INVESTIGATING THE WAVE ENERGY CAPACITY WITHIN THE OMAN COASTAL AND TERRESTRIAL WATERS

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Synopsis

This research paper aims at calculating the energy of waves as renewable and clean energy within the Omani coast up to a depth of fifty meters in the terrestrial Waters from the coast and estimates the amount of available energy. Hence, four positions on the coastline have been studied which are two positions along the northern coast and two positions along the eastern coast. The wave and wind characteristics for each position are extracted daily in five months from the Windfinder website and used in calculations. Comparison of the final results indicates which position and at what depth have more capacities to produce more wave power than the other points.

Keywords— Renewable Energy, Wave Energy, Wave Power, Coast of Oman, Oman Terrestrial

1. Introduction

The research and study on clean and renewable energy sources are essential, critical and seems inevitable due to a significant reduction in carbon-based energy sources associated with an increase in the number of environmental pollutants and its climate impacts.
Hence, the recognition, research and finding new solutions for the use of renewable sources are expanding; in the first step, in order to achieve the desired result, it is necessary to study and calculate the existing capacity for each geographic area in terms of the climate and capacities of the region.
There have been many studies around the world about potential energy in waves.
Wave energy capacity is estimated to range from 1 to 10 terawatts, especially in the deepwater areas worldwide. (Panicker N. N., 1976)
In the field of potential wave calculation, studies have been carried out around the world such as the potential of wave power on the Moroccan Atlantic coast, the wave energy potential of the French Atlantic coast and the potential use of wave energy in South Africa.
These calculations illustrate that the highest and lowest wave power on the Moroccan Atlantic coast is 29.94 kW/m with a depth of 45 m and 7.83 kW/m with a depth of 47 m. (Sierra, J. P, 2016)
For the French Atlantic coast, these values are maximum 42.56 kW/m and minimum 7.19 kW/m in the depth of water 89 m and 30 m respectively. (White A., 2016)
These values were also obtained for the coasts of South Africa at about 22 kW/m as the maximum wave power and approximately 8 kW/m as the minimum wave power. (Lavidas G., 2016)
In the area close to the area studied in this paper, the research was conducted, on the northern coast of the Gulf of Oman and the region limited (in the coastal areas of the Chabahar port) to one of the southern provinces of Iran and is close to the Arabian Sea. (Saket A., 2012)
The data used in the above research relate to the data well directional Wave rider buoy installed by Iran meteorological organisation near the port of Chabahar. This research shows that the average monthly wave power is between 5.16 kW/m and 0.97 kW/m. The average annual energy is also estimated at 2.8 kW/m. (Saket A., 2012)
Oman has limited resources of the carbon-based fuel such as oil or gas, and this will be aggravated due to the increasing need for energy on the

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country's development path, the development of industry and population growth.
According to the available statistics, the total energy produced in Oman in 2011 was about 65 per cent using crude oil and about 35 per cent of gas. However, according to "Oman Energy Policy, laws and regulations handbook (2015) "no research or studies has been done specifically for estimating the number of energy waves along the coast of Oman or its coastal waters. (Inc. Ibp, 2015)
Considering the above, Oman, having more than 2000 km of maritime border adjacent to the Arabian Sea and the Gulf of Oman, has a potential and permanent source of wave energy that needs special attention.
Since no research has been conducted in the Oman coastal waters so far, the necessity of measuring and estimating the wave power as a basis for further research seems essential.

2. Materials and Methodology

2.1 Study area and Materials

2.1.1 Area of study

Oman has two long coastlines, to the east by the Arabian Sea and the north by the Gulf of Oman. Therefore, two positions on the north coast and two on the east coast have been studied to obtain the desired results and to evaluate the energy levels of waves on both sides of the Omani coast. The first two positions are "Dibbab"(position 1) at longitude 56.2538° E and latitude 25.6365° N, and "Qurayyat" (position 2) at longitude 58.9034° E and latitude 23.2652° N, respectively, located on the west and east of the north coast in the Gulf of Oman. (Figure 1)
The second two positions are "Al Ashkharah" (position 3) at longitude 59.5671° E and latitude v, and "Raysut port" (position 4) at longitude 53.9954° E and latitude 16.9415° N, respectively, in the north and south of the east coast in the Arabian Sea. (Figure 1). The Selected Positions Parameters are indicated in table 1.

2.1.2 materials and data

Characteristics of the wave and wind are collected daily within the period of a Five-month in 2019.

The data used in this study are collected daily from the Windfinder website, which has global coverage and receives the parameters related to the waves from the reference, NOAA (National Oceanic and Atmospheric Administration, U.S.- The Department of Commerce) and weather information from GFS (The Global Forecast System) and WRF (The Weather Research and Forecasting) with a refresh rate of six hours for all information.
In order to find a more precise result, the above information is taken into account eight times a day at three-hour intervals.
For each position, the wave height, period, direction, wind speed and direction are recorded and considered in the calculations.
The values of wave height, period, direction, wind speed and direction are extracted based on the recorded data for all positions. The collected data are used as input parameters in equations and numerical modelling to calculate and analyse waves, including average wave period, average wave height, wavelength, maximum horizontal and vertical wave velocity, hydraulic pressure fluctuation, Energy density and estimate wave power. (Tables7 to 10)
In total, more than 20 parameters have been calculated by using numerical modelling to investigate wave behaviour.

Calculations of the energy density and wave power are performed for a depth of 1 meter and 5 meters (as a coastal strip) and a depth of 10, 20, 30, 35 and 50 meters within territorial waters.
The total data collected from the satellite for this study comprise more than 8000 data that is recorded and calculated daily for all four positions.

2.2 Methodology and Numerical modelling

There are two methods for calculating wave power; these two methods depend on the wave information.
In the first method, if the wave spectrum information, including the frequency, direction and amplitude of the wave is available for a large number of waves, the wave power is obtained from the following formula(1)(Laing, 1998).

$P = \rho g \int_0^{2\pi} \int_0^{\infty} C_g\,(f, h) E(f, \theta) df d\theta$ (1)

Where g is the acceleration of gravity, ρ is represented the seawater density, C_g indicate wave group velocity and E is the wave spectrum, which is dependent on the wave direction(θ) and wave frequency(f). (Komen, G.J, 1994)

Another method of calculating and estimating wave power, according to available data, is used in this research and is as follows. (2) (Sierra, J. P, 2016)

$E = \frac{\rho g^2}{64\pi} T_e H_s{}^2$ (2)

This formula gives a reasonable estimate of wave power, especially in the deepwater range, and depends on the mean wave period (T_e) and significant wave height (H_s).

Where $T_e = \alpha T_p$ (3)

The T_p are the wave pick period and the value of α depends on the dominant wave spectrum of the region, which is considered to be approximately 0.9(the value of α is 0.86 for a Pierson-Moskowitz spectrum) (Sierra, J. P, 2013)?

In the shallow water, especially close to the coast, when the wave hits or approaches the seafloor, all the wave characters change and affect the shape of its propagation.
Therefore, as the water depth decreases, the wave velocity decreases, but the wave period does not change.

To study the propagation waves (for linear and nonlinear forms), the group velocity need to be calculated with is related to the wave speed, water depth and wavelength and defined as follows (formula 2): (Whitham, 1974)

$C_g = \frac{\partial \omega}{\partial k}$ (4)

Calculation of wave group velocity varies with the depth of water and can be obtained from the following formula (3) (Fadaeenejad M., 2014).

$C_g(f, h) = \frac{g}{4\pi f}(1 + \frac{2kh}{\sin h(2kh)}) \tan h(kh)$ (5)

Where $k=2\pi/\lambda$ and λ is the wavelength, h is the depth of water.
in shallow water $C_g(f, h) = \sqrt{gh}$ (6)
and in deep water $C_g(f, h) = \frac{g}{4\pi f}$ (7)
The sea wave frequency in radians is described as formula (8):

$\omega^2 = gk\ \tan(kh)$ (8)

And the ω is equal to $2\pi f$ where the f is the wave frequency
For the condition that the water depth is greater than the wavelength $\tan(kh) = 1$
And for the condition that the water depth is less than the wavelength $\tan(kh) = kh$ (Lamb,1932)

Horizontal water velocity is (Lamb, 1932)

$u = a\omega \frac{\cosh(kz+kd)}{\sinh(kd)} \cos(kx - \omega t)$ (9)

And vertical water velocity is

$w = a\omega \frac{\sinh(kz+kd)}{\sinh(kd)} \sin(kx - \omega t)$ (10)

Where the a is wave amplitude, *k is wave number*

2.3 Analysis and results

Calculation of wave data in **Dibbab** Port (first position) shows that the average wave height in the study period is 0.5 meters, and the wave peak period is 18 seconds.
Table (2) shows the calculated values of this region. The minimum wave power is obtained at a depth of 1 meter and equal to 0.98 kW/m and maximum power at a depth of 50 m and equals to 4.55 kW/m. (Table 3)
In the **Qurayyat** as the second position, the average wave height is 0.43 meters and the wave peak period is 18 s same as the Dibbab port. The maximum wave power is achieved at a depth of 50 meters with a value of 3.39 kW/m, where the minimum wave power is equal to 0.73 kW/m at a depth of 1 meter. (Table 4)
The **Al Ashkharah** as third position, the average wave height and the wave peak period are 1.07 m and 13.76 s respectively. The maximum power is 18.8 kW/m at a depth of 50 m, and the minimum power is indicated at a depth of 1 m with the value of the 4.5 kW/m. (Table 5)
In the last position, **Raysut Port,** the wave peak period is 15 s, and the average wave height is

equal to 1.06 m. The minimum wave power happens at a depth of 1 m with a value of 4.4 kW/m, and the maximum wave power is 17.2 kW/m at a depth of 50 m. (Table 6)
The magnitude of changes in energy density from the first position to the last position is equal to 0.3, 0.2, 1.5 and 1.4, respectively.
The value of the energy density estimation in each position, with the change in water depth, is almost constant, and no specific change is shown. (Figure 3)
In comparison, the difference in energy density in the third and fourth positions is about six times greater than in the first and second positions. (Figure 3)
In June and July, the average wave power is in the maximum value at all position where the minimum value of the average wave power is almost recorded in March.
The highest and lowest amount of maximum pressure fluctuation due to the wave is noted in the third position (Al Ashkharah**)** with 1.07 meters and the second position(Qurayyat) with 0.433 meters respectively. (Tables 7 to 10)
The highest group velocity is related to the two positions of Dibbab and Qurayyat with the value of 14.39 m/s while the Raysut Port with the group speed of 11.97 m/s, shows the lowest value. (Tables 7 to 10)
The calculations show that wave power varies from 0.98 kW/m to more than 18.5 kW/m in the four studied positions. (Figure 2)
Although the amount of wave power is directly related to the increase in water depth, the calculations show that the wave power does not increase much from the depth of 30 meters to 50 meters, while the range of these changes is very noticeable on shallow and low water depths of 1 to 10 meters. (Figure 2)
At position one and two, the rate of change in wave power from a depth of 1 meter to 10 meters and even up to 20 meters is increasing, but no steep slope is observed. (Figure 2)
From a depth of 20 to 50 meters, no significant change in the amount of wave power was observed for the first two positions studied. (Figure 2)
The rate of change of wave power for the third and fourth positions differs from the first two positions. In the latter two positions, the slope of the wave power changes dramatically from 1 meter to 20 meters and this incremental trend continues even to a depth of 30 meters. (Figure 2)
From a depth of 30 meters to 50 meters, there is no appreciable change in the amount of wave power in the two latter positions. (Figure 2)
The wave characteristic conditions in the northwest and northeast of the northern coastline in the Gulf of Oman are such that the maximum potential of the wave power at the maximum depth is equivalent to the lowest wave power at the minimum depth calculated at two locations on the eastern coastline in the Arabian Sea. (Figures 5 and 6)
In other words, the potential power generation capacity of the waves in the eastern coastline is more than four times that of the northern coastline. Besides, the wave power potential is shown slightly more in the north of the east coast and the Al Ashkharah area than the southern end of the east coast of the Raysut Port. (Figures 7 and 8)
The result of this low discrepancy means that, as can be expected, the wave power along the eastern coastline is at a minimum depth (1 m) with a power exceeding 4.4 kW/m and at the maximum calculated depth (50 m) with Power between 17 to more than 18 kW/m (Tables 5 and 6).
It should be noted that this is the amount of power produced per meter, and given the more than a thousand kilometres of the east coast, the amount of energy hidden in the waves is determined.
For the last two positions that have higher potential than the first two positions in terms of wave power, the wave height rose diagram based on the wave direction, as well as the wind speed, rose diagram based on the wind direction, is plotted during the study period in this paper. (Figures 4 and 5)
Investigation and analysis of wave direction and altitude, along with wind direction and velocity, are among the crucial considerations in selecting and installing existing energy conversion equipment.
The wave height rose graph for position three, the highest dispersion of waves, indicates to the south and partly in the southeast, and close to the average height of the wave.
However, higher values of wave height, located on the south to the southwest direction. (Figure 4)

Similar to the third position, in the wave height rose graph for the fourth position, the highest number of waves, with near-average wave height, is in the direction between south and southeast. In comparison, fewer waves with a height higher than or above the average are observed in the south direction. (Figure 5)

The wind speed rose diagram for the third position demonstrates the most wind direction along with the maximum wind speed, in the direction between south and west, with a significant amount on the southwest. Also, the wind is indicated in a direction between northeast to the southeast with a low velocity and somewhat close to the mean wind velocity. (Figure 6)

In the wind speed rose diagram for the fourth position, the maximum wind direction is plotted in the south to the southwest direction at the maximum wind speed is illustrated in the direction between south and southwest.

For this position, no significant winds can be observed in other directions. (Figure 7)

2.2. Figures and Tables

Figure 1 shows the location of the four selected areas and figure 2 indicated the wave power compression based on the water depth. Figure 3 shows all locations the energy density compression based on the water depth.

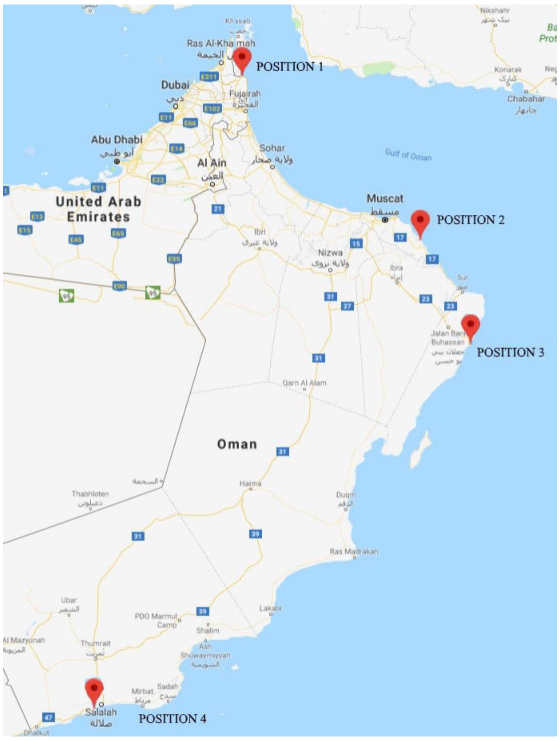

Figure 1: Position of all study areas

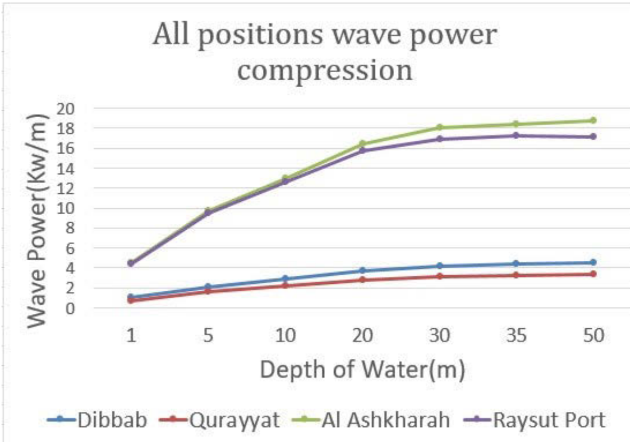

Figure 2: Wave power in different water depth in all positions

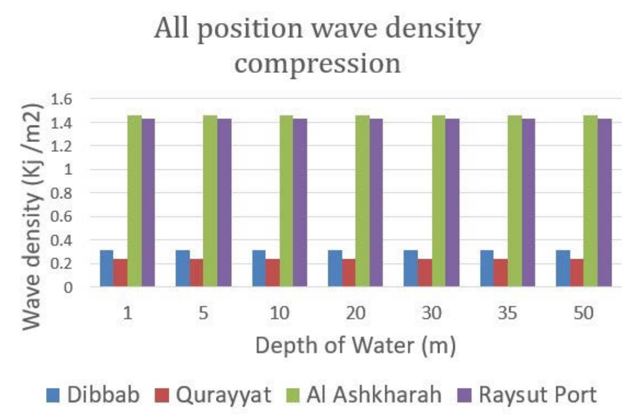

Figure 3: Wave density in different water depth in all positions

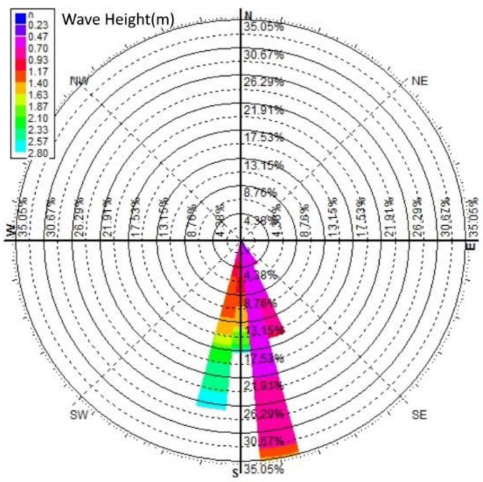

Figure 4: position3-Wave height rose plot based on wave direction

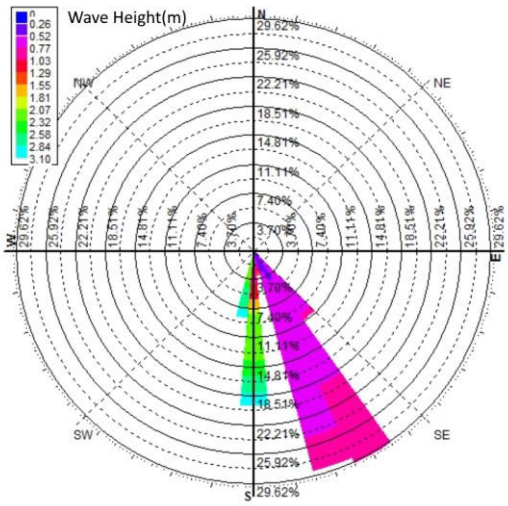

Figure 5: position4-Wave height rose plot based on wave direction

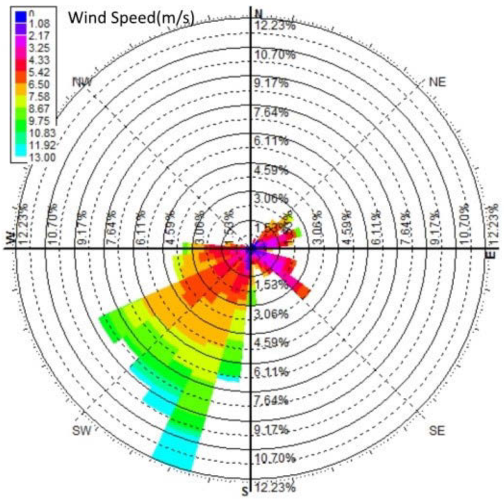

Figure 6: position3-Wind Speed rose plot based on wind direction

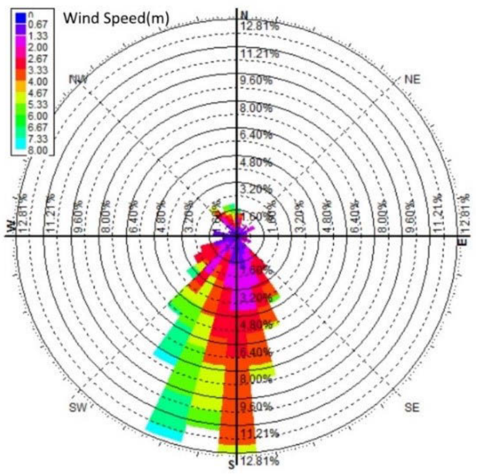

Figure 7: position4-Wind Speed rose plot based on wind direction

The following tables indicate the position parameters and the wave characteristics in all study points.

Table 1: Selected Positions Parameters

Position No.	*City name*	*state*	*Latitude*	*Longitude*	*Station Elevation (m)*	*Time Zone UTC+*
1	Dibbab	Musandam	25.6365° N	56.2538° E	95	4
2	Qurayyat	Muscat	23.2652° N	58.9034° E	10	4
3	Al Ashkharah	Sur	21.8515° N	59.5671° E	0	4
4	Raysut Port	Salalah	16.9415° N	53.9954° E	36	4

Table 2: Position Wave Characteristics

Wave parameters	***Position Name***			
	Dibbab	*Qurayyat*	*Al Ashkharah*	*Raysut Port*
Average wave height(m)	0.5	0.43	1.07	1.06
Max. period(s)	18	18	16	15
Average wave period(s)	8.32	6.98	10.2	10.4

Table 3: Position1 Wave Parameters *(Dibbab)*

Depth of water(m)	50	35	30	20	10	5	1
Energy Density(kJ/m2)	0.316	0.316	0.316	0.316	0.316	0.316	0.316
Wave power(kW/m)	4.55	4.34	4.20	3.74	2.88	2.12	0.98

Table 4: Position2 Wave Parameters (Qurayyat)							
Depth of water(m)	50	35	30	20	10	5	1
Energy Density(Kj/m2)	0.235	0.235	0.235	0.235	0.235	0.23	0.23
Wave power(Kw/m)	3.39	3.23	3.12	2.78	2.14	1.58	0.73

Table 5: Position3 Wave Parameters (Al Ashkharah)							
Depth of water(m)	50	35	30	20	10	5	1
Energy Density(Kj/m2)	1.458	1.45	1.45	1.45	1.45	1.45	1.45
Wave power(Kw/m)	18.8	18.4	18.0	16.5	13.0	9.7	4.5

Table 6: Position4 Wave Parameters (Raysut Port)							
Depth of water(m)	50	35	30	20	10	5	1
Energy Density(Kj/m2)	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Wave power(Kw/m)	17.2	17.2	16.9	15.7	12.6	9.4	4.4

Table 7: Position1 Wave characteristics calculation							
	Water depth(m)						
Parameters	50	35	30	20	10	5	1
Gravity	9.81	9.81	9.81	9.81	9.81	9.81	9.81
Fluid Density	1025	1025	1025	1025	1025	1025	1025
Wave mean period	15.5	15.5	15.5	15.5	15.5	15.5	15.5
Average Wave height	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Wave speed	19.0	16.7	15.7	13.2	9.6	6.9	3.1
Wave length	294.5	258.6	243.2	204.7	149.0	106.8	48.3
Group velocity	14.4	13.7	13.3	11.8	9.1	6.7	3.1
Max. horizontal velocity	0.1	0.1	0.2	0.2	0.3	0.4	0.8
Max. vertical velocity	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Max. pressure fluctuation	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Mass transport velocity	0.0	0.0	0.0	0.0	0.0	0.0	0.2

Table 8: Position2 Wave characteristics calculation							
	Water depth(m)						
Parameters	50	35	30	20	10	5	1
Gravity	9.81	9.81	9.81	9.81	9.81	9.81	9.81
Fluid Density	1025	1025	1025	1025	1025	1025	1025
Wave mean period	15.5	15.5	15.5	15.5	15.5	15.5	15.5
Average Wave height	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Wave speed	19.0	16.7	15.7	13.2	9.6	6.9	3.1
Wave length	294.5	258.6	243.2	204.7	149.0	106.8	48.3
Group velocity	14.4	13.7	13.3	11.8	9.1	6.7	3.1
Max. horizontal velocity	0.1	0.1	0.1	0.2	0.2	0.3	0.7
Max. vertical velocity	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Max. pressure fluctuation	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Mass transport velocity	0.0	0.0	0.0	0.0	0.0	0.0	0.2

Table 9: Position3 Wave characteristics calculation							
	Water depth(m)						
Parameters	50	35	30	20	10	5	1
Gravity	9.81	9.81	9.81	9.81	9.81	9.81	9.81
Fluid Density	1025	1025	1025	1025	1025	1025	1025
Wave mean period	13.8	13.8	13.8	13.8	13.8	13.8	13.8
Average Wave height	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Wave speed	18.2	16.2	15.3	13.0	9.6	6.9	3.1
Wave length	250.7	223.1	210.8	179.1	131.4	94.6	42.9
Group velocity	12.9	12.6	12.4	11.3	8.9	6.6	3.1
Max. horizontal velocity	0.3	0.3	0.3	0.4	0.6	0.8	1.7
Max. vertical velocity	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Max. pressure fluctuation	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Mass transport velocity	0.0	0.0	0.0	0.0	0.0	0.1	1.1

Table 10: Position4 Wave characteristics calculation							
	Water depth(m)						
Parameters	50	35	30	20	10	5	1
Gravity	9.81	9.81	9.81	9.81	9.81	9.81	9.81
Fluid Density	1025	1025	1025	1025	1025	1025	1025
Wave mean period	12.9	12.9	12.9	12.9	12.9	12.9	12.9
Average Wave height	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Wave speed	17.7	15.9	15.1	12.9	9.5	6.9	3.1
Wave length	228.4	205.1	194.4	166.1	122.6	88.5	40.2
Group velocity	12.0	12.0	11.8	10.9	8.8	6.6	3.1
Max. horizontal velocity	0.3	0.3	0.3	0.4	0.6	0.8	1.7
Max. vertical velocity	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Max. pressure fluctuation	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Mass transport velocity	0.0	0.0	0.0	0.0	0.0	0.1	1.1

3. Conclusion

As mentioned, in this study, four areas along the coast of Oman were studied from the perspective of the wave energy capability from the shallow coastal to the depth of fifty meters in the territorial waters.

The selected areas have different geographical and access features, covering almost the entire coastline. Among these regions, the Qurayyat area has the lowest wave energy potential, and the Ashkharah region has the highest wave power capacity.

Also, the highest amount of wave energy is due to the depth of water in the depths of between thirty to fifty meters (in the territorial water range). Therefore, it seems that the use of coastal equipment for energy conversion is not economical and that there is more justification for the use of floating systems and deep-water energy conversion equipment. (Parmeggiani, S.,2013)

Oman, as one of the oldest countries in the field of marine, has a long history in this field. Utilising this historical potential and interest can help to develop and exploit this natural and renewable resource.

Establishing the necessary infrastructure by investing and setting up research centres in the field of oceanography, the formation of courses in marine science at universities and research centres, investing in the installation of comprehensive marine data collection equipment (including coastal and offshore) and the formation of databases can be beneficial.

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