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WAVE ENERGY POTENTIAL OF PENINSULAR MALAYSIA

Muzathik AM[1#], Wan Nik WB[1], Ibrahim MZ[2] and Samo KB[3]
[1] Maritime Technology Department, University Malaysia Terengganu, Kuala Terengganu, Malaysia
[2] Engineering Science Department, University Malaysia Terengganu, Kuala Terengganu, Malaysia
[3] Institute of Oceanography (INOS), University Malaysia Terengganu, Kuala Terengganu, Malaysia
[#] Institute of Technology, University of Moratuwa, Moratuwa, Sri Lanka

E-mail: muzathik64@yahoo.com, niksani@umt.edu.my

ABSTRACT

Wave power potential along the east coast of Peninsular Malaysia, facing South China Sea, bounded by latitudes 3.5^0 N and 6.5^o N and longitudes 102^0 E and 104.0^o E, is investigated based on two-hourly data, covering a 12-year period. The correlation between maximum wave height (H_{max}) and significant wave height (H_s) for the east coast of Peninsular Malaysia can be given by $H_{\max} = 1.494 H_s + 0.01324$. The values of peak periods (T_p) and mean periods (T_{mean}) can be correlated with new model as $T_{mean} = a_1 * \exp - ((T_p - b_1)/c_1)^2 + a_2 * \exp -((T_p - b_2)/c_2)^2 + a_3 * \exp - ((T_p - b_3)/c_3)^2$ where, $a_1 = -269.9$, $b_1 = 9.609$, $c_1 = 2.225$, $a_2 = 271.9$, $b_2 = 9.615$, $c_2 = 2.242$, $a_3 = 3.254$, $b_3 = 6.903$ and $c_3 = 7.812$. Total wave energy was around 1.8 x 10^7 Wh/m in an average year, whereas the average wave power less than 6500 W/m. More than sixty percent of the annual wave energy is provided by significant wave heights less than 1.2 m. The wave peak periods less than 8 s accounted for more than seventy percent of total wave energy. The main directions in terms of wave energy for whole year are north, which accounts for more than 40%, followed at some distance by northeast, southwest and south. During northeast monsoon season, in general main directions in terms of wave energy are north and northeast, which accounts more than 80% of total wave energy.

Keywords: significant wave height, wave direction, wave energy, wave period, wave power

INTRODUCTION

The development of renewable energy sources together with the expansion of those currently exploited is crucial in reducing the emissions of greenhouse gases as prescribed by the Kyoto protocol. Amongst renewable energy sources, ocean waves contain the highest energy density. This allows for substantial energy generation in relatively small areas from a virtually inexhaustible energy source. Ocean wave energy has the potential to become commercially viable quicker than other renewable technologies, achieving the fastest growth rate of all energy sources and generating significant wealth [1-3]. Wave energy presents a number of advantages with respect to other CO_2-free energy sources such as high availability factor compare with other resources (e.g. wind, solar), resource predictability, high power density, relatively high utilization factor and low environmental and visual impact [4]. It has been estimated that if less than 0.1% of the renewable energy available within the oceans could be converted into electricity, it would satisfy the present world demand for energy more than five times over. Environmentally, wave energy conversion appears to be relatively benign. The majority of environmental impacts occur during the construction and installation phases, but once in operation wave energy converters (WEC) release no greenhouse gases and are unlikely to affect migratory fish patterns or coastal eco-systems [5-6]. A WEC can even have positive environmental effects, as the mooring lines that keep the WEC in place provide artificial reef habitat for sea life [7-8]. In spite of these advantages, wave energy exploitation is still in its infancy due to technological challenges still ahead. Ocean wave energy has not yet been exploited to any significant extent in Malaysia, or elsewhere in the world. However, wave energy conversion still remains a part of novel technologies to be explored for most countries [9]. Countries with wave conditions favorable for energy conversion have been pursuing ways to further develop this novel technology.

A research and development program on wave energy was established by the International Energy Agency in 1978, the program was lead by Ireland, Japan, Norway, Sweden, United Kingdom and USA [10]. In the last few decades various locations have been investigated for the availability of wave power for energy conversion. Studies on wave power potential of UK [11-13], Denmark [14], Belgium [15], Portugal [16], Baltic Sea [17-18], USA [19-24], India [25-26], Argentina [27], Brazil[28], New Zealand, Ireland, Japan, Chile, Korea, Norway and Sweden [29], Australia [30], China [31], Spain [32-33], Canada [34] and Swedish [35] can be found in the related literature. The highest energy ocean waves are concentrated off the western coasts in the 40^o–60° latitude range north and south. Waves are bigger and more powerful along the west part of the Earth's because of the prevailing west-to-east winds. The annual average power in the wave fronts varies in these areas between 30 and 70 kW/m, with peaks up to 100 kW/m in southwest of Ireland, in the Southern Ocean [36]. Based on these studies, annual wave power potentials are given for few locations in Table-1.

Waves at different places have certain characters and energy densities. The amount of energy that can be created using wave technologies varies from day-to-day and site-to-site, depending on locations and weather conditions. Nevertheless, wave energy can be accurately predicted within a period of a few days. In this study as well as in the design stages of a WEC to ensure that it will convert the energy efficiently over a sufficient wave period range while accommodating the large distribution of powers, the knowledge of the statistical characteristics of the local wave climate is essential. Therefore, it is important to map the available energy to optimize the benefits from prospective developments.

Table-1. Annual wave power for different locations in the world.

Location	Wave power (kW/m)	Location	Wave power (kW/m)
Belgium	10	Ireland	57-77
Canada	33	Italy	10-5
China	1-35	Japan	6-7
Denmark	7-24	Norway	20-40
France	4-40	Portugal	30-40
Greece	2-4	UK	45-75
India	10-32	USA	4-32

The potential for the wave energy extraction can be obtained from analysis of the wave climate. Measured data can give a general idea of the existing conditions as well as valuable information concerning some tendencies. Nevertheless, this approach has some limitations especially due to the facts that the time period of the measurement is in general limited.

Although wave energy potential has been reported for few countries around the world, reliable and yearlong wave data is still needed for Malaysia. This study therefore addresses this need. To evaluate the amount of ocean wave power potential at east coast of Peninsular Malaysia the wave data collected by the Department of Maritime Technology, University Malaysia Terengganu and Malaysian Meteorology Department are used.

STUDY AREA AND DATA FROM IN SITU MEASUREMENTS

The area of interest in this study is bounded by latitudes 3.5° N and 6.5° N and longitudes 102.0° E and 104.0° E (Figure-1). The investigation was based on one and two-hourly data collected at wave measurement stations covering the period from January 1998 to August 2009. In order to give a better perspective on the representative wave conditions in the coastal area of east Peninsular Malaysia, a medium term analysis based on in situ measurements is presented.

The datasets used for the wave energy potential analysis were acquired from the Department of Maritime Technology, University Malaysia Terengganu (UMT) and Malaysian Meteorology Department (MMD) which are available at a one and two hours frequencies (sampling interval). The acoustic wave and current (AWAC) instruments belong to UMT was deployed at 20 m water depth, 5 km from shore covering the period from June 2008 to August 2009.

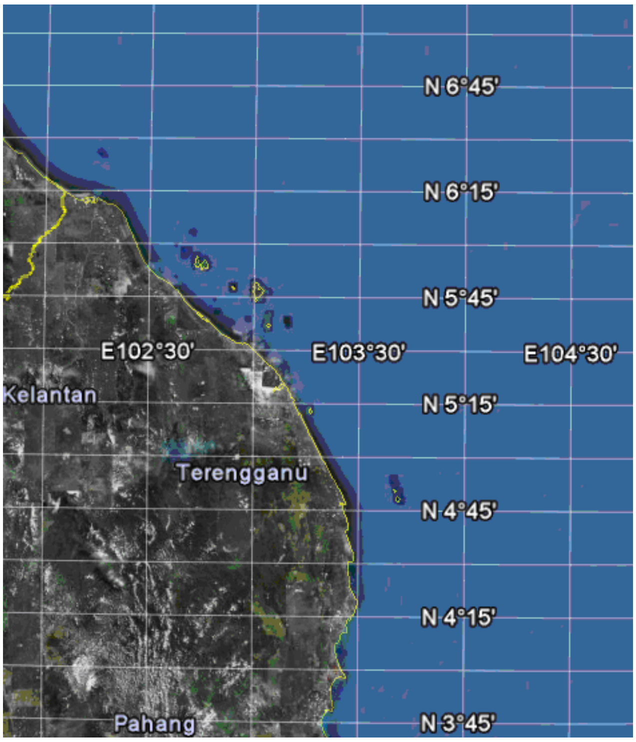

Figure-1. Location map of the study area of east coast of Peninsular Malaysia [37].

The availability of standard meteorological data and spectral wave data, and wave height and period statistics are shown in Table-2. The standard meteorological data provides at each location the significant wave height H_s, which is calculated from the energy spectrum. Similarly, the wave period is given with the average wave mean period, T_m, calculated from the energy spectrum of similar waves. The time series data consist of the wave height, the wave period, and wave direction. In the data, there were missing dates and values. In some case there are continuous zero readings for the wave height, which are ignored in the calculations. In some instances, dates were available with no values; in other cases, the dates themselves were missing. The missing values were interpolated using the available data. Once the continuous hourly data sets were created, the values were averaged to a one-day frequency in order to be able to asses for daily wave energy values and then summarized for each month of the year at location according to the energy bins. Using these summaries and the performance data, monthly energy potential was calculated for each month.

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WAVE ENERGY RESOURCE CHARACTERIZATION

Regular ocean waves are the sum of numerous smaller wave components. Each wave component has its own height, period, and direction of propagation. But when evaluating the incident energy in a complex sea state, there are many interacting waves, so there is not a single wave height and wave period. To measure the incident energy of a complex sea state, two characteristic values are used: significant wave height, H_s (m), and energy period, T_e (s). Both of these values are independent of the direction of wave propagation. The significant wave height is the average height of the highest 1/3 of waves or is defined as four times the root-mean-square (RMS) elevation of the sea surface (H_{rms})

$$H_s = 4H_{rms} = 4\sqrt{m_0} \qquad (1)$$

where m_0 is the zeroth moment (or variance) of the wave spectrum. Energy period T_e is one of several representative wave periods measures in use although it is favored for wave energy approaches as it weights waves according to spectral energy content [38]. This measurement closely corresponds to the wave height that an observer would estimate when describing ocean activity [5]. The energy period of a sea state is defined as the period of a single sinusoidal wave that would have the same energy as the sea state. All wave energy converter performance data is given in terms of H_s because it is easily measured. However, T_e is not easily determined from observed wave data. T_e is defined as T_e=m_{-1}/m_0, where m_{-1} is the reciprocal of the first spectral moment (the mean frequency). There are several simpler measures of wave period that are commonly used: the peak period, T_p, which is measured as the average time between wave crests; the zero-crossing period, T_Z, which is the inverse of the average number of times that the ocean level moves up across the mean water level per second; and the power period, T_{pow} which is the period of a sinusoidal wave with the same incident power as the sea state. Figure-2 illustrates the concept of significant wave height and zero-crossing period.

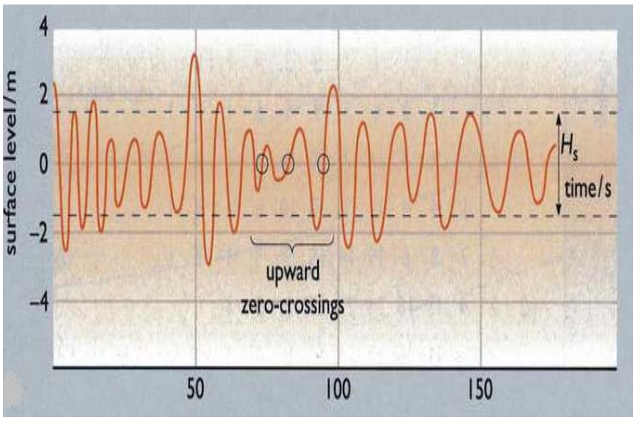

Figure-2. Illustration showing the zero-crossing period and significant wave height [5].

The relationship between T_e and these other wave period measurements depends on the spectral distribution of the component waves. The spectral distribution is a description of the energy density of the sea state as a function of wave component frequency; it gives a sense of how much energy can be expected to be in a wave for a given wave frequency. The spectral distribution of irregular seas can be modeled to very high precision using models. Different parameters are supplied to these models to ensure that they closely fit the observed wave activity. When a model has been properly fitted to a location, a simple scalar coefficient is used to approximate the relationship between T_e and any other wave-period. The Canadian Hydraulics Center assumed that $T_e = 0.9T_p$ for Canada's Pacific and Atlantic coasts [5]. For this study, it will be assumed,

$$T_e = 0.9T_p \qquad (2)$$

In the present studies, simulated ocean waves are sinusoidal. The energy flux, $J_{sin,}$ (W/m of wave front) transported by purely progressive sinusoidal wave is given by [39]

$$J_{\sin} = kT_e H_w^2 \qquad (3)$$

where k = 976 W/s m^3, T_e is wave period (s), H_W is the height (m) of the sinusoidal wave. For more realistic ocean waves, coefficient k is 500 W/s m^3 as stated by Boyle [5]. The energy flux, J, transported by realistic non-sinusoidal waves is

$$J = kT_e H_s^2 \qquad (4)$$

where H_s is significant wave high found from wave energy spectra. The energy transported by real waves is approximately half of the flux transported by sinusoidal waves. Practical utilization of ocean wave energy shows that in the range of 20% of the energy J_{sin} can be absorbed by WEC in reality [40].

In order to analyze the weeks, months and years variations of the wave height, wave period and wave power, the data are averaged to get the typical variation of wave properties in a period by

$$H_{averaged}, T_{averaged}(k) = \frac{1}{M}\sum_{i=1}^{M} H_i, T_i(i,k) \qquad (5)$$

$$P_{averaged}(k) = \frac{1}{M}\sum_{i=1}^{M} P_i(i,k) \qquad (6)$$

where M is the number of year of available data. The mean power at a station is estimated by calculating the mean of the averaged wave power, $P_{averaged}$. Similarly the maximum wave power for a typical year is estimated by calculating the maximum of $P_{averaged}$. The maximum power would simply give the maximum observed power for a single extreme event rather than the power available for energy extraction.

While waves propagate in the deepwater seas they are unaffected by the sea bottom. However, as they travel towards the shoreline they eventually reach a point from which the seabed starts to affect their propagation through refraction, shoaling and bottom friction. This threshold defining the change between deepwater and intermediate or transitional water depths is not the same for all waves but depends on their length, or period. From this point onwards, waves dissipate part of their energy as a result of their interaction with the seabed. For this reason, wave energy is, generally speaking, greater in deepwater. Nonetheless, wave energy converters must be located in relative proximity to the shoreline due to practical reasons, among which the water depth limits imposed by the anchoring or the foundations. Thus, the optimum location of a wave farm is a compromise in which the technology of the wave energy converters to be deployed, the coastline shape and the bottom slope.

RESULTS AND DISCUSSIONS

Wave height, period and direction

The east coast of Peninsular Malaysia was selected to characterize the wave energy potential. The two-hourly values of significant wave height, peak period, and mean wave direction within the period 1998-2009 were analyzed for these areas. The year around variation of significant wave height (H_s) and the maximum wave height (H_{max}) were plotted as shown in Figure-3.

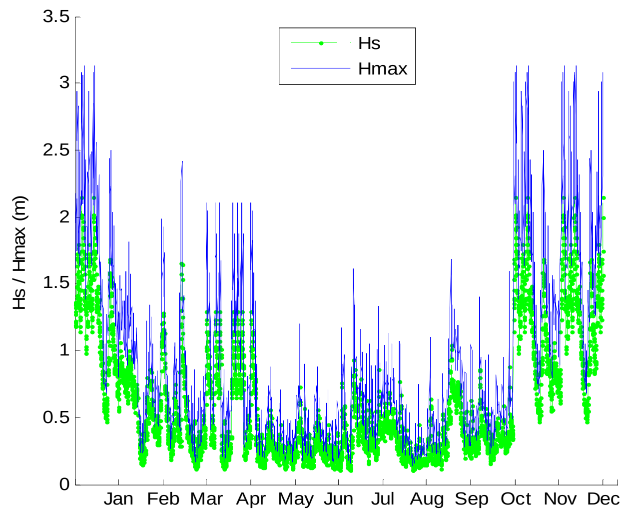

Figure-3. Year around variation of H_s and H_{max}.

The results from the measurements are presented below. They include the classes of significant wave height, maximum wave height, mean and peak periods and also the wave direction distributions, corresponding to whole years and monsoon seasons. In order to show the random variability in the actual situation, the joint significant wave height (H_s) and peak wave period (T_p) distribution was tabulated considering eleven significant wave height intervals and eight peak period intervals as shown in Table-3, leading to eighty eight combined intervals. Further, the joint H_s and mean wave period (T_{mean}) distribution was also tabulated considering similar number of intervals as joint H_s and T_p distribution, as shown in Table-4. Ascribing each two-hourly sea state to the appropriate interval, the percentage of the total time in an average year corresponding to the different intervals was obtained. For illustration the results for the location of latitude 5 ^{o} 35' N and longitude 102 ^{o} 55.5' E on east coast of Peninsular Malaysia are shown in Tables 3 and 4. The distribution of H_s and T_p agrees with the global wave statistics, belongs to Sea area 62 by BMT Fluid Mechanics Limited [41].

During the monsoon period the joint significant wave height (H_s) and peak wave period (T_p) distribution was tabulated considering eleven significant wave height intervals and eight peak period intervals as shown in Table-5 for the same location.

A similar analysis was carried out combining mean wave direction (θ_m) and significant wave height. Eight sectors were considered for the mean wave direction (N, NE, E, SE, S, SW, W and NW). With the same significant wave height intervals as Table-5, eighty eight combined intervals of the (H_s, θ_m) distribution were considered. The sea states in the period 1998-2009 were ascribed to these intervals and the corresponding time percentages computed for the same location is given in Table-6.

For the characterization and computation of wave energy, the wave spectra were assumed to be the same during the sampling interval of two hours. The wave energy in the sea states of each of the combined (H_s, T_p) and (H_s, θ_m) intervals in the 1998-2009 period was calculated and referred to a one-year period to obtain the value in an average year; the total annual wave energy was obtained as the sum of all the intervals. Table-7 shows the results of the (H_s, T_p) analysis at same location before, with wave energy data expressed in kWh/m width of wave front per year and the values within brackets (Table-7) shows the percentage of the total energy corresponding to each interval.

From an energetic point of view, northeast monsoon season is more relevant and that is why the results are structured in whole year and northeast monsoon periods. Northeast monsoon season is considered here as the 3-month period from November to January. Table-8, Table-9 and Table-10 show the results of an average year joint H_s and wave power (P), (T_p, P) and monsoon period (H_s, P) distribution, respectively with wave power data expressed in percentage of the total power corresponding to each interval.

More than 60% of the annual wave energy is provided by mid-height waves, with significant wave heights between 0.2 m and 1.2 m (Table-8). With regard to the wave period, waves with peak periods between 2 and 8 s accounted for more than 70% of the total wave energy (Table-9). The reason are deepwater wave power is linearly related to wave period and higher periods tend to be associated with mid-height waves.

The studies reveal that the annual average wave energy was 17.69 MWh/m and the average wave power at 4.04 kW/m. In the calculation of power for east coast of Peninsular Malaysia, for the averaged values of H_s=1.22 m and T_p=5.87 s, one can consider based on available wave power. If considering only numerical values of H_s, one can obtain H_s = 0.61 m only. To better visualize the monthly variation of wave energy, it is plotted as a bar chart at latitude 5 ^{o} 35' N and longitude 102 ^{o} 55.5' E in Figure-4. It is observed that monthly averaged wave power varies between 0.15 kW/m and 6.49 kW/m. From this one can see that the wave power and stirring month in a year are not much different in the east coast of Peninsular Malaysia. Also, it can be observed that, in general, monthly mean wave power is lower in the middle of the year when compared to that in the start and end of the year.

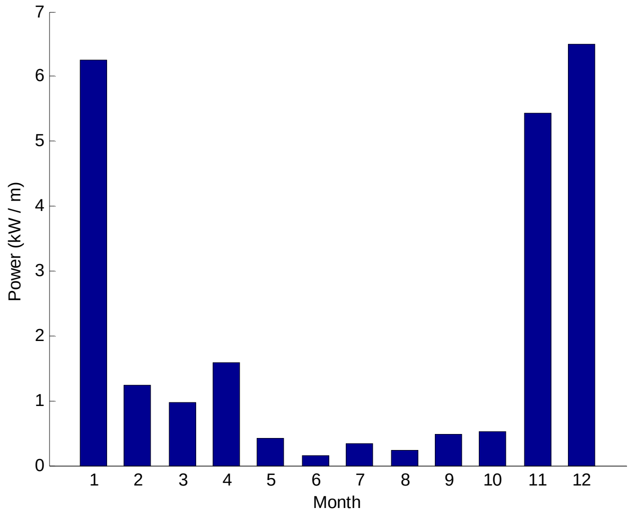

Figure-4. Monthly average wave power (kW/m).

The intensity of wave energy fluctuates seasonally, with the highest energy density occurring during the northeast monsoon, when there are more storms and winds, and lower energy densities occurring in the southwest monsoon. Figure-5 shows the seasonal variance of H_s, T_p and incident wave power which are calculated by equations 6 and 7 at latitude 5 ^{o} 35' N and longitude 102 ^{o} 55.5' E on the east coast of Peninsular Malaysia. It is apparent that the east coast of Malaysian wave climate may be divided into three seasons: the first season covers from November to January, the second season covers from February to April and third season covers from May to October, which is representing calm season for east coast of Peninsular Malaysia.

The main directions in terms of wave energy for whole year are N, which accounts for more than 40%, followed at some distance by NE, SW and S (Figure-6a). Further, its high wave energy potential is available during northeast monsoon season and in general the main directions in terms of wave energy are N and NE, which accounts more than 80% of the total wave energy (Figure-6b), which may be used as a reference for this area.

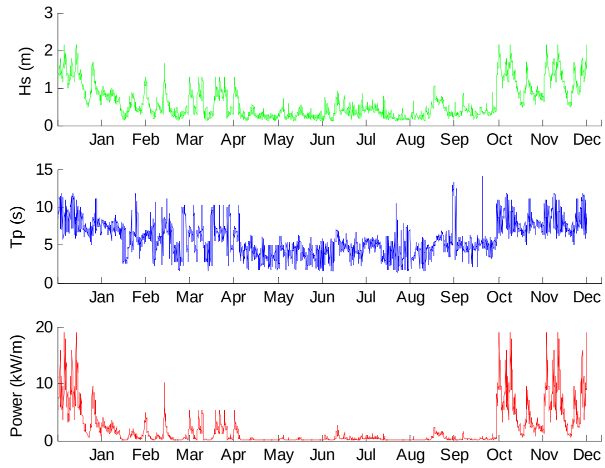

Figure-5. Seasonal variance of H_s, T_p and incident wave power at latitude 5 ^{o} 35' N and longitude 102 ^{o} 55.5' E.

Wave heights correlation

The minimum, maximum, mean and standard deviation values of the H_S and H_{max} for the study area are 0.11 m, 2.15 m, 0.61 m, 0.45 m, 0.16 m, 3.13m, 0.93 m and 0.67 m, respectively. The values of H_{max} observed from measurement show that they were approximately 1.5 times those of the H_s values and that they co-vary with correlation coefficient of 0.999, which is shown in Figure-7. The concept of statistical nature of wave height was originally proposed by Longuet-Higgins [42] and showed that the wave amplitudes in a narrow banded spectrum will be Rayleigh distributed. This study indicates that the correlation between H_{max} and H_s for the east coast of Peninsular Malaysia can be given by Equation (7).

$$H_{\max} = 1.494 H_s + 0.01324 \quad (7)$$

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ARPN Journal of Engineering and Applied Sciences

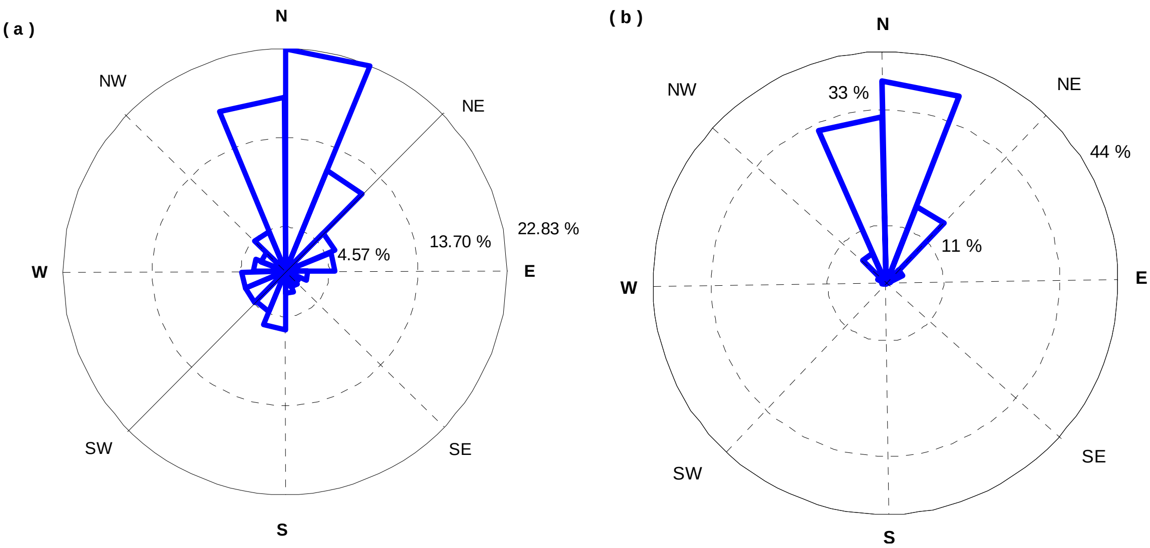

Figure-6. Percentage of total wave energy vs mean wave direction (a) for whole year, (b) for northeast monsoon season at latitude 5 ^{o} 35' N and longitude 102 ^{o} 55.5' E.

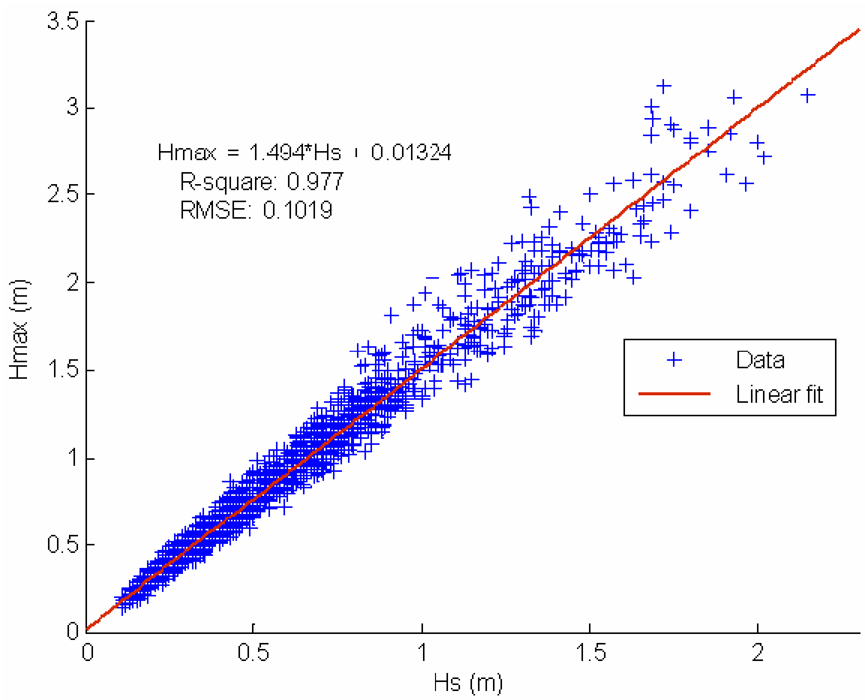

Figure-7. The correlation between H_{max} and H_s at latitude 5 ^{0} 35' N and longitude 102 ^{0} 55.5' E.

Figure-8 shows monthly averaged H_s and H_{max} variation. It is observed that maximum wave heights varies between 1.13 m and 3.13 m and monthly mean significant wave height varies between 0.27 m and 1.24 m. From this one can see that the wave heights and stirring month in a year are not remarkably different in the east coast of Peninsular Malaysia. Also, it can be observed that, in general, monthly mean significant wave height is lower in the middle of the year when compared to that in the start and end of the year.

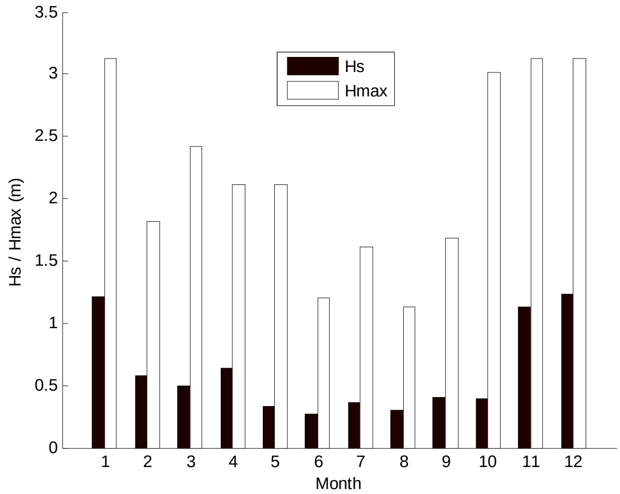

Figure-8. Variation of monthly averaged H_s and H_{max} at latitude 5 ° 35’ N and longitude 102 ° 55.5’ E.

Wave periods correlation

The minimum, maximum, mean and standard deviation values of the T_p and T_{mean} for the study area are 1.43 s, 14.03 s, 5.88 s, 2.21 s, 1.82 s, 6.59 s, 3.85 s and 1.88 s, respectively. The values of T_p observed from measurement show that they were not linearly correlating with T_{mean} values and them correlating with Gaussian 3 general model with correlation coefficient of 0.839; which is shown in Figure-9. From this study the correlation between T_{mean} and T_p for the east coast of Peninsular Malaysia can be given by Equation 8.

$$T_{mean} = a_1 * \exp - ((T_p - b_1)/c_1)^2 + a_2 * \exp - ((T_p - b_2)/c_2)^2 + a_3 * \exp - ((T_p - b_3)/c_3)^2 \quad (8)$$

where, a_1 = -269.9, b_1 = 9.609, c_1 = 2.225, a_2 = 271.9, b_2 = 9.615, c_2 = 2.242, a_3 = 3.254, b_3 = 6.903 and c_3 = 7.812.

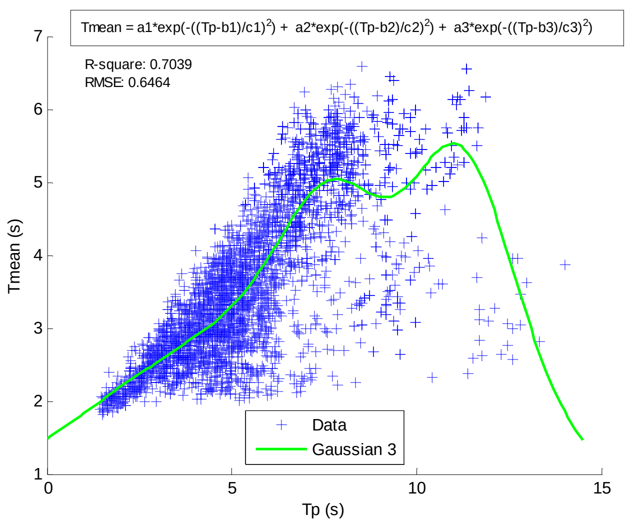

Figure-9. The correlation between T_{mean} and T_p at latitude 5 ⁰ 35’ N and longitude 102 ⁰ 55.5’ E.

Figure-10 shows monthly averaged T_{mean} and T_p variation. It is observed that the wave mean period varies between 2.76 s and 5.28 s and monthly averaged wave peak period varies between 3.94 s and 8.28 s. One can see that the wave periods and stirring month in a year are not remarkably different in the east coast of Peninsular Malaysia. Also, it can be observed that, in general, monthly mean wave periods value is similar in the whole year.

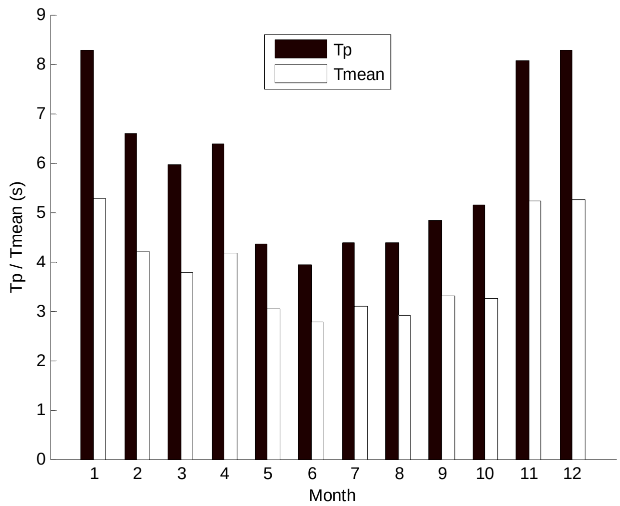

Figure-10. Monthly averaged T_{mean} and T_p variation at latitude 5 ⁰ 35’ N and longitude 102 ⁰ 55.5’ E.

CONCLUSIONS

Wave energy has a number of significant advantages with respect to other renewable energy sources - predictability, abundance, high load factor and low environmental impact, among others. Its late beginning relative to other CO_2-free energy sources is down to the technological challenges that it poses. In addition to developing commercially viable wave energy converters, the resource characterization is a crucial point towards the exploitation of wave energy. Wave power along the east coast of Peninsular Malaysia was analyzed at a time scale of months to examine the seasonal dependencies. The area of interest is the east coast of Peninsular Malaysia bounded by latitudes 3.5° N and 6.5° N and longitudes 102° E and 104.0° E. The study was based on one and two-hourly data collected from wave measurement stations covering the period from January 1998 to August 2009. Availability and the structure of data from wave measurements are discussed. Seasonal trends of wave heights, wave periods, wave directions and wave power are also discussed. The wave power potential was calculated from significant wave height and wave peak period.

These preliminary investigations show that the east coast of Peninsular Malaysia could provide a source of low wave power. The wave climate in the east coast is among the harsh in Peninsular Malaysia. The total wave energy was found to be around 1.8 x 10^7 Wh/m in an average year, whereas the average wave power less than

ARPN Journal of Engineering and Applied Sciences

6500 W/m. It may be concluded that states in the east coast of Peninsular Malaysia can consider northeast monsoon period for wave energy exploitation. Moreover, the wave climate of the area was studied in order to characterize the sea states behind the wave energy availability. It was found that in this area more than 60% of the annual wave energy is provided by significant wave heights less than 1.2 m and waves with peak periods less than 8 s accounted for more than 70% of the total wave energy. The main directions in terms of wave energy for whole year are N, which accounts for more than 40%, followed at some distance by NE, SW and S. Further, its high wave energy potential is available during northeast monsoon season and in general the main directions in terms of wave energy are N and NE, which accounts more than 80% of the total wave energy, which may be used as a reference for this area.
The values of H_{max} observed from measurement show that they were approximately 1.5 times those of the H_s values and that they co-vary with correlation coefficient of 0.999. The correlation between H_{max} and H_s for the east coast of Peninsular Malaysia can be given by $H_{\max} = 1.494 H_s + 0.01324$. Further, the values of T_p observed from measurement show that they were not linearly correlating with T_{mean} values and they correlating with "Gaussian 3" general model with correlation coefficient of 0.839. The correlation between T_{mean} and T_p can be given by $T_{mean} = a_1 * \exp - ((T_p - b_1)/c_1)^2 + a_2 * \exp - ((T_p - b_2)/c_2)^2 + a_3 * \exp - ((T_p - b_3)/c_3)^2$ where, $a_1 = -269.9$, $b_1 = 9.609$, $c_1 = 2.225$, $a_2 = 271.9$, $b_2 = 9.615$, $c_2 = 2.242$, $a_3 = 3.254$, $b_3 = 6.903$ and $c_3 = 7.812$.

For wave energy conversion, the power that can be extracted depends on the response curves and efficiencies of the wave energy converters that can be used. Although the available wave power is low, the accessible wave power off the east coast of Peninsular Malaysia is still a considerable energy source. With advancing technological capabilities, increasing wave energy conversion efficiencies and introducing new methods to harvest the wave power, the results might eventually be better than expected.

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ARPN Journal of Engineering and Applied Sciences

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Table-2. Summary of data used from sources within latitudes 3.5° - 6.5° N and longitudes 102° E - 104° E.

Data source	**Wave data period** (yr)	**Sampling interval** (h)	**Sampling time** (No. of sample / burst) (min)	**Mean H_s** (m)	**Standard deviation of H_s** (m)	**Mean T_m** (s)	**Standard deviation of T_m** (s)
MMD	1998-2009	1	20	0.88	0.58	3.27	1.84
UMT	2008-2009	1 and 2	20 (1024)	0.61	0.45	3.85	1.88

Table-3. Percentage of total time in an average year corresponding to sea states with different H_s and T_p.

	Peak time, T_p (s)							
H_s (m)	**< = 2**	**2 - 4**	**4 - 6**	**6 - 8**	**8 - 10**	**10 - 12**	**12 - 14**	**> 14**
< = 0.2	1.21	4.02	5.00	1.16	0.18	0.05	0.00	0.00
0.2 - 0.4	0.71	12.99	16.53	1.80	2.26	0.32	0.27	0.02
0.4 - 0. 6	0.00	2.15	8.58	3.77	0.64	0.14	0.00	0.00
0.6 - 0. 8	0.00	0.25	2.56	7.19	0.39	0.16	0.00	0.00
0.8 - 1.0	0.00	0.11	0.64	6.30	1.53	0.07	0.00	0.00
1.0 - 1.2	0.00	0.00	0.21	3.24	1.60	0.25	0.00	0.00
1.2 - 1.4	0.00	0.00	0.11	2.24	2.58	1.16	0.00	0.00
1.4 - 1.6	0.00	0.00	0.16	1.05	1.44	0.82	0.00	0.00
1.6 - 1.8	0.00	0.00	0.00	0.89	1.26	0.71	0.00	0.00
1.8 - 2.0	0.00	0.00	0.00	0.30	0.41	0.27	0.00	0.00
> 2.0	0.00	0.00	0.00	0.14	0.16	0.00	0.00	0.00

Table-4. Percentage of total time in an average year corresponding to sea states with different H_s and T_{mean}.

	Mean time, T_{mean} (s)							
H_s (m)	**< = 2**	**2 - 4**	**4 - 6**	**6 - 8**	**8 – 10**	**10 - 12**	**12 - 14**	**> 14**
< = 0.2	0.53	11.01	0.09	0.00	0.00	0.00	0.00	0.00
0.2 - 0.4	0.37	32.58	1.96	0.00	0.00	0.00	0.00	0.00
0.4 - 0. 6	0.00	10.57	4.70	0.00	0.00	0.00	0.00	0.00
0.6 - 0. 8	0.00	1.76	8.68	0.11	0.00	0.00	0.00	0.00
0.8 - 1.0	0.00	0.78	7.69	0.18	0.00	0.00	0.00	0.00
1.0 - 1.2	0.00	0.37	4.52	0.41	0.00	0.00	0.00	0.00
1.2 - 1.4	0.00	0.00	5.66	0.43	0.00	0.00	0.00	0.00
1.4 - 1.6	0.00	0.00	3.24	0.23	0.00	0.00	0.00	0.00
1.6 - 1.8	0.00	0.00	2.63	0.23	0.00	0.00	0.00	0.00
1.8 - 2.0	0.00	0.00	0.98	0.00	0.00	0.00	0.00	0.00
> 2.0	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00

VOL. 5, NO. 7, JULY 2010 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Table-5. Percentage of total time occurrence of H_s and T_p during monsoon season.

	Peak time, *Tp* (s)							
Hs (m)	**< = 2**	**2 - 4**	**4 - 6**	**6 - 8**	**8 - 10**	**10 - 12**	**12 - 14**	**> 14**
< = 0.2	0.17	0.50	0.94	0.72	0.17	0.00	0.00	0.00
0.2 - 0.4	0.06	4.36	3.48	2.43	2.48	0.17	0.00	0.00
0.4 -0. 6	0.00	0.55	4.08	7.95	1.05	0.33	0.00	0.00
0.6 -0. 8	0.00	0.06	0.88	11.53	0.94	0.06	0.00	0.00
0.8 - 1.0	0.00	0.06	0.33	11.92	3.70	0.17	0.00	0.00
1.0 - 1.2	0.00	0.00	0.39	4.36	3.86	0.61	0.00	0.00
1.2 - 1.4	0.00	0.00	0.28	4.53	6.24	2.65	0.00	0.00
1.4 - 1.6	0.00	0.00	0.33	2.43	3.48	1.99	0.00	0.00
1.6 - 1.8	0.00	0.00	0.00	2.04	2.98	1.71	0.00	0.00
1.8 - 2.0	0.00	0.00	0.00	0.72	0.99	0.66	0.00	0.00
> 2.0	0.00	0.00	0.00	0.33	0.39	0.00	0.00	0.00

Table-6. Percentage of total time in an average year of sea states in different ranges of θ_m and H_s.

Hs (m)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**Total** (%)
< = 0.2	2.17	2.51	1.21	1.26	1.07	0.94	1.05	1.42	11.62
0.2 - 0.4	6.71	5.59	4.16	1.85	4.27	5.32	4.47	2.53	34.91
0.4 -0. 6	5.84	1.83	1.58	0.25	1.21	1.60	1.62	1.35	15.27
0.6 -0. 8	6.53	0.68	0.32	0.05	1.39	0.71	0.25	0.62	10.55
0.8 - 1.0	6.99	0.75	0.09	0.00	0.14	0.14	0.21	0.34	8.65
1.0 - 1.2	3.65	0.94	0.00	0.00	0.05	0.09	0.11	0.46	5.30
1.2 - 1.4	3.79	1.92	0.14	0.00	0.00	0.00	0.02	0.23	6.10
1.4 - 1.6	2.17	1.14	0.00	0.00	0.00	0.00	0.00	0.16	3.47
1.6 - 1.8	1.85	0.98	0.00	0.00	0.00	0.00	0.00	0.02	2.85
1.8 - 2.0	0.71	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.98
> 2.0	0.16	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.30
Total (%)	40.57	16.76	7.49	3.40	8.13	8.79	7.74	7.12	100.00

VOL. 5, NO. 7, JULY 2010 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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Table-7. Annual wave energy (kWh/m year) and percentage of the total annual wave energy within brackets corresponding to sea states in different ranges of H_s and T_p..

	Peak time, T_p (s)							
H_s (m)	**< = 2**	**2 - 4**	**4 - 6**	**6 - 8**	**8 - 10**	**10 - 12**	**12 - 14**	**> 14**
< = 0.2	2.54 (0.01)	16.47 (0.09)	26.18 (0.15)	9.46 (0.05)	2.36 (0.01)	0.53 (0.00)	0.00 (0.00)	0.00 (0.00)
0.2 - 0.4	3.10 (0.02)	128.53 (0.73)	313.21 (1.77)	49.27 (0.28)	84.53 (0.48)	10.35 (0.06)	9.24 (0.05)	1.73 (0.00)
0.4 - 0. 6	0.00 (0.00)	69.48 (0.39)	382.07 (2.16)	284.64 (1.61)	52.41 (0.30)	10.90 (0.06)	0.00 (0.00)	0.00 (0.00)
0.6 - 0. 8	0.00 (0.00)	15.44 (0.09)	266.63 (1.51)	1006.70 (5.69)	66.16 (0.37)	30.85 (0.17)	0.00 (0.00)	0.00 (0.00)
0.8 - 1.0	0.00 (0.00)	11.95 (0.07)	106.86 (0.60)	1417.60 (8.01)	407.87 (2.31)	25.41 (0.14)	0.00 (0.00)	0.00 (0.00)
1.0 - 1.2	0.00 (0.00)	0.00 (0.00)	53.31 (0.30)	1089.70 (6.16)	680.99 (3.85)	151.49 (0.86)	0.00 (0.00)	0.00 (0.00)
1.2 - 1.4	0.00 (0.00)	0.00 (0.00)	37.10 (0.21)	1072.90 (6.07)	1598.60 (9.04)	907.67 (5.13)	0.00 (0.00)	0.00 (0.00)
1.4 - 1.6	0.00 (0.00)	0.00 (0.00)	86.57 (0.49)	682.42 (3.86)	1132.60 (6.40)	792.52 (4.48)	0.00 (0.00)	0.00 (0.00)
1.6 - 1.8	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	686.40 (3.88)	1287.80 (7.28)	896.63 (5.07)	0.00 (0.00)	0.00 (0.00)
1.8 - 2.0	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	341.84 (1.93)	530.71 (3.00)	409.36 (2.31)	0.00 (0.00)	0.00 (0.00)
> 2.0	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	169.44 (0.96)	266.76 (1.51)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

Table-8. Percentage of total time in an average year corresponding to sea states with different H_s and P.

	Wave power (kW/m)							
H_s (m)	**< = 2.5**	**2.5 - 5**	**5 - 7.5**	**7.5 - 10**	**10 -12. 5**	**12.5 - 15**	**15 - 17.5**	**> 17.5**
< = 0.2	11.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2 - 0.4	34.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4 -0. 6	15.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6 - 0. 8	10.53	0.02	0.00	0.00	0.00	0.00	0.00	0.00
0.8 - 1.0	3.72	4.93	0.00	0.00	0.00	0.00	0.00	0.00
1.0 - 1.2	0.05	4.25	1.00	0.00	0.00	0.00	0.00	0.00
1.2 - 1.4	0.00	0.68	3.33	2.08	0.00	0.00	0.00	0.00
1.4 - 1.6	0.00	0.00	0.66	2.01	0.80	0.00	0.00	0.00
1.6 - 1.8	0.00	0.00	0.00	1.03	0.84	0.75	0.23	0.00
1.8 - 2.0	0.00	0.00	0.00	0.00	0.14	0.30	0.41	0.14
> 2.0	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.16

VOL. 5, NO. 7, JULY 2010 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-9. Percentage of total time in an average year corresponding to sea states with different T_p and P.

	Wave power (kW/m)							
T_p (s)	**< = 2.5**	**2.5 - 5**	**5 - 7.5**	**7.5 - 10**	**10 -12. 5**	**12.5 - 15**	**15 - 17.5**	**> 17.5**
< = 2	1.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2 - 4	19.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 - 6	33.36	0.27	0.16	0.00	0.00	0.00	0.00	0.00
6 - 8	16.76	7.21	2.10	1.58	0.14	0.30	0.00	0.00
8 - 10	3.61	2.31	2.49	2.24	0.96	0.41	0.27	0.16
10 - 12	0.64	0.09	0.25	1.30	0.68	0.48	0.37	0.14
12 - 14	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
> = 14	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table-10. Percentage of total time during monsoon corresponding to sea states with different H_s and P.

	Power (kW/m)							
H_s (m)	**< = 2.5**	**2.5 - 5**	**5 - 7.5**	**7.5 - 10**	**10 -12. 5**	**12.5 - 15**	**15 - 17.5**	**> 17.5**
< = 0.2	2.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2 - 0.4	12.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4 -0. 6	13.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6 - 0. 8	13.41	0.06	0.00	0.00	0.00	0.00	0.00	0.00
0.8 - 1.0	6.29	9.88	0.00	0.00	0.00	0.00	0.00	0.00
1.0 - 1.2	0.00	6.79	2.43	0.00	0.00	0.00	0.00	0.00
1.2 - 1.4	0.00	1.21	7.62	4.86	0.00	0.00	0.00	0.00
1.4 - 1.6	0.00	0.00	1.49	4.80	1.93	0.00	0.00	0.00
1.6 - 1.8	0.00	0.00	0.00	2.37	1.99	1.82	0.55	0.00
1.8 - 2.0	0.00	0.00	0.00	0.00	0.33	0.72	0.99	0.33
> 2.0	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.39