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Ocean Wave Properties of Terengganu for Renewable Energy Potential

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Abstract: Wave energy has a number of significant advantages with respect to other renewable energy sources. The wave resource characterization is a crucial point towards the exploitation of wave energy. Wave power along the Terengganu coast was analyzed at a time scale of months to examine the seasonal dependencies. These investigations show that the Terengganu coast could provide a source of low wave power. The wave climate in the Terengganu coast is among the harsh in Malaysia. The maximum wave height varies between 1-13 m and 3.13 m. The month of December has the highest probability of occurrence of significant wave heights greater than 2 m (2.15%), the possibility of this occurrence begins in November and lasts through January. Similarly, the month of December has the highest probability of occurrence of maximum wave heights greater than 2 m is 44.09% followed by January (40.86%) and November (32.78%). An identical evolution is seen for the wave heights in the classes 1-2 m, the highest frequency of occurrence is in December and represents 68.01% of the total of the month. The wave mean period varies between 2.76 and 5.28 sec and monthly averaged wave peak period varies between 3.94 and 8.28 sec. The main directions in terms of wave energy is North. Further, its high wave energy potential is available during northeast monsoon season. It may be concluded that the Terengganu coast of Malaysia can consider northeast monsoon period for wave energy exploitation.

Key words: Significant wave height, terengganu, wave direction, wave energy density, wave period, wave power density

INTRODUCTION

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 renewable 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. 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 (Falnes and Lovseth, 1991; Duckers, 2004; Clement *et al*., 2002). Wave energy presents a number of advantages with respect to other renewable energy sources such as high availability factor compare with other resources e.g. wind, solar, resource predictability, high power density, relatively high utilization factor, low environmental and visual impact (Henfridsson *et al*., 1997; Wan Nik *et al*., 2009). 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. 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

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Malaysia, or elsewhere in the world. However, wave energy conversion still remains a part of novel technologies to be explored for most countries (Salter, 1974). Countries with wave conditions favorable for energy conversion have been pursuing ways to further develop this novel technology.

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 (Winter, 1980; Crisp and Scott, 1981), Denmark (Kofoed *et al*., 2006), Belgium (Beels *et al*., 2007), Portugal (Pontes *et al*., 2005), Baltic Sea (Bernhoff *et al*., 2006), USA (Bretschneider and Ertekin, 1989; Walker *et al*., 2005; Hagerman *et al*., 1989; Kim, 1997; Beyene and Wilson, 2007; Zafer *et al*., 2009), India (Sivaramakrishnan, 1992; Baba, 1987), Argentina (Lanfredi *et al*., 1992), Brazil (Beserra *et al*., 2007), New Zealand, Ireland, Japan, Chile, Korea, Norway and Sweden (Boud, 2003), Australia (Harries *et al*., 2006), China (Dahai *et al*., 2009), Spain (Iglesias *et al*., 2009; Iglesias and Carballo, 2009), Canada (David and James, 2009) and Swedish (Rafael *et al*., 2009) can be found in the related literature. The highest energy ocean waves are concentrated off the western coasts in the 40-60° latitude range north and south. The annual average power in the wave fronts varies in these areas between 30 and 70 kW m^{-1}, with peaks up to 100 kW m^{-1} in southwest of Ireland, in the Southern Ocean (The National Commission on Energy Policy, 2004).

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 Wave Energy Converters (WECs) 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. 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 Terengganu coast of Malaysia the wave data collected by the Department of Maritime Technology, University Malaysia Terengganu and Malaysian Meteorology Department were used.

MATERIALS AND METHODS

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 and 104.0° E. The investigation was based on one and two-hourly data collected at wave measurement stations covering the period from 1998-2009. In order to give a better perspective on the representative wave conditions in the coastal area of Terengganu, 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 one and two hours sampling intervals. The acoustic wave and current instruments belong to UMT was deployed at 20 m water depth, 5 km from shore covering the period from June 2008-August 2009.

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 wave peak period, T_p. 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 and seasons.

Wave energy modeling: 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 one third of waves or is defined as four times the Root-mean-square (RMS) elevation of the sea surface (H_{rms}). 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 (Boyle, 2004). 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. 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.

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 (Cornett, 2006). This study also used the above equation.

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:

$$J_{sin} = KT_eH^2_w \tag{1}$$

where, k = 976W/sm^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/sm^3 as stated by Boyle (2004). The energy flux, J, transported by realistic non-sinusoidal waves is:

$$J = KT_eH^2_s \tag{2}$$

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.

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:

$$H_{averaged}, T_{averaged}(k) = \frac{1}{M}\sum_{i=1}^{M} H_i, T_i(i,k) \tag{3}$$

$$P_{averaged}(k) = \frac{1}{M}\sum_{i=1}^{M} P_i(i,k) \tag{4}$$

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 DISCUSSION

The Terengganu coast of 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

Table 1: Percentage of total time in an average year corresponding to sea states with different H_s and T_p

H_s (m)	Peak time, T_p (s) <= 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 2: 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

for these areas. To better visualize the monthly variation of wave energy is plotted as a bar chart in Fig. 1.

The results from the measurements are presented below, including 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 1. 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.

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 in Table 2, 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 2.

For the characterization and computation of wave energy, the wave spectra were assumed to be the

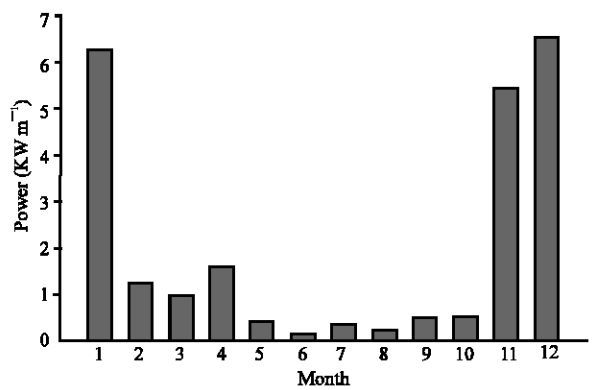

Fig. 1: Monthly average wave power (kW m^{-1})

same during the sampling 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 3 shows the results of the (H_s, T_p) analysis at same location, with wave energy data expressed in kWh m^{-1} width of wave front per year.

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

Table 3: Annual wave energy (kWh m^{-1} year) and % within brackets, corresponding to sea states

	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	16.47	26.18	9.46	2.36	0.53	0.00	0.00
0.2-0.4	3.10	128.53	313.21	49.27	84.53	10.35	9.24	1.73
0.4-0. 6	0.00	69.48	382.07	284.64	52.41	10.90	0.00	0.00
0.6-0. 8	0.00	15.44	266.63	1006.70	66.16	30.85	0.00	0.00
0.8-1.0	0.00	11.95	106.86	1417.60	407.87	25.41	0.00	0.00
1.0-1.2	0.00	0.00	53.31	1089.70	680.99	151.49	0.00	0.00
1.2-1.4	0.00	0.00	37.10	1072.90	1598.60	907.67	0.00	0.00
1.4-1.6	0.00	0.00	86.57	682.42	1132.60	792.52	0.00	0.00
1.6-1.8	0.00	0.00	0.00	686.40	1287.80	896.63	0.00	0.00
1.8-2.0	0.00	0.00	0.00	341.84	530.71	409.36	0.00	0.00
>2.0	0.00	0.00	0.00	169.44	266.76	0.00	0.00	0.00

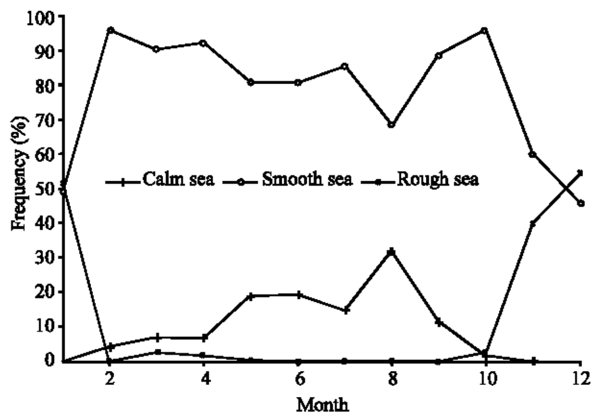

Fig. 2: Annual average evolution (%) of periods of calm, smooth and rough seas

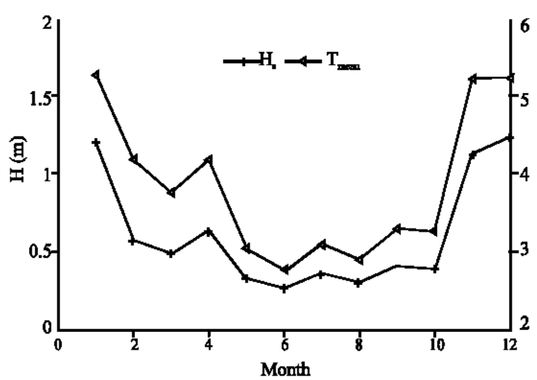

Fig. 3: Monthly average values of the wave parameters (H_s and T_{mean})

3-month period from November to January. More annual wave energy is provided by mid-height waves, with significant wave heights between 0.2 and 1.2 m. With regard to the wave period, waves with peak periods between 2 and 8 sec accounted more total wave energy. The studies reveal that the annual average wave energy density in the study area was 17700 kWh m^{-1} and the average wave power density at 4.04 kW m^{-1}. For energy computation one cannot rely on the numerical average of H_s calculated as 0.61 m as the wave power calculation is based on H_s square. Therefore, a better approach is by using available wave power. Through back calculation on available wave power the annual averaged for H_s and T_p are 1.22 and 5.87 sec, respectively. It is observed that the monthly averaged wave power density varies between 0.15 kW m^{-1} and 6.49 kW m^{-1}. From the results of analyses that the wave power over stirring month in a year are not much different in the Terengganu coast the annual average evolution of periods of calm sea, significant wave heights smaller than 0.2 m (according to Douglas sea scale) as well as of the alternating occurrence of smooth seas and rough seas are presented in Fig. 2. From this results it is observed that the duration of the periods of calm is maximum in August (about 30.0% of the total time) and minimum in November, December and January (0%). Smooth seas occur more than 50.0% of the time in whole year and more than 90.0% of the time in February, March, April and October. Rough seas occur more than 40.0% in November, December and January and other months less than 5.0%. The ratio between smooth seas and rough seas being about 1.0 in January, 1.5 in November and 0.9 in December.

The highest average values of the wave parameters are encountered in November, December and January (more than 1.2 m significant wave height and more than 4 sec mean period as illustrated in Fig. 3).

The results from the measurements are presented in Fig. 4 and 5 and they include the classes of significant wave height (Fig. 4), mean periods (Fig. 5), corresponding to the whole year.

From the analysis of the results the following features of the wave climate in the study area can be identified. Much of the wave energy occurs during the northeast monsoon period. The northeast monsoon is considered the five-month period extending from November through

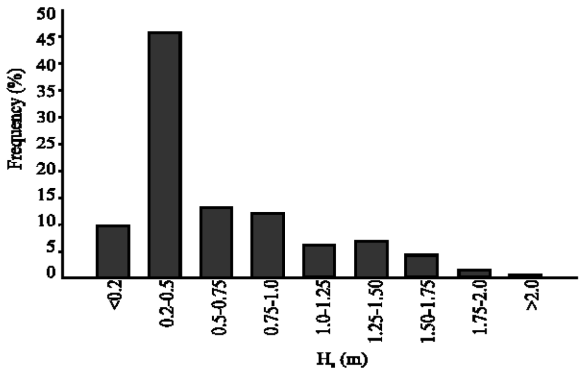

Fig. 4: Classes of significant wave height for whole year

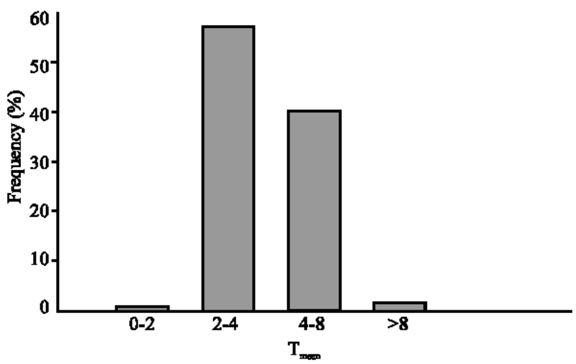

Fig. 5: Classes of wave mean period for whole year

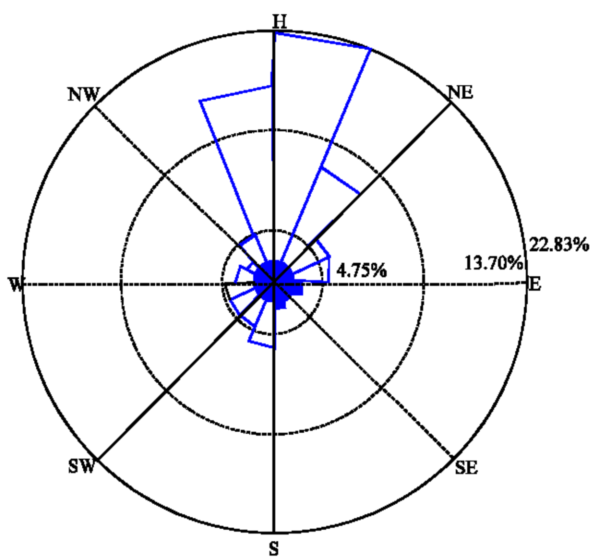

Fig. 6: Percentage of total wave energy vs mean wave direction for whole year

March. The month of December has the highest probability of occurrence of significant wave heights

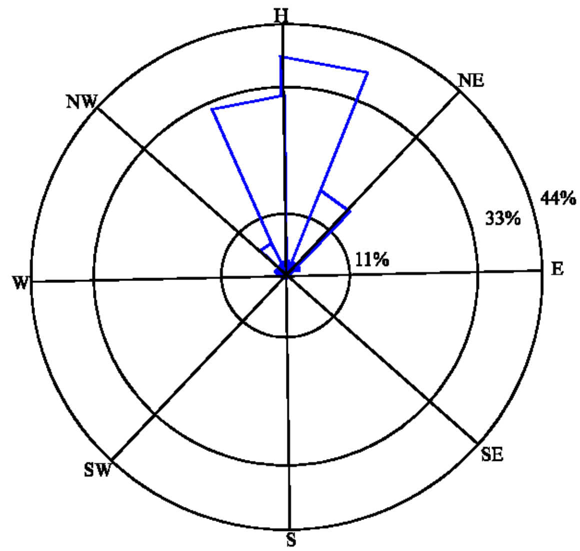

Fig. 7: Percentage of total wave energy vs mean wave direction for northeast monsoon season

begins in November and lasts through January. Similarly, the month of December has the highest probability of occurrence of maximum wave heights greater than 2 m is 44.09% followed by January (40.86%) and November (32.78%). An identical evolution is seen for the wave heights in the classes 1-2 m, the highest frequency of occurrence is in December and represents 68.01% of the total of the month. The frequency of occurrence of wave heights greater than 1 m is greatest in December (70.25%), whereas no such waves occur in June to August. Waves with heights smaller than 1 m occur more than 29% throughout the year, with a minimum in December and a maximum (100%) in June to August. In the case of maximum wave height, heights greater than 1 m is greatest in November (57.22%), whereas less than 1% waves occur in June. Maximum waves heights; smaller than 1 m occur less than 10% in November, December and January.

Regarding wave periods, values greater than 6 sec were encountered in November to March with a minimum in March (1.34%) and a maximum in January (6.99%). The periods greater than 6 sec are characteristic of northeast monsoon only. The periods less than 2 sec were encountered in May to September with a minimum in May (0.81%) and a maximum in July (3.76%). The wave periods 2-4 sec occurred more than 40.56% in February to October with a minimum in April (40.56%) and a maximum in June (97.78%). The other class of wave periods (2-4 sec) occurred more than 59.44% in November to April other than March with a minimum in April (59.44%) and a maximum in November (92.50%).

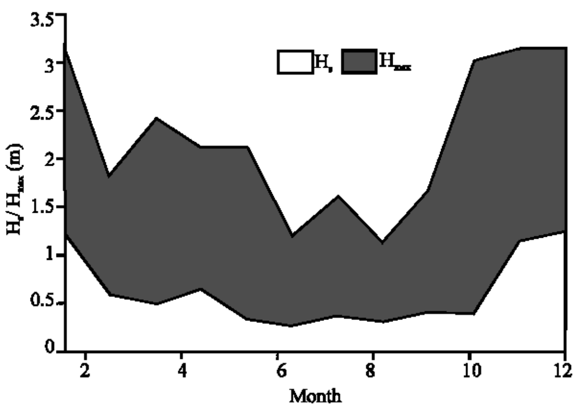

Fig. 8: Variation of monthly averaged H_s and H_{max}

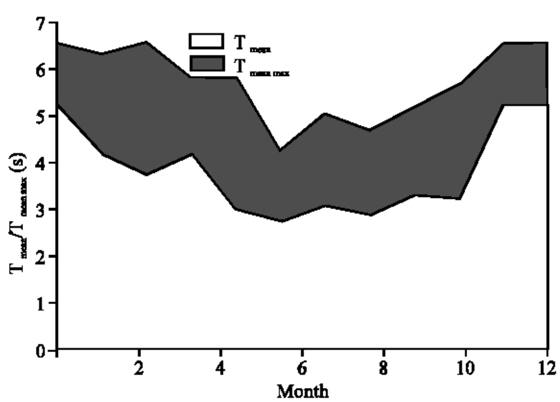

Fig. 9: Variation of monthly averaged T_{mean} and T_p

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 (Fig. 6). 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 (Fig. 7), which may be used as a reference for this area.

Fig.8 shows monthly averaged H_s and H_{max} variation. It is observed that maximum wave heights varies between 1.13 and 3.13 m and monthly mean significant wave height varies between 0.27 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 Terengganu coast of 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.

Fig. 9 shows monthly averaged T_{mean} and T_p variation. It is observed that the wave mean period varies between 2.76 and 5.28 sec and monthly averaged wave peak period varies between 3.94 and 8.28 sec. One can see that the wave periods and stirring month in a year are not remarkably different in the Terengganu coast of Malaysia. Also, it can be observed that, in general, monthly mean wave periods value is similar in the whole year.

CONCLUSION

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 green 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 Terengganu coast of Malaysia was analyzed at a time scale of months to examine the seasonal dependencies. The area of interest is the Terengganu coast of Malaysia. The study was based on two-hourly data collected from wave measurement stations covering the period from January 1998 to August 2009. These investigations show that the Terengganu coast of Malaysia could provide a source of low wave power. The wave climate in the Terengganu coast is among the harsh in Malaysia. The total wave energy density was found to be 17700 kWh m^{-1} in an average year, whereas the average wave power density varied between 0.15-6.49 kW m^{-1}.

Moreover, the wave climate of the area was studied in order to characterize the sea states behind the wave energy availability. From the results it is observed that the duration of the periods of calm is maximum in August and minimum in November, December and January. Smooth seas occur more than 50.0% of the time in whole year and more than 90.0% of the time in February, March, April and October. Rough seas occur more than 40.0% in November, December and January and other months less than 5.0%. The ratio between smooth seas and rough seas being about 1.0 in January, 1.5 in November and 0.9 in December. The main directions in terms of wave energy for whole year are N, 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 may be used as a reference for this area. It may be concluded that the Terengganu coast of Malaysia can consider northeast monsoon period for wave energy exploitation.

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