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Preliminary appraisal of wave power prospects in Lebanon

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Abstract:

The present work is the first attempt to methodologically assess the wave power prospects off the coast of Lebanon. Working around 1.5 years of buoy data, measurements for the significant wave height and wave period were inputted to establish a joint frequency table that was related to power matrixes of three selected wave energy converters. The spatial and temporal representability of the analysis was extended through assessing altimeter data of H_s over 20 years and for three points off the coast of Lebanon; southern Lebanon, buoy location off the coast of Beirut, and northern Lebanon. The altimeter data indicated that H_s values as measured through the buoy is within 1 standard deviation of the offshore regional mean, however adopting the regional mean value of H_s would more than double the potential power from waves from 4.6 kW/m to 9.8 kW/m. This puts the wave resources in the lower end of what is 'technically viable' and therefore it can be concluded that, given the current state of technology, wave power cannot contribute to the 12% target of renewable energy in the Lebanese energy mix by 2020. A re-evaluation of the wave power prospects post-2020, based on an actual and more robust data collection system, is recommended.

Highlights

► Wave power potential off the coast of Beirut (Lebanon) is assessed. ► Wave activity is overlaid with power matrixes of 3 wave power converters. ► Altimeter satellite data of H_s is obtained for more representability of data. ► Wave power is not currently attractive, yet a revisit in 2020 is recommended.

Keywords: Wave energy converter ; Lebanon ; Significant wave height ; Wave period ; Mediterranean sea

1. Introduction

The world-wide potential of the wave power resource is estimated to be approximately 2 TW [1]. Nearer to shore, the European Thematic Network on Wave Energy puts the potential at 1.3 TW globally, with a technically exploitable resource of 100-800 TWh/year [2]. Broken down according to power range, the global technical resources are estimated to be 100-500 TWh/year for the power range of 20-30 kW/m and estimated at twice that potential for lower power regions of 10-20 kW/m [3]. However, the Eastern Mediterranean region is not known for its wave power resources like other regions, such as Western Europe and particularly the United Kingdom, where the most common power range for offshore waves are between 30-70 kW/m [1].

As such, wave energy has not been considered for Lebanon nor have any assessments been undertaken to shed light on its prospects. This paper serves as the first attempt to methodologically approach the issue of wave energy by quantifying the wave resources and consequent energy potential off Lebanon's coast. The potential of wave power in Lebanon is evaluated in the context of delivering the 12% renewable energy target by 2020 set by the Lebanese Council of Ministers in 2009 and reaffirmed in the 2009 Copenhagen Climate Change Summit and in the Ministry of Energy and Water's (MEW) Policy Paper [4].

This paper utilizes the only available data on wave parameters from one single buoy installed in 2003-2004 by the National Directorate for Meteorology in Lebanon in order to establish the potential of wave power from three selected offshore wave energy converters. The representability of the data, both in terms of spatial and temporal representability, is established through the use of altimeter data covering three locations off the Lebanese coast and an extended timeframe of 20 years.

2. The Lebanese Electricity Sector

Detailed information on the Lebanese electricity sector can be found in [4 -8]. In summary, the sector is a publically owned monopoly with nominal installed power capacity of approximately 2312 MW, of which 2038 MW are thermal power plants and 274 MW are hydro. However, actual availability of thermal plants has varied from as low as 1500 MW (and sometimes lower) to a maximum of 2000 MW due to several shortcomings such as restoration requirements, plant failures, fuel supply problems, and external hostilities [5]. In the transmission and distribution (T&D) networks, technical losses are on average 15% in Lebanon, while non-technical losses, such as theft, amount to a further 20% of electricity produced [4]. These problems have led to daily blackouts averaging 6 hours for the entire country, which the Lebanese economy mostly countered through diesel back-up self-generation. Taking 2009 as a point in case, the daily electricity demand was consistently greater than supply, as shown in Figure 1. If no additional supply sources are secured, this situation is expected to worsen as electricity demand is projected to increase 7% annually between 2009 and 2015 [9].

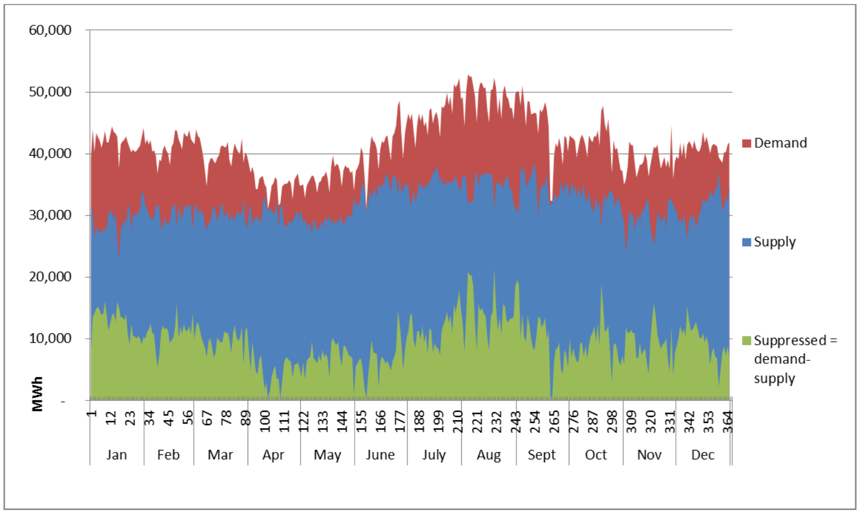


Fig. 1. Daily demand, supply, and suppressed electricity in 2009 [9]

The Lebanese Ministry of Energy and Water published its strategy for the power sector in June 2010, aiming at eliminating blackouts to acceptable international standards and yielding profits to the government of Lebanon (GoL) by 2015 and onwards [4]. The Policy Paper reiterates the GoL's pledge in the Copenhagen Summit to supply 12% of its total energy requirements (excluding the transportation sector) from renewable energy sources by 2020. However, the road map to achieve this target was not clearly defined although the Policy Paper refers to wind power, solar energy, hydro and waste-to-energy as possible options. To this end the UNDP-CEDRO * project has undertaken and is undertaking several resource assessments that have resulted in the publication of the National Wind Atlas [11], the National Bioenergy Assessment [12], and will result in the National Geothermal Assessment Lebanon. These assessments provide a clearer understanding of the availability of renewable resources and the extent to which they could contribute to the Lebanon's energy mix.

3. Wave Energy Resource Characterization for Lebanon

The main properties of waves can be defined in terms of period, or the time (in seconds) taken for successive peaks (or troughs) to pass a given fixed point, height, or the difference between peaks and troughs, wave lengths, or the distance between successive peaks (or troughs) of waves, and direction [13]. Given the impossibility of measuring all the heights and periods independently, an averaging process is used to estimate the total power of waves that includes the calculation of 'significant wave height' (H_s), defined as four times the root mean square of the water elevation variance, which is approximately equal to the average of the highest one-third of the waves, and the energy period (Te) that is defined the period of a simple sinusoidal wave that would carry the same energy as the sea-state [14]. The power in the waves is commonly expressed in kilowatts per unit length (kW/m), quantifying the amount of power per meter of wave-front and is given by Equation 1 [13].

* CEDRO stands for 'Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon' [10].

$$P = \frac{H_s^2 * T_e}{2} \quad \text{(Eq. 1)}$$

The meteorological authority in Lebanon does not possess measurements of T_e, and therefore an alternative and conservative assumption based on a standard Joint North Sea Wave Project (JONSWAP) frequency spectrum that $T_e = 0.9*T_p$ (as done in [14, 15] is adopted, where Tp is the peak period and is defined as the time between wave crests [14].

Data availability is the main barrier to robust resource assessment of wave power potential in the country. The National Directorate for Meteorology had three buoys located in the North, Center (off the coast of Beirut) and South of Lebanon, however only the Beirut buoy provided reliable data for 18 months at one hour intervals. The recordings spanned from December 2002 to May 2004.

Due to maintenance purposes, some months did not have complete coverage. To ensure the reliability of the calculations, we have removed months in specific years where the number of hours of recorded data was less than 85% than the total number of hours in this specific month and specific year. This method of removing deficient data was followed in [14]. Figure 2 summarizes the monthly average significant wave height (H_s) of waves off the coast of Beirut as captured through the installed buoy in 2003.

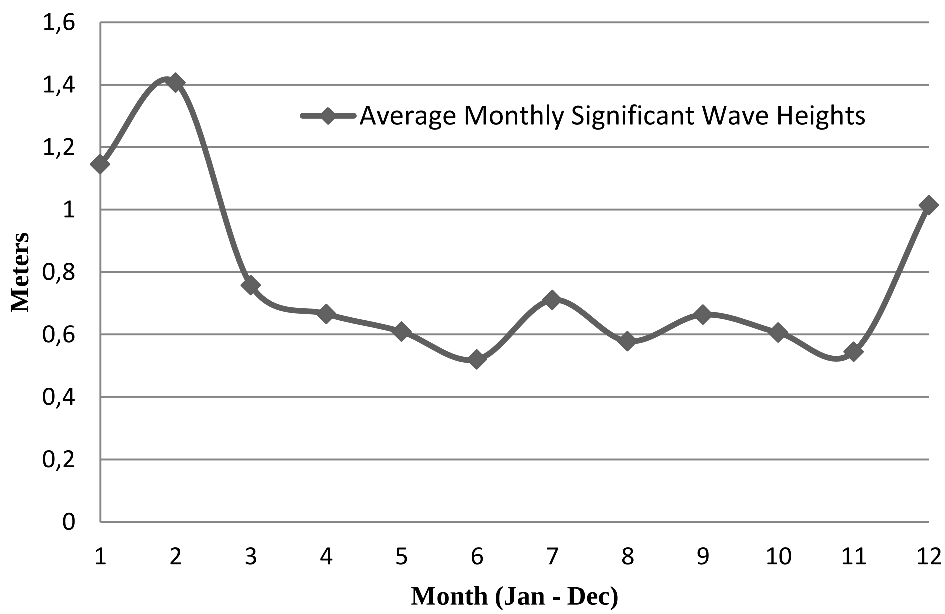


Figure 2. Average Monthly Significant Wave Heights

Figure 2 indicates that the average significant wave heights in Beirut are quite low throughout the year. The maximum average monthly H_s is approximately 1.41 meters (m) realized in the months of January and February, and yet H_s declines consistently from February until June, where *Hs* relatively stabilizes until the month of November. The yearly average value for the significant wave height in 2003 was 78.1 cm. This value falls within 1 standard deviation below the mean altimeter significant wave height statistic as measured through satellite missions from 1992-2005 for the identified East Mediterranean region. The mean for the region over this period is indicated to be 1.14 meters, with standard deviation (m) of 0.74 [16]. The issue of the Beirut buoy data as recorded from December

2002 to May 2004 being representative for the entire Lebanese coast and the inter-annual variability of the wave heights is discussed in Section 5.

The average yearly power off the Beirut coast is considered low and is equal to 4.6 kW/m. This value is comparable to other countries in the Mediterranean such as Greece, which has wave energy potential ranging from 3 to 7 kW/m [17] and Italy, which has values ranging from 1.6 kW/m to 9.05 kW/m [18]. It is lower than power values in other countries such as Turkey, which has wave energy potential between 4 and 17 kW/m [19], Japan, the values of which range from 11 kW/m to 19 kW/m [13], and around the British Isles and the western coasts of Europe where wave power ranging between 30-70 kW/m [1]. A 'good' location will have an annual average range of wave power between 20-70 kW/m [2].

With respect to the direction of the waves, Figure 3 graphs the wave direction off the coast of Beirut, also as measured by the existing buoy between December 2002 and May 2004. Although direction will not be used further in this study (H_s and T_e being independent of wave direction [14]), their characterization is essential for later studies, especially in case of real installation of wave power converting devices in Lebanon in the future.

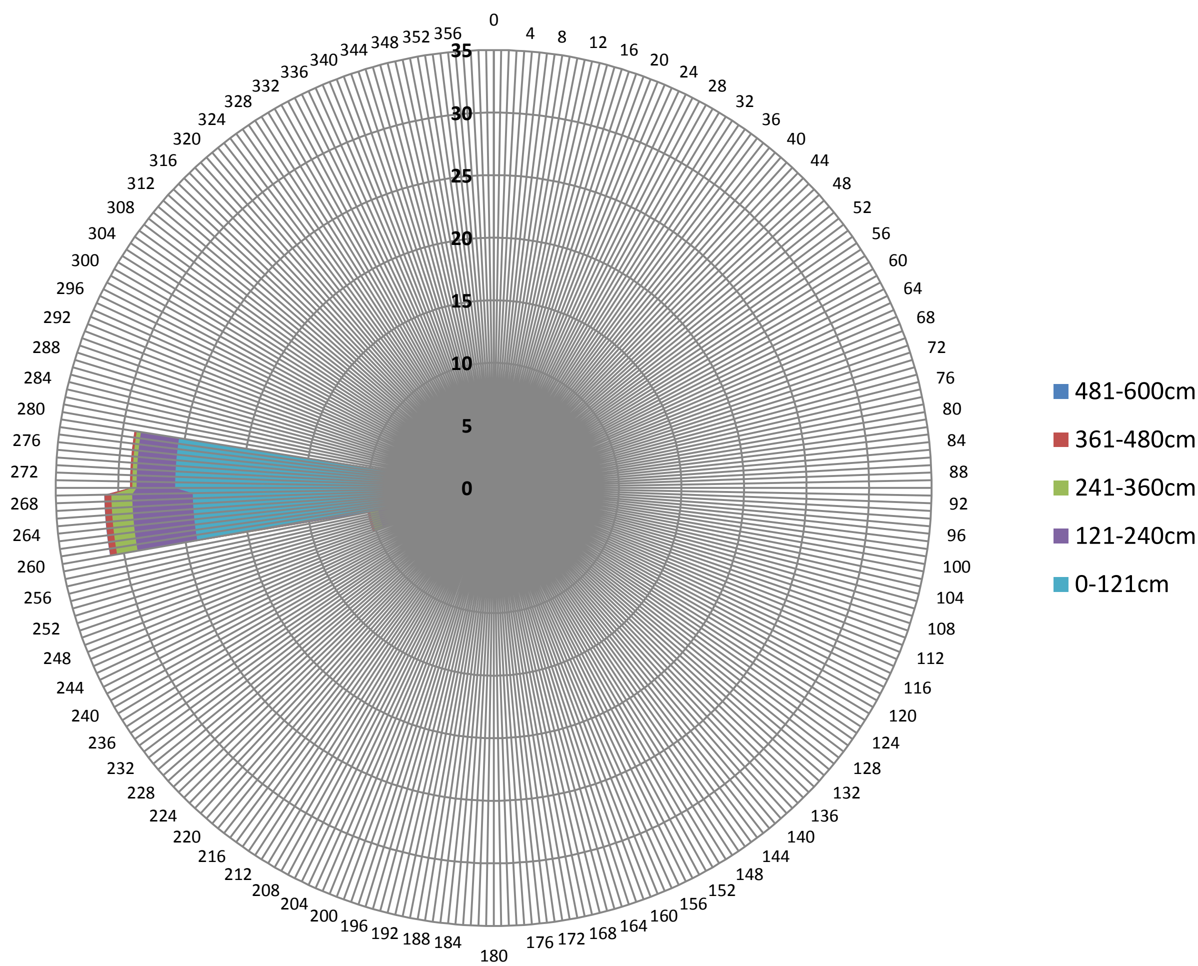


Figure 3. Wave Rose for year 2003 (Significant Wave Height)

The overwhelming majority of the waves off Beirut’s coast originate and travel from west (with minor southerly) to east.

Table 1 shows the joint frequency distribution (or sea-state scatter diagram) of H_s and T_e that indicates the number of hours particular combinations of H_s and T_e (i.e., sea-state) occur during a specific period of time (usually one year). The joint relative frequencies were computed through a Matlab code. Forcing the values into entries in Table 1 has introduced rounding errors due to the fact that measurements of H_s and T_e assume values falling in-between the 0.5 increments. This joint frequency is essential in calculating the power delivered by various wave energy converters. In fact, manufacturers of wave energy converters tabulate a power matrix that has H_s and T_e or T_p as rows. The different entries in the table are the power that the wave energy converter delivers for a particular combination of wave height and period, when operating under nominal conditions. When the number of hours a combination of height and period occurs is multiplied by the power delivered by the same combination in the power matrix, a new table with energy bins is created. Each bin is the energy delivered by the corresponding combination of wave height and period. By summing the entries in the table, the total energy generated by the device during a specific period of time is calculated. In our particular case, we tabulate the joint frequency for the period stretching from December 2002 to May 2004.

		T_e in seconds															
Duration of Occurrence in Hours		**5**	**5.5**	**6**	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**	**9.5**	**10**	**10.5**	**11**	**11.5**	**12**	**12.5**
	0.5	330	801	479	682	134	81	1	43	42	7	0	2	3	2	0	0
	1	328	658	439	1338	608	303	0	106	70	1	0	0	2	1	0	0
	1.5	22	104	93	233	225	307	0	146	90	17	1	14	3	0	0	0
	2	2	25	25	115	124	198	0	121	134	12	0	13	5	0	0	1
H_s in meters	**2.5**	0	2	1	30	54	81	0	96	82	12	0	6	2	0	0	0
	3	0	0	0	13	15	46	0	38	61	18	0	3	4	0	0	0
	3.5	0	0	0	1	2	11	0	19	45	21	1	13	2	3	0	0
	4	0	0	0	0	0	0	0	7	48	24	0	11	8	2	0	0
	4.5	0	0	0	0	0	0	0	0	21	17	1	10	8	3	0	0
	5	0	0	0	0	0	0	0	0	5	10	0	0	7	3	0	1
	5.5	0	0	0	0	0	0	0	0	0	2	0	1	2	2	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0

Table 1. Wave activity off Beirut’s coast

4. Wave energy converters

Wave energy converters (WECs) convert wave energy into electricity through a power take-off system that is usually a turbine driven by pressurized oil, air, or water [14]. Wave energy converters can be divided into different types of classifications. The European Marine Energy Center, for example, classifies wave energy converters into six classes; attenuators, point absorbers, oscillating water columns, oscillating wave surge converters, overtopping and terminator devices, and submerged pressure differential devices [20]. A detailed description of various WECs can be found in [1, 2, 13, 14, 21, 22]. In this paper, the main focus shall be on one sample from common WECs; attenuators, overtopping and terminator devices, and point absorbers – as done in [14].

Attenuators are devices whose principal axis is directed perpendicular to the wave-front [13]. The most prominent attenuator device is the Pelamis wave energy converter. The Pelamis is made of five tubes, connected by hinged joints. As the Pelamis rides the waves, a relative movement (vertical and horizontal) between the tubes and hinged joints is created. This movement is resisted by hydraulic rams which pump high pressure oil through hydraulic motors that in turn drive electrical generators [23]. On the other hand, the overtopping/terminator devices work by storing the incident waves in a reservoir above the sea level. The released water then operates hydraulic turbines and return to the sea. The Wave Dragon overtopping wave energy converter is a common device being explored. Wave reflectors optimize the volume of water that is overtopped to the reservoir. Water then passes through a number of traditional hydropower turbines [13, 24]. Point absorbers are mostly floating devices that convert energy incident from all directions. They have small dimensions compared to the wavelength of the incident waves [13]. The AquaBuoy is one of the more prominent point absorbers. The technology consists of a buoy connected to a submerged vertical acceleration tube containing a piston. As the buoy rides the waves the vertical movement of the piston compresses two stroke hose pumps that consequently send pressurized sea water into a Pelton turbine that drives an electrical generator. However, the company Finavera that had established Aquabuoy has sold the technology to an undisclosed client in 2010 [25]. No updates on the AquaBuoy system could be found since this sale.

The Pelamis Power Matrix is shown in Table 2. Given Table 1 above, Table 2 has been trimmed in order to correspond with the wave activity off Beirut's coast. In fact, as noticed from Table 1, the height of the waves off Beirut does not rise above 6 meters, and thus it would be purposeless to tabulate the power output of the Pelamis above this limit. Finally, we assume that $T_e = T_{pow}$. T_{pow} is the period of a sinusoidal wave with the same incident power as the sea state [14].

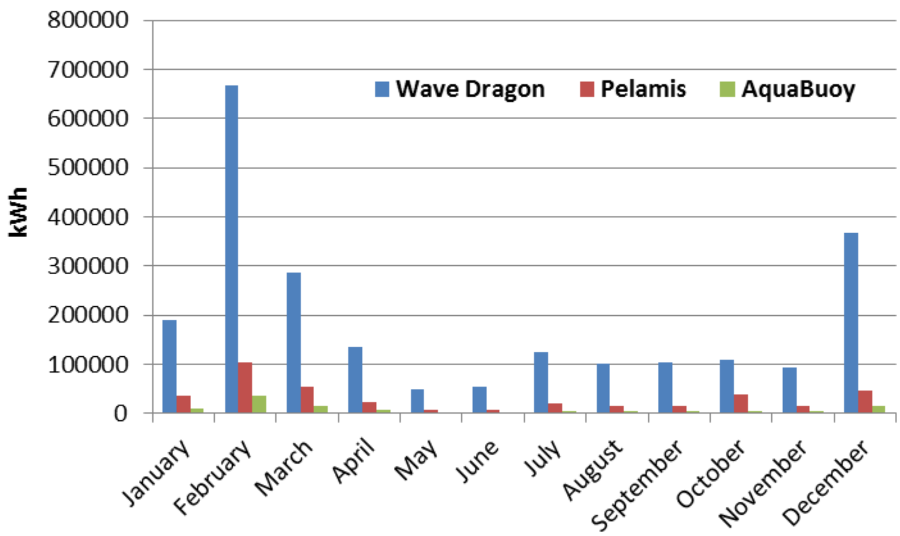
	T_{pow} in seconds																
	Power in kW	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
H_s in meters	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
	1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
	2	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
	2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
	3	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
	3.5	0	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
	4	0	0	462	502	540	546	530	499	475	429	384	366	339	301	367	237	213
	4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
	5	0	0	0	739	726	731	707	687	670	607	557	521	472	417	369	348	328
	5.5	0	0	0	750	750	750	750	750	737	667	658	586	530	496	446	395	355
	6	0	0	0	0	750	750	750	750	750	750	711	633	619	558	512	470	415

Table 2. Pelamis (750 kW) Power Matrix [14]

The same energy calculations are implemented using the Wave Dragon and the AquaBuoy devices in order to compare the performances of these different devices in the Lebanese wave climate. For the present purposes, the 7 MW Wave Dragon and 250 kW AquaBuoy power converters are utilized as they coincide with published information. Both the Wave Dragon and AquaBuoy power matrixes are shown in [14].

4.1. Power Generation

As mentioned before, each energy bin is the energy delivered by the corresponding combination of wave height and period. By summing the entries in the table, the total energy generated by the device during a specific period of time can be obtained. Taking a one-year period, the capacity factor, or the percentage of wave energy output actually produced relative to the energy produced had the wave energy converter been operating at the rated output during the entire year, can be calculated for the three wave energy converters. Figure 4 shows the annual production of the 750 kW Pelamis, the 250 kW AquaBuoy, and the 7 MW wave dragon that correspond to their respective power matrixes.



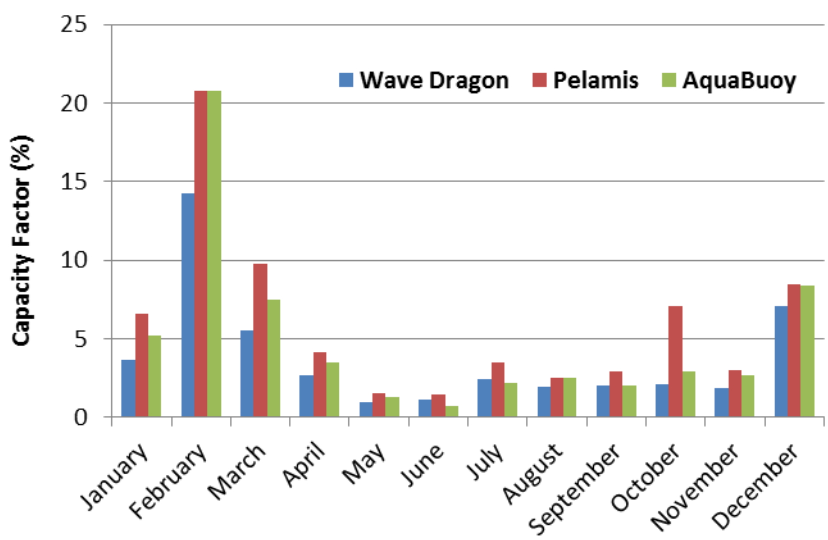


Figure 4. Monthly power output (upper figure) and corresponding monthly capacity factor (lower figure) of 3 WECs (if located off the coast of Beirut)

The capacity factors in 2003 of all three WECs is quite low, equaling 4%, 5%, and 6% for the Wave Dragon, AquaBuoy, and Pelamis, respectively. Most generation occurs in the winter months of December, January, and February, after which production gradually decreases to the lows of May and June, remaining low up to October. As a matter of comparison, annual capacity factors of these WECs in Canada ranged between 21.3 to 32.1% for the Wave Dragon, 9.8% to 18.4% for the AquaBuoy, and 17.1% to 26.2% for the Pelamis [14]. Many wave energy converters presently in operation have capacity factors between 25 and 40 percent [26]. However, the buoy data used, as shall be discussed in Sections 5 and 6, underestimates the power production possibilities found off the coast of Lebanon.

5. Representability of the buoy data

A major limitation in this paper is the lack of representative wave data for the wave climate off the shores of Lebanon. Only 1.5 years of hourly data off the coast of Beirut where obtained from the National Directorate for Meteorology in Lebanon. Due to the difficulties in maintaining buoys, the Directorate could not extend the life-service of the Beirut buoy and could not establish an effective monitoring regime to the North and South of the country by installing and carefully operating its two other buoys.

Wave energy is a consequence of wind energy [2]. Ocean waves are generated by wind passing over stretches of water through three main processes; (1) tangential stress, (2) turbulent air flow which varies shear stresses and pressure fluctuations, and (3) additional wave growth from forces on the up-wind face of the wave [13]. Therefore, it is to be expected that windier areas will have relatively more intense waves. However, the buoy used in this study off the coast of Beirut is found in a relatively calm area, as can be shown in Figure 5 (Point 1), whereas areas with more wind to the North of the country (Point 2), in particular, may offer better wave power potential. This has been one of the main reasons for carrying out this assessment.

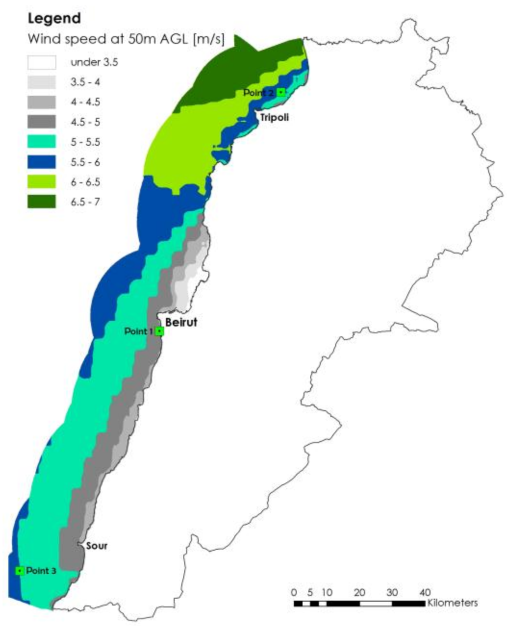


Figure 5. Central Estimate offshore wind map at 50 meter height [11]

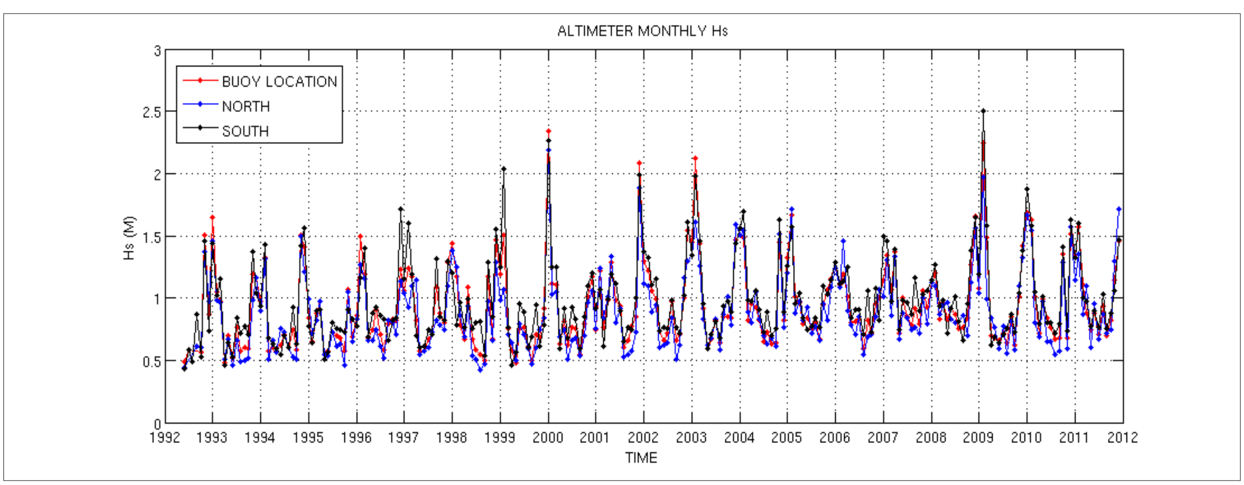
Figure 5 shows the wind speed at 50 meter height. Converting this map to wind speed at 10 meter height brings the approximate average yearly wind speed in off-shore Beirut to between 4.5-5 m/s using an assumed shear value of 0.1 [27]. In Northern Tripoli, the mean wind speed is between 5.5-6 m/s. There is thus almost a 1 m/s speed difference between the sites off the coast of Beirut and Northern Lebanon. Studies have shown that such a difference can have a noticeable effect, yet only for higher wind speeds [28].

In order to improve the spatial and temporal representability of the data, altimeter data can be used to get longer time series of H_s, and to extend the spatial domain of investigation. Currently, satellite altimeter H_s measurements are available routinely over a two-decade time period covering the seven altimeter missions ERS-1, ERS-2, TOPEX-Poseidon, GEOSAT Follow-ON, Jason-1, Jason-2 and ENVISAT. Satellite altimeter data has been shown to give very robust and accurate estimates of H_s [29-32]. The altimeter H_s data used in this study are issued from the IFREMER CERSAT altimeter H_s database [32]. The database is constructed using the Geophysical Data Records (GDR) issued from the specific space agencies for each altimeter, and correcting H_s measurements according to methods developed in previous studies [29].

Altimeter H_s are provided every 5 to 7 kilometers along acquisition tracks with repeating visiting times that are different between missions and satellites. The altimeter measurement footprint is narrow (a few kilometers) and due to the relatively poor time-space sampling, the estimate of H_s monthly mean value in a given geographical location necessitates the consideration of altimeter measurements over a large area centered on the particular location [33].

Furthermore, altimeter data are not valid close to the coast, due to the pollution of the signal from reflection by land. In the present study, the altimeter data were selected within a radius of 100 km, at the buoy location (33°51'N – 35°28'E) and at northern (34°30'N -35°54'E) and southern (33°12'N - 35°E) locations (points are indicated in Figure 5).

Figure 6 shows the altimeter monthly mean values (top) and standard deviations (bottom) of H_s at the buoy, north and south locations, over 20 years. The inter-annual variability is large, particularly during winter. The data at the 3 locations are well-correlated, altimeter H_s being slightly larger in the south (black line) than in the north (blue line) location. Values at the buoy location (red line) are between the north and south ones. This is also observed on the average annual cycle of H_s, as can be seen in Figure 7.



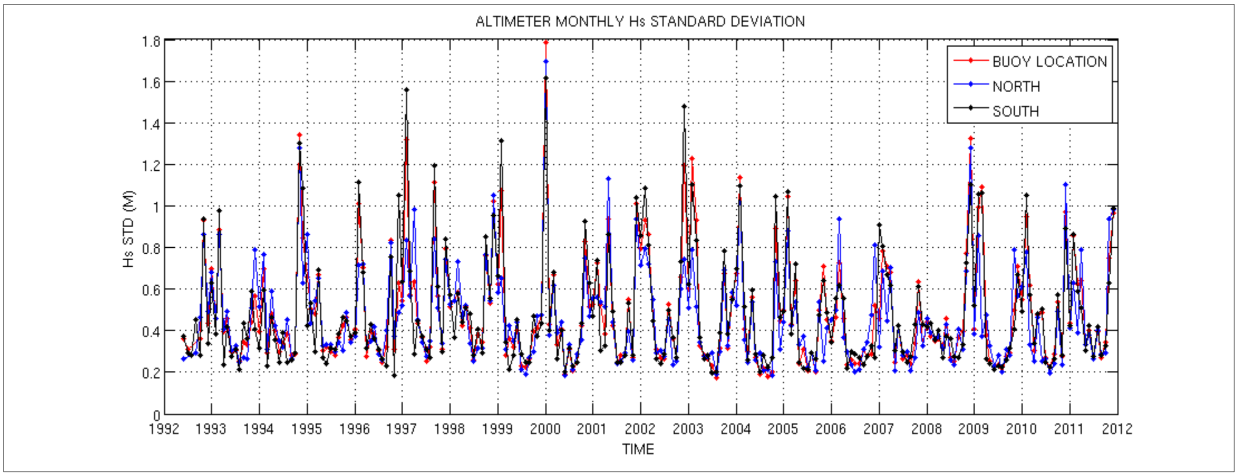


Figure 6. Monthly altimeter mean values (top) and standard deviations of Hs at three locations, over 1992-2012

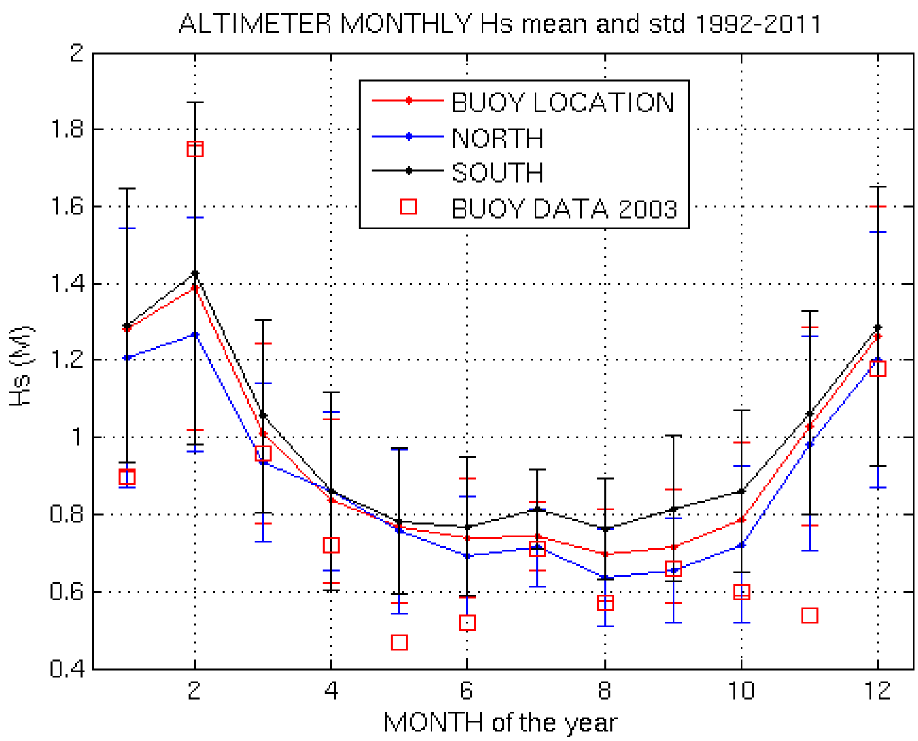


Figure 7. Average annual H_s cycle, estimated from altimeter (and 2003 buoy) data, over 1992-2012 (vertical segments represent ± 1 standard deviation)

Altimeter and buoy data can be compared in Figures 7 and 8. Figure 8 zooms in to focus on the time-scale of 2003 where buoy data was present, and compares this data with the northern and southern selected altimeter *Hs* points. The correlation between buoys and altimeter data is very good. In Figure 8, the buoy measurement is systematically less than the altimeter data. There is no reason for the two measurements to be exactly similar, given that the buoy measurement is relatively closer to the coast whereas the altimeter measurement involves a large offshore area (100 km). Figure 7 shows that the buoy data (red square) for the year 2003 follows the average *Hs* annual cycle deduced from long time series of altimeter data. The differences are within one standard deviation of the altimeter estimates at the buoy location, with the exceptions in May, June and November.

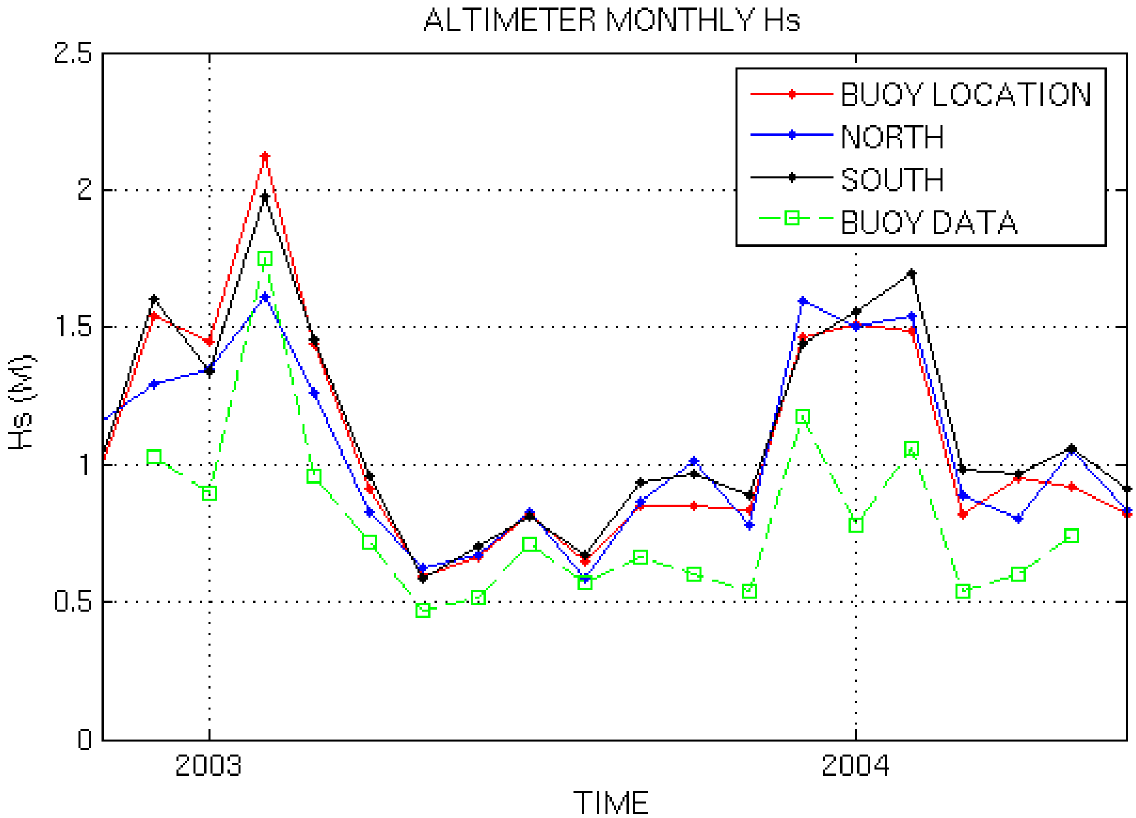


Figure 8. Monthly altimeter and buoy mean values

6. Discussion and future recommendations

The average yearly power off the Lebanese coast, as calculated through the buoy measurements of *Hs* and peak period over the 2002-2004 timeframe, and as made more representative of the Lebanese offshore wave environment through the altimeter data, is too low for economical wave energy generation. Even in oceans where wave potential is significantly better, the net present value of wave energy converters is negative under current market conditions [34,35]. The reason for this is that wave energy is in its' infancy or 'research and development' phase, with only a handful of technologies at the pre-commercial demonstration phase [2]. It has been indicated that there are over 1000 wave energy conversion techniques patented in Japan, North America and Europe [1]. High capital costs coupled with low wave resources currently make wave energy conversion in the offshore (i.e., deeper water locations in the 50-100 m depth range[†]) unfeasible for Lebanon. From the measured (i.e., buoy) data obtained, the power output was indicated to be 4.6 kW/m.

[†] Whittaker & Folley [26] define the near-shore environment as having a water depth of between 10-20 meters (m), while deeper water locations have a depth range of 50-100 m. Waveplam [36] indicates three deployment zones; on-shore where adjacent water depth is less than 15 m, near-shore, where water depth are below 25 m, and off-shore where water depth exceeds 25 m.

However, it was indicated in Section 4 that the power output of the three assessed wave energy converters is an underestimation. This is the case given that the buoy data, as seen in Figures 7 and 8, indicates lower *Hs* values. If the average sea area region *Hs*, indicated to be 1.14 [16], was inputted in Equation 1, and assuming the same average wave period value[‡], then the wave energy potential would be 9.8 kW/m, as indicated in [13]. This power value falls within the lower bounds indicated as 'technical resources' [3]. This value is, however, more representative of the Lebanese offshore case although it is still far from a 'good' location indicated to be between 20-70 kW/m (see Section 3).

A more comprehensive and consistent data collection method for various wave parameters off the coast of Lebanon, based on actual buoy installations and operation, is recommended. Particular focus should be placed on southern Lebanon, where the measured altimeter *Hs* is higher than in other locations along the Lebanese coast. Yet investigations have also to be conducted for the northern-most location where wind speeds are known to be higher, as modeling in the National Wind Atlas [11]. Although altimeter data did not indicate higher *Hs* for the offshore wave climate in Northern Lebanon, validating *Hs* closer to the shoreline in the North, where wind speeds are relatively higher, will enable a more valid conclusion with respect to wave power potential. This is typical of the Mediterranean Sea, where wave conditions, similar to wind conditions, are characterized by high space and time variability due to (mainly) being located at the boundary between three meteorological weather patterns and the existence of large chains of mountains that create barriers to airflows yet inducing funneling affects and katabatic wind [38]. This creates uncertainty in the interpretation of significant wave height data from numerical wave models and satellites.

Moreover, the near-shore environment, defined here as having a depth of between 10 to 20 meters [26] and which has not been assessed in this paper, offers some advantages over locations further offshore, particularly in terms of applying oscillating wave surge converters. As waves travel from the deep ocean to the shoreline, the natural processes of wave shoaling, refraction, diffraction, surf breaking, white capping, and sea bed friction and marine currents all modify the wave properties and the power available to a wave farm [26]. A near-shore site will reduce both the cost and power losses in the cable bringing power back to shore, as well as potentially reducing installation and maintenance costs, where the latter can account up to 40% of the net present value of costs of a WEC [39]. In near-shore sites, the exploitable resource is often indicated to be 10-20% lower than that its' respective offshore site [26], and yet in some stated cases, given the bathymetry and incident wave characteristics, increased power capture is possible due to an increase in surge wave force associated with the larger horizontal water particle motions that occur in shallow water [39]. Modeling the wave transformations at near-shore sites will enable a better understanding of the techno-economic feasibility of Oscillating Water Column systems in the near future.

Finally, the three selected wave energy converters, the 750 kW Pelamis, the 7 MW Wave Dragon and the 250 kW AquaBuoy, are not necessarily optimal for the wave characteristics as measured and modeled off the coast of Lebanon. The primary reason they were selected was due to the existing publication of their power matrixes. The configuration and maximum power rating must be considered to have a more suitable wave energy resource representation [26]. Future research into wave power conversion off the coasts of Lebanon should, therefore, focus on the converters that are optimized to generate energy from the lower end of available 'technical resources'.

[‡] This assumption is inaccurate and yet conservative as there is a positive correlation between significant wave heights and wave period [37]. Wave period is not available in the altimeter database.

In all cases, wave power technology is still in the nascent stage, and given the relatively low wave power potential off the coast of Lebanon, it could be confidently surmised that wave power cannot contribute to the 12% renewable energy target by 2020 as set by Lebanon. However, a re-visiting of wave power potential for Lebanon in 2020 would be a necessity to take into account the development of this technology, which may yet lead to novel concepts more suited to milder wave conditions, and in all cases, will factor in the expected reduction in associated costs.

7. Conclusion

The present work is the first attempt to methodologically assess the wave power prospects off the coast of Lebanon. Although the eastern Mediterranean Sea is not known for its strong wave climate, the actual wave power implications have not been duly assessed. Working around the 1.5 years of buoy data as collected off the coast of Beirut by the National Directorate for Meteorology, measurements for the significant wave height and wave period where inputted to establish a joint frequency table that was then related to the power matrixes of three selected wave energy converters. The capacity factors in 2003 of all three WECs was quite low, equaling 4%, 5%, and 6% for the Wave Dragon, AquaBuoy, and Pelamis, respectively.

The spatial and temporal representability of the analysis was extended through assessing altimeter data of *Hs* over 20 years and for three points off the coast of Lebanon; southern Lebanon, buoy location off the coast of Beirut, and northern Lebanon. The altimeter data indicated that *Hs* values as measured through the buoy is within 1 standard deviation of the mean, however adopting the mean regional value of *Hs* would more than double the potential power from waves from 4.6 kW/m to 9.8 kW/m. This places the wave power prospects in Lebanon within the lower bounds of what is ‘technical viable’. This realization, coupled with the importance of assessing near-shore wave potential, supports better actual wave data collection to take into account the offshore, near-shore, and on-shore wave power prospects in the future. In all cases and given the current state of the technology, wave power cannot contribute to the 12% target of renewable energy in the Lebanese energy mix by 2020, however a reassessment of this beyond this date is recommended and should be based on a robust and actual data collection network.

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