours) and expected power output of a WEC (in kW) and multiplying both of these data at the same sea state gives an estimation of the electricity production (in MWh) at the selected sea state. Summation of the electricity production for all sea states gives the total electricity production of the WEC at the selected location over a certain period. In this study, the electricity production was estimated on a monthly basis that the monthly scatter diagrams were then developed. The electricity production was estimated for each type of WEC (one unit), assuming that all the WEC devices can be oriented toward the incoming wave direction.

Fig.11 show the variations of the monthly electricity production for each type of WEC (one unit) at three selected offshore locations east of

the Bunguran Island (Stations 7, 11, and 14, as shown in Fig.2). The values of the monthly electricity productions are also tabulated in Table 1. The temporal variations at the three stations show a similar trend, where the electricity production is high during the North East Monsoon Season whereas the electricity production is low during the South West Monsoon Season. The electricity production during transition seasons are midway between those for the North East Monsoon Season and South West Monsoon Season. The WEC-1 device has the highest electricity production (111.4 MWh) at Station 14 in January. The WEC-2 device also has similar performance at Station 14 in January, with a value of 111.0 MWh. The WEC-3 device has the lowest electricity production (0.2–0.3 MWh) at Station 7 in June and July. In general, the WEC-1 and WEC-2 devices have similar performance whereas the performance of the WEC-3 device is inferior compared with the other two devices.

The WEC-1 device has the highest annual electricity production (465.3 MWh) at Station 11. As shown in Table 1, the WEC-1 device has the highest electricity production at all stations. The WEC-2 device has similar performance to the WEC-1 device whereas the WEC-3 device has the lowest electricity production. Table 1 also shows the annual average power for each type of WEC and station and it is apparent that the WEC-1 device has the highest annual average power.

Table.1 Electricity production for each type of WEC at three stations (Stations 7, 11, and 14).

Month	WEC-1			WEC-2			WEC-3			Unit
	St. 14	St. 7	St. 11	St. 14	St. 7	St. 11	St. 14	St. 7	St. 11	
Jan	111.4	105.1	110.0	111.0	102.1	109.0	41.2	37.4	40.3	MWh
Feb	76.9	79.6	76.3	75.0	77.3	174.1	27.7	27.5	27.3	
Mar	47.9	44.8	47.3	44.9	40.9	44.0	15.6	14.3	15.2	
Apr	15.3	13.8	15.1	13.8	12.4	13.6	5.2	5.2	5.2	
May	1.9	2.9	2.5	1.4	2.1	1.6	1.4	1.5	1.2	
Jun	1.3	2.5	2.7	0.8	0.8	1.4	0.6	0.2	0.6	
Jul	3.0	5.2	5.9	1.6	2.2	3.1	0.9	0.3	0.9	
Aug	3.6	6.1	7.1	1.9	2.6	3.9	1.0	0.4	1.1	
Sept	3.8	5.5	6.0	1.6	2.2	2.6	1.2	0.7	1.0	
Oct	24.3	24.7	25.9	16.5	16.5	17.4	7.1	6.5	7.0	
Nov	61.5	57.4	61.3	48.9	44.1	48.1	19.0	17.1	18.6	
Dec	107.4	99.0	105.2	99.0	87.2	95.5	37.9	33.0	36.6	
Yearly	458.3	446.4	465.3	416.4	390.5	414.2	158.8	144.0	155.3	MWh
Average Power	52.3	51.0	53.1	47.5	44.6	47.3	18.1	16.4	17.7	kW

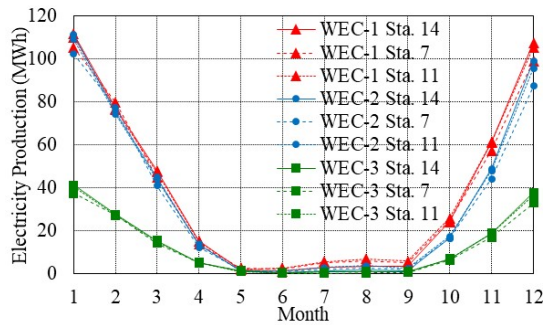


Fig.11 Variations of the monthly electricity production for each type of WEC

6. CONCLUSION

The waters around the Natuna Islands were identified as potential sites for wave energy extraction and therefore, a detailed study was performed to understand the characteristics at these sites and the possibilities of harnessing wave energy using current WEC technologies. Based on the sea state data, it is concluded that the waters in the eastern region of the big island (Bunguran Island) have more potential for wave energy extraction compared to western region. Therefore, three offshore stations east of the Bunguran Island were selected to estimate the electricity production using three types of WECs. Based on the seasonal wave data, there are temporal variations of the wave characteristics, where the highest sea state occurs during the North East Monsoon Season. In contrast, a relatively calm sea state with smaller wave heights is expected to occur in the South West Monsoon Season, Transitional Season 1, and Transitional Season 2.

The electricity production for each WEC at the east side of Bunguran Island (represented by stations 7, 11, and 14) was estimated based on the performance characteristics of the WECs and sea state data. The WEC-1 device has the best performance, producing electricity up to 111.4 MWh. Similar performance shown by the WEC-2 device (111.0 MWh). Both of these devices attain maximum performance in January, which is the peak of the North East Monsoon Season. The WEC-3 device has the lowest electricity production (0.2 MWh) in June (during the South West Monsoon Season). The results showed that the electricity production, during the South West Monsoon Season, is very low for all types of WECs. In general, electricity production is highly influenced by temporal variations of the wave characteristics and therefore, it is imperative to carefully plan, select, and design the WEC device in order to reach optimum level in harvesting wave energy in waters within vicinity of the Natuna Islands.

The use of hindcasting wave data to obtain the

characteristics of the sea states and estimate energy resources at a selected site provides a reliable basis for preliminary design of WECs. However, for detailed design purposes, it is necessary to conduct site-specific wave measurements. In this manner, the electricity production, wave energy conversion method, device capacity factor, and production cost can be determined with higher accuracy.

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8. REFERENCES

- [1] Kementerian Koordinator Bidang Kemaritiman Republik Indonesia, <https://maritim.go.id/menko-maritim-luncurkan-data-rujukan-wilayah-kelautan-indonesia/> [last accessed 27 August 2018]
- [2] Dewan Energi Nasional, "Indonesia Energy Outlook 2016," 2016A.M. Cornett, "A Global Wave Energy Resource Assessment," ISOPE 579, 2008.
- [3] A.M. Cornett, "A Global Wave Energy Resource Assessment," ISOPE 579, 2008.
- [4] ASEL, "Potensi Energi Laut Indonesia," 2014 (in Bahasa Indonesia).
- [5] D. Dunnett, J.S. Wallace, "Electricity generation from wave power in Canada," *Renewable Energy* 34, 2009, 179–195
- [6] Sam Behrens, Jennifer Hayward, Mark Hemer, Peter Osman, "Assessing the wave energy converter potential for Australian coastal regions," *Renewable Energy* 43, 2012, 210–217.
- [7] G. Hagerman and R. Bedard, "Guidelines for Preliminary Estimates of Power Production by Offshore Wave Energy Conversion Devices," E21 EPRI Specification, Electric Power Research Institute (EPRI), 2003.
- [8] B. Cahill and T. Lewis, "Wave Period Ratios and The Calculation of Wave Power," *Proceedings of the 2nd Marine Energy Technology Symposium, METS2014*
- [9] PT Bina Rekreasi Utama, <http://biru-eng.com/> [last accessed 28 August 2018]
- [10] Oceanweather Inc., www.oceanweather.com/metocean/seafine/index.html [last accessed 28 August 2018]
- [11] L. Raghupathi, D. Randell, P. Jonathan and K.C. Ewans, "Consistent Design Criteria for South China Sea with a Large-Scale Extreme Value Model," *Offshore Technology Conference Asia, Kuala Lumpur*, 2016.

- [12] M. Lehmann, F. Karimpoura, C.A. Goudey, P.T. Jacobson, and M.R. Alama, "Ocean wave energy in the United States: Current status and future perspectives," *Renewable and Sustainable Energy Reviews*, 74, 2017, pp. 1300–1313
- [13] D. Silva, E. Rusu and C.G. Soares, Evaluation of Various Technologies for Wave Energy

Conversion in the Portuguese Nearshore, *Energies* 2013, 6, 1344-1364; ISSN 1996-1073.

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