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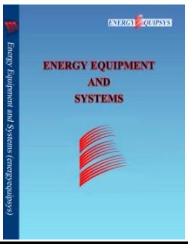

Development of a mathematical model to design an offshore wind and wave hybrid energy system

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ABSTRACT

Fossil Fuels are always considered as environmental pollutants. On the other hand, the political and economic situations highly affect the price of these fuels. Offshore wind and wave, as renewable energy sources, represent the better alternatives for electricity generation. Therefore, it is necessary that wind speeds effectively be estimated due to the absence of field measurements of the wind speed above the surface of the sea in many regions. In this paper, the annual-average wind speed above the sea is calculated mathematically. Wind data obtained from onshore monitoring stations were analyzed to obtain wind power density above the sea. In addition, this study provides information on the variation of the wave energy using Beaufort scale and wind speeds. This allows an approximate estimation of energies corresponding to various wave heights in that region. Besides, a mathematical model was developed to assess wave and wind hybrid energy system. Thus, using a mathematical model, wind-wave hybrid system components were: wind turbine, wave converter and foundation. The wave energy converter (WEC) selected for the hybrid device is Wavestar prototype which was combined with a wind turbine. As for case study, the wind speed as well as the resulting wind and wave power potential in the area of Eastern Mediterranean Sea and the North Sea were determined and the assessment were done for the designed hybrid system. It can be concluded that the annual energy production from hybrid wind-wave device in the North Sea is 64.3% more than its value in the Mediterranean Sea.

Keywords: Offshore Wind Energy; Wind Power Density; Mean Wind Speed; Wave Energy; Hybrid Energy System.

1. Introduction

Fossil fuels have been the principal origin of energy nowadays, but using this source is going toward unknown future. This means that fossil fuels could run out in the near future because of the increasing consumption of this kind of fuel by humanity. Furthermore, the effects of using fossil fuels are increasingly affecting the environment harmfully. For example, greenhouse gases have been an important issue for humanity since the day it was discovered as a contributor to global warming issue. Due to that and many other issues, it was urgent to seek a new source of energy which is clean, free and available enough for a far future.

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Executing experiments and carrying out research, man could find a wide range of free power represented by solar, oceans, wind, and other kinds of natural free energy. The oceans are considered as a huge source of energy divided into many types such as the offshore wind, tidal, wave power, and thermal gradient [1]. The offshore energy sector is growing increasingly to be one of the most important free energy sector in Europe [2]. It is expected that by 2020, the setup output will be something like 40 GW for offshore and 3.6 GW for ocean energy systems [3]. The United Kingdom was ranked to be the first in the world who had the biggest capacity of installed offshore system, which was 55.9% of European systems in 2014 [4].

1.1. Literature overview

Offshore wind systems are the mechanisms installed in the sea, whereas ocean energy is divided into tidal, wave, and thermal gradation energy of the ocean. Offshore wind energy is the most growing technology, but the ocean energy is still in its first stages [3]. In 2011, the total offshore energy capacity installed was about 4117 MW which is about 1.73% of the whole capacity. This number was 14384 MW in the year 2016. It is expected that the installed capacity will be about 10% of the total capacity in 2020. Nowadays, about 90% of the offshore systems are in Europe.

Offshore winds are the winds at sea which are usually stronger and steadier compared to onshore winds, this can result in greater and more trustworthy energy production. In addition, there is the possibility of constructing huge offshore turbines in comparison to the onshore turbines, that’s because onshore turbines are restricted by the residential areas and may be totally neglected by stakeholders [5]. Although the offshore wind industry is growing increasingly, there is a lack of certainty with designing the wind system structure in the sea. Dolores Esteban et al. [6] concluded that the structural ambiguities consisted of issues for soil composition and transition piece (TP) design. They also inspected the applied offshore wind criterions related to substructure design. There is an increasing need to consume the produced electricity instantly or it must be stored for use when winds vanish or have a very little power to operate the turbines and cover the demands [7].

One of the main issues still obstructing the development of offshore wind energy is the lack of wind speed measurements over sea areas, due to the technical challenges and high costs associated with wind measurement in the ocean. Thus, to exploit offshore wind energy potential efficiently, precise wind resource assessment is required.

Among the available wind data sources, *in-situ* measurements (i.e. buoys, offshore meteorological masts, satellites, onboard ships, vessels, etc.) are the most suitable data source in terms of precision and are widely used as the primary reference source compared with other wind data sources; Ebuchi et al. [8], Carvalho et al. [9] and Soukissian and Papadopoulos [10] are the best relevant examples. Even when such measurements exist, they are only for a certain period of time and can be sparse in the case where a large region is considered for analysis.

Recently, a major interest is focused on the use of numerical weather prediction (NWPs) models as a source of wind data for offshore wind energy, and several authors have investigated the accuracy of NWP (Gallego et al. [11], Berge et al. [12], Jimenez et al. [13]). Despite the promising performances of NWP models on offshore winds forecasting, offshore winds still remain a modeling challenge when compared to the typical open sea and the onshore winds due to the fact that they are strongly influenced by the local topography, discontinuity between land and sea roughness and also by thermal gradients resulting from land-sea temperature differences [14].

Till now, the utilization of ocean energy is still limited, that is due to the high cost of produced energy using wave and tidal mechanisms compared to other renewable energy resources [15]. The most growing domain in the sector of renewable energy is wave energy conversion, which had attracted more interests by Scientists and manufacturers over the past few years, so there was a great improvement in the field of wave energy conversion mechanisms which take out the wave motion energy [16]. For instance, the power take-off optimization for the interconnected floaters studied by Zheng, S. et al.[17]. Past studies focused on reducing the cost of producing energy [15].

Nowadays, combined wave-wind systems don’t exist in a real form, they are only proposed as computer prototypes. In addition, wave energy converter farms are not constructed in the sea so far. Consequently, there is a need to set combined wave- wind energy into execution, especially with the offshore wind field prosperity [18].

Waves are usually associated with winds, so it's possible to exploit this power by constructing wind turbines which are integrated with wave energy harvesters. There are only very few research studies that have discussed combined utilization of wave and offshore wind energies and they discussed the estimation of wave and offshore wind energy resources; Veigas et al. [19–21], Fusco et al. [22], Anderson et al. [23] and Sheng et al. [24] or the integration methods of the produced energy; Lund [25] and Stoutenburg et al. [26], also explored combinations based on the use of the support structure for an offshore wind turbine as a basis for an energy storage system, a wave energy harvesting system, and a uranium-from-seawater mining system; Slocum [27].

1.2. Research motivation and objectives

As earlier mentioned, the available wind and wave energy must be accurately estimated at the site so that this energy can be utilized by a hybrid wind-wave model. There is an increasing need to start constructing combined wave-wind energy system to be a commercial model. The point here is to support offshore wind energy using wave energy harvesters, this means that we can exploit wave and offshore wind powers at the same time. In conclusion, a power saver sample for combined wave-wind energy must be improved.

The objective of the present study is to explore the possibility of utilizing the offshore wind and wave energy for power generation. Using available potential of wind and wave energy in a sea, this mathematical model was developed to assess wind-wave hybrid system components. First, by knowing onshore measured wind speed data taken from coastal monitoring station, a mathematical model was assigned for calculation of offshore wind speed. By adding wave height to the model, a mathematical model was developed to assess and predict the potential of using wind and wave energy in the sea. Thus, the present model will prove to be much more realistic for hybrid offshore wind and wave energy production. Finally, to demonstrate practical capability of presented assessment model, two case studies (case A and case B) were considered in the area of Eastern Mediterranean Sea and the North Sea.

2. Mathematical model

The flowchart in Fig. 1 shows the steps involved in the engineering improvement in assessing the wave and wind hybrid energy system according to our proposed methodology.

2.1. Wind speed gradient

The speed of the wind varies along the turbine height. To be exact, it increases with increased height of the turbine over the land [28]. Two methods can be followed to set the wind profile: the first one is the power law, and the other is logarithmic. The power law method is more common than logarithmic method [29]. The difficulties of the logarithmic method are the stability parameter and the friction velocity. Consequently, the wind profile based on power law method was used by the most of the researchers. The power law is given by the following equation [30]:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\propto} \tag{1}$$

where v_2 is wind speed at height h_2; v_1 is wind speed at height h_1; h_2 computed height; h_1 reference height and α power law exponent.

The experiments show that when α=0.14 (1/7), it is suitable for most of the locations. In this case, the method is called the one-seventh power law [29].

In the field of wind power, the wind speed graduations depending on the height can be calculated based on the wind specified at a reference height of 10 m using the following equation:

$$\frac{v_2}{v_{10}} = \left(\frac{h_2}{10}\right)^{1/7} \tag{2}$$

2.2. Estimating offshore winds from onshore meteorological measurements

The data taken from the meteorological station has been mathematically corrected throughout three levels in order to calculate the annual average offshore wind speed.

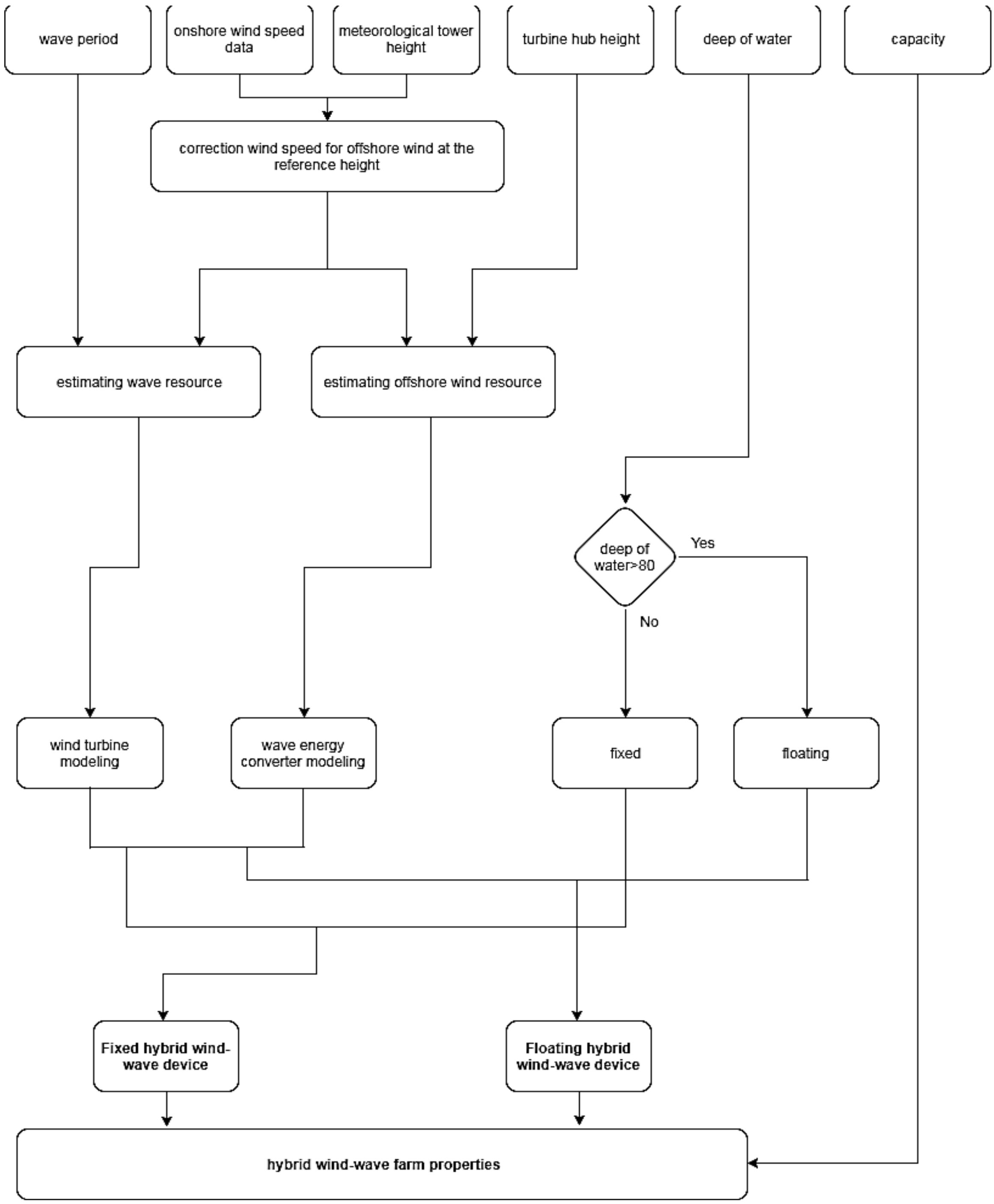

Fig. 1. Flowchart of the proposed methodology for assessing the engineering improvement of wave and wind hybrid energy system

a) The measured value of the wind speed taken from the station's data has been corrected in order to obtain the wind speed at the reference height of 10 m by using Eq. (2) [31].

b) The wind in the sea drifts when it approaches the land and makes an angle approximately estimated by 15 to 20° in the direction of the lower pressure. However, this angle increases to about 30-40°) above the medium roughness land. Therefore, the meteorological station is considered as a land-station close to the coastline so the correction coefficient of the location is equal to 1.0.

c) The correction of data should be taken into consideration for the thermal difference between the sea and the air. Given the small absolute thermal differences between the air and the sea (|ΔT|≤5°), the effects resulting from this temperature difference on the wind speed and its direction are considered insignificant.

Consequently, v_{sea} is linearly related to v_{land}, and the linear regression equation is [32]:

$$v_{sea} = 1.62 + 1.17 v_{land} \quad (3)$$

Eq. (3) is recommended for operational use. According to Eq. (3), v_{sea} may not be equal to zero when v_{land} is zero. In other words, when onshore conditions are calm, it is not necessary that winds in offshore will also be calm.

2.3. Statistical analysis of wind data

The possibility of wind power at a specific location can be estimated using statistical analysis. In this way, we can assess the amount of power produced by an installed turbine at the determined area. These techniques have been discussed by a number of authors including Fang[33], Murthy et al.[34], Karthikeya et al.[35], Mostafaeipour et al.[36], Bataineh et al.[37] and Fagbenle et al.[38]. Using statistical analysis, the values of random variables can be estimated in terms of probability distribution. It is worthy of note that wind speed is a random variable, so it can be estimated using the method mentioned before.

2.3.1. Probability Density Function

The probability density function, $p(v)$, is the expression of the wind speed frequency of occurrence. It's used to define the wind speed between v_a and v_b [39]:

$$P\left(v_a \le v \le v_b\right) = \int_{v_a}^{v_b} P(v)\,dv \quad (4)$$

And $P_{density}$ expresses the mean available wind power density which is calculated using the following equation:

$$P_{density} = \frac{\bar{P}}{A} = \frac{1}{2}\rho \int_0^{\infty} v^3 P(v)\,dv \quad (5)$$

where ρ is air density (1.225 kg/m^3).

2.3.2. Cumulative Distribution Function

The probability of the wind speed being smaller than or equal to a given value, v, is expressed by the cumulative distribution function $F(v)$. This is given as follows [39]:

$$F(v) = \int_0^{v} P\left(v'\right) dv' \quad (6)$$

On the other hand, the probability density function can be expressed as a derivative of the cumulative distribution function as follows:

$$P(v) = \frac{dF(v)}{dv} \quad (7)$$

The velocity duration curve depends basically on the cumulative distribution function. In other words, the velocity duration curve =8760×(1- $F(v)$), reserving the x and y axes .

2.3.3. Rayleigh Probability Distributions

This distribution is considered as the simplest velocity probability distribution which is used to express the wind source, this is because the only value needed is the mean wind speed, $\bar{V}$. The available data may not be given as instant values, so these data are usually given as mean values during a period of time [40]. Considering the situation mentioned above, the probability density function and the cumulative distribution function are calculated as follows [39]:

$$P(v) = \frac{\pi}{2}\left(\frac{v}{\bar{V}^2}\right)\exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{V}}\right)^2\right] \quad (8)$$

$$F(v) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{V}}\right)^2\right] \quad (9)$$

2.4. Wind Turbine Modeling

The use of wind power as a renewable source has become common due to the cost of fossil fuel and environmental issues [41]. The power curve of wind turbine operation represents the power produced and transferred, this curve symbolizes a relation between the wind speed and the power. This relationship can be expressed as:

$$p(v) = \begin{cases} 0 & v \langle v_{ci} \ or\ v \rangle v_{co} \\ q(v)| & v_{ci} \le v < v_r \\ P_r & v_r \le v \le v_{co} \end{cases} \quad (10)$$

where $p(v)$ is the electric power in Watt, v_{ci} is the cut-in wind speed in m/s, v_{co} is the cut-out wind speed in m/s, v_r is the rated wind speed in m/s, P_r is the rated power in W and $q(v)$ is the nonlinear relationship between power and wind speed (Fig. 2) [42].

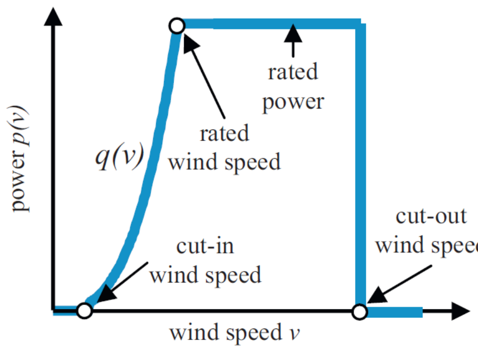

Fig. 2. Representation of the power curve [42]

To estimate the energy production of a wind turbine, the power curve must be used with the wind speed distribution known. A wind turbine theoretical energy can be calculated by multiplying the wind speed by its corresponding power output, then adding them together (Fig. 3).

The amount of a wind turbine power in a year, $\bar{P}_{\mathrm{T}}$, is [43]:

$$\bar{P}_{\mathrm{T}} = \sum_{v=v_{ci}}^{v=v_{co}} p(v) \times f(V=v) \qquad [\mathrm{kW}] \tag{11}$$

where $f(V = v)$ is the frequency of occurrence of wind speed v. Also the energy production of a wind turbine in a year is expressed as:

$$E_T = 8760 \times \bar{P}_T \qquad [\mathrm{kWh}] \tag{12}$$

2.5. Estimation of wave energy from wind velocity

It is known that the sea waves result from the relation between the solar energy and the pressure differences which causes the wind which hits the surface of the sea. It is possible to reach the wave speed from the offshore wind speed [44].

2.5.1. The calculation of wave's height

It is possible to calculate the wave's height depending on the average wind speed at the 10 m reference height in the offshore by using Beaufort scale. The Beaufort scale splits the wind into 13 cases. It is possible to estimate the average height of sea waves in meters with a good approximation based on these 13 wind speeds [45].

2.5.2. Energy and power density of a sea surface wave

The energy density, which is the amount of energy in Joules per area unit, of a sequential sea surface wave can be calculated by considering the oscillation of a column of water upright to the plane. Consequently, the time dependent wave equation can be obtained using Newton's second law as follows [44]:

$$w^2 = \frac{A\rho g}{m}\frac{d^2h}{dt^2} = -w^2 h \tag{13}$$

where m is the mass which has the following general solution:

$$w = \sqrt{\frac{A\rho g}{m}}\, h(t) = a\exp(\pm iwt) \tag{14}$$

where w is the angular frequency and a is the amplitude of the wave.
Using Newton's energy formula, the energy can be calculated as follows:

$$E = \frac{1}{2}m|v|^2 = \frac{1}{2}m\left|\frac{dh}{dt}\right|^2 = \frac{1}{2}A\rho g a^2 \tag{15}$$

where an energy density expression can be given by:

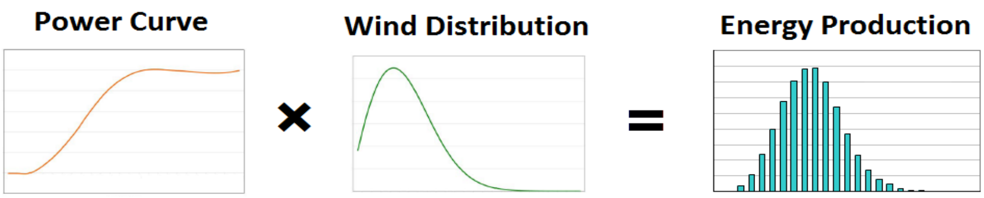

Fig. 3. Calculation annual energy production

$$E = \frac{1}{8}\rho g H^2 \qquad \left[\mathrm{Jm^{-2}}\right] \tag{16}$$

where $H = 2a$ is the wave height in meters. The power density is then calculated using the following equation:

$$P = \frac{E}{T} \qquad \left[\mathrm{Wm^{-2}}\right] \tag{17}$$

where T represents the period of the wave in seconds.

2.6. Modeling wave converter

The Wavestar prototype, Fig. 4, is selected as a hybrid device which is a wave converter along with a wind turbine.

2.6.1. The operation principle

The system consists of a number of arms which have floats at its end. Using one-way bearings, these arms are suited to a horizontal shaft using levers. The shafts which move in a slow motion transfer this motion to a gearbox of a generator, just like the method used in wind turbines. Shaft torque generated by the upward movement of the float is transferred to the generator by means of a gearbox [46].

2.6.2. Wavestar prototype at Roshage

A test prototype of wave energy converter (WEC) was installed by Wavestar in 2009 at the Western coast of Denmark. This prototype was of a 600 kW WEC [47]. After testing the prototype, it proved a good functionality that it had no major design problems, and it hadn't been affected by sea storms. Tables 1 and 2 present the model Wavestar prototype parameters and also the power matrix of the generated electrical power [48].

2.6.3. Energy produced by Wavestar prototype

In order to estimate the energy generated by a WEC in a certain period of time, the average height of waves can be used which is calculated from the Beaufort scale for each day of a year and also knowing the wave period for the region of study. Thus the energy generated by a WEC can be computed from Table 2.

2.7. Fixed hybrid wind-wave device

A basic sample is a hybrid prototype on the basis of monopile wind turbine and four floating (two Wavestar prototype WEC for each wind turbine) on the same structure. This sample is shown in Fig. 5. This design fits a prototype of 80 m depth under sea.

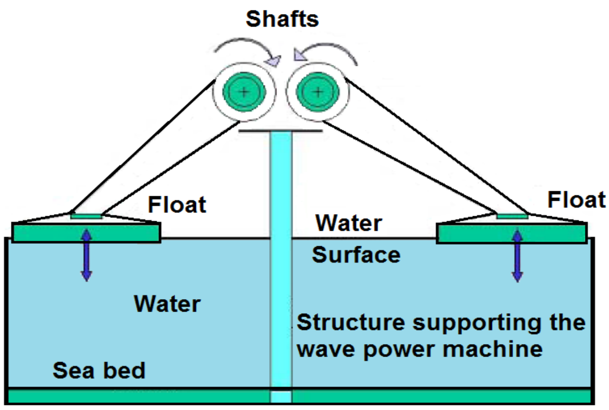

Fig. 4. Principle of operation [46]

Table 1. Wavestar prototype parameters [48]

Main parameters	
Number of floats	2
Float diameter [m]	5
Length of arm [m]	10
Storm protection [m]	3
Min. power take-off [kW]	0
Max. power take-off [kW]	600

Table 2. Wavestar prototype electrical power matrix in [kW] [48]

Wave height H (m)	Wave period T (sec)										
	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
0.0-0.5	0	0	0	0	0	0	0	0	0	0	0
0.5-1.0	0	49	73	85	86	83	78	72	67	63	59
1.0-1.5	54	136	193	205	196	182	167	153	142	132	123
1.5-2.0	106	265	347	347	322	294	265	244	224	207	193
2.0-2.5	175	429	522	499	457	412	372	337	312	288	267
2.5-3.0	262	600	600	600	600	540	484	442	399	367	340
3.0-	Storm protection										

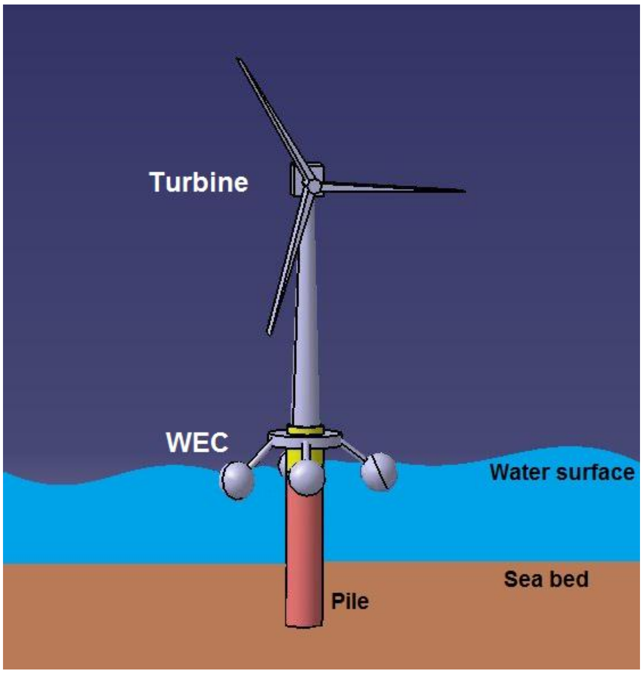

Fig. 5. Fixed hybrid wind-wave device

2.8. Floating hybrid wind-wave device

The cost of the fixed system depends on the depth of water, that is to say that as the depth increases the cost will increase obviously. A hybrid floating wind-wave device which is moored using a catenary and a spar is shown in Fig. 6. There are four floats associated with the wind turbine. This prototype is suitable for water depth of more than 80 m.

2.9. Hybrid wind-wave device annual energy production

The hybrid wind-wave device annual energy production is the annual energy produced from wind turbine plus the annual energy produced from two Wavestar prototype WEC. This energy is expressed as:

$$E = E_T + 2 * E_{wec} \qquad [\text{kWh}] \qquad (18)$$

3. Study cases

To check presented model reliability, two global case studies have been evaluated for wind and wave energy applications.

3.1. Case A

Figure 7 shows Syria situation and the city of Latakia governorate on the eastern coast of the Mediterranean. In this study, daily mean wind speed data during the period (2006 – 2010) obtained from Al-azhari meteorological station, which is located at 35°32'30.7"N; 35°46'00.5"E at an altitude of 11.4 m and 25 m distance to the coast, was used [49].

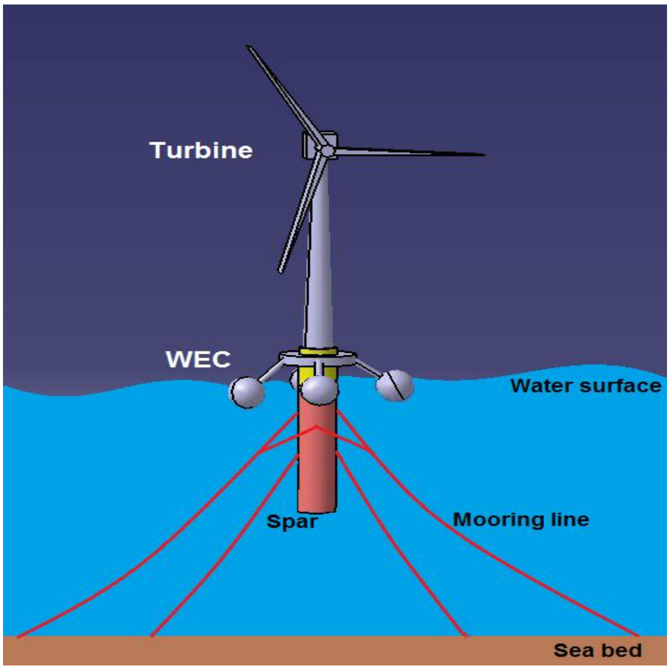

Fig. 6. Floating hybrid wind-wave device

Fig. 7. Syria location with Latakia governorate on the eastern coast of the Mediterranean Sea [50]

Fig. 8. United Kingdom location with Hempstead governorate close to the North Sea [52]

3.2. Case B

The daily mean wind speed data (for 2015) obtained from weather station, which is located in Hempstead in United Kingdom close to the North Sea (Figure 8) [51].

4. Results and Discussion

In order to predict the potential of wind and wave energy in sea and design a wind-wave hybrid system, a computer code was developed in the programming environment MATLAB based on the flowchart in Fig. 1.

4.1. Calculation of offshore wind speed from onshore meteorological measurements for case A

By applying Eq. (2) on the wind data taken from the meteorological station, the wind speed at the 10 m reference height was calculated. Figure 9 shows the values of monthly onshore wind speed at 10 m height. From Fig. 9, the monthly mean wind speed at the reference height of 10 m varies between 2.1- 4.5 m/s with an annual average wind speed of 3.2 m/s.

Figure 10 shows the offshore wind speed at 10 m reference height after substituting the onshore wind data at 10 m reference height in Eq. (3). It is obvious that the highest wind speed value occurs in February while the lowest wind speed value occurs in August. It also shows that the annual mean wind speed is 5.3 m/s.

Comparison between the annual mean onshore and offshore wind speed at different heights is shown in Fig. 11. The value of offshore wind speed at certain height is greater than that of onshore wind speed. Note that the curve of onshore wind speed profile has a sharp increase with respect to the height in comparison with that of offshore wind speed.

4.2. Offshore wind-power estimates for case A

By applying Eq. (2) on offshore wind speed at 10 m reference height, the wind speed is calculated at 90 m height which is the most common height used for offshore wind turbines. Table 3 summarizes the monthly wind speed at 10 m and 90 m altitude.

It can be seen from Table 3 that the monthly mean wind speed at extrapolated height (90m) varies between 5.5-9.3 m/s with an annual average of 7.3 m/s. Figure 12 shows the offshore wind speed distribution at hub height of 90 m. The maximum frequency (10.4%) occurs at offshore wind speed of 5.8 m/s. The annual mean wind power density at hub height is shown in Fig. 13. It is evident that the maximum power density of 44.5 Wm^{-2} occurs at offshore wind speed of 11.6 m/s with an annual mean of 445 Wm^{-2}.

Table 3. Calculated monthly mean offshore wind speed m/s at 10 m and 90 m height for case A

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
V_{10}	6.7	6.8	6.3	5.6	4.8	4.4	4.2	4	4.5	4.6	5.4	6.2	5.3
V_{90}	9.2	9.3	8.6	7.7	6.5	6	5.7	5.5	6.2	6.3	7.4	8.5	7.3

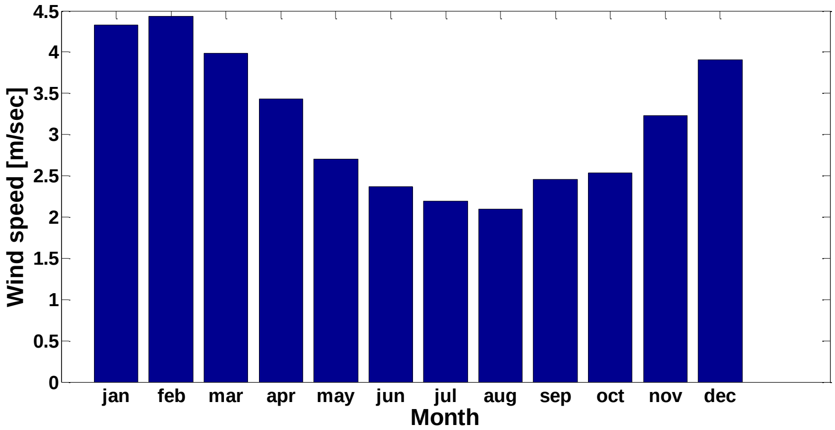

Fig. 9. Monthly mean onshore wind speed at the 10 m reference height for case A

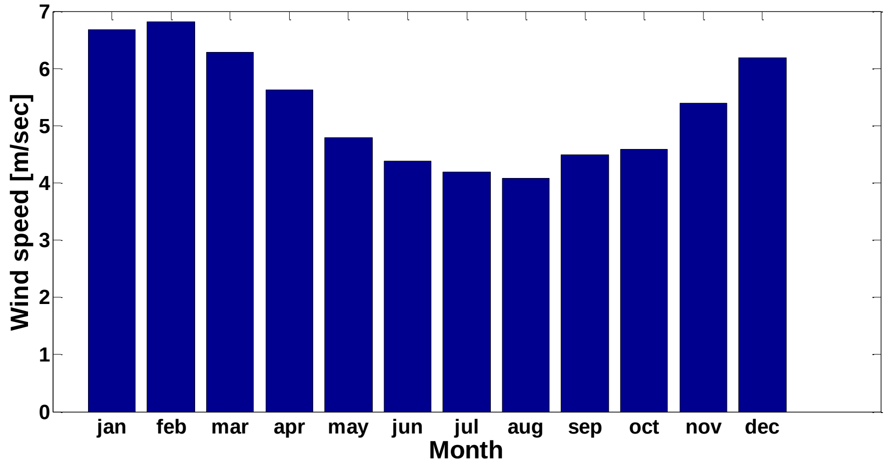

Fig. 10. Monthly mean offshore wind speed at the 10 m reference height for case A

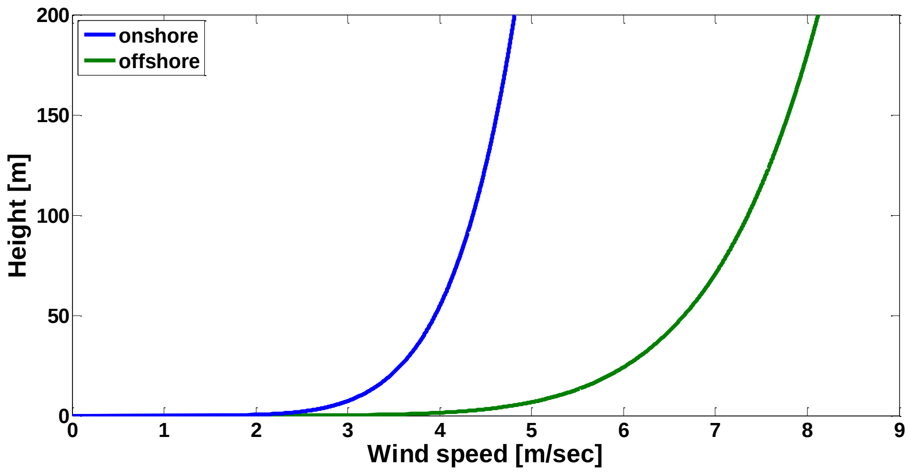

Fig. 11. Annual mean onshore and offshore wind speed at different heights for case A

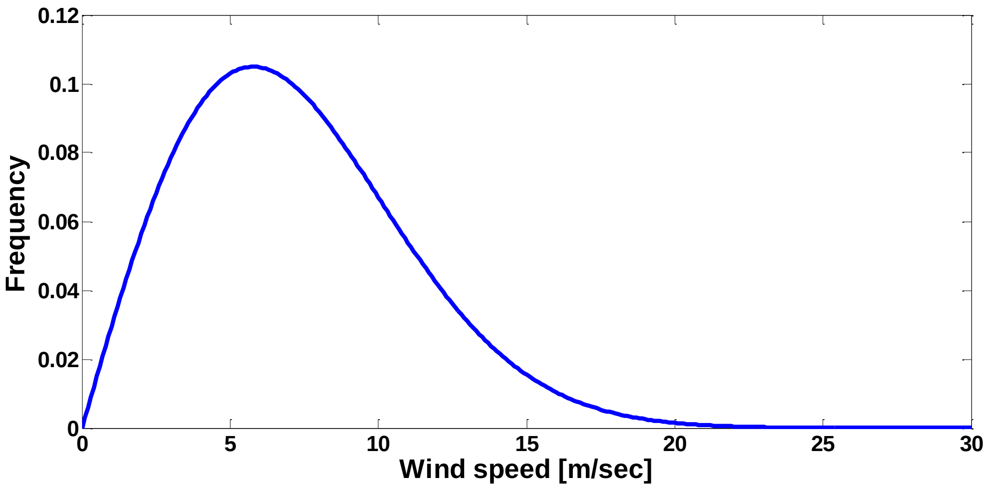

Fig. 12. Offshore wind speed distribution at hub height for case A

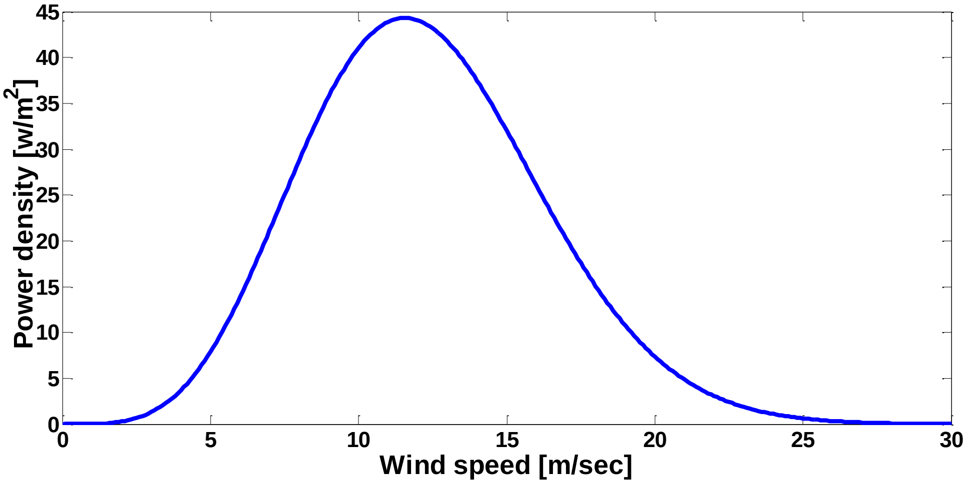

Fig. 13. Offshore annual mean wind power density at hub height for case A

4.3. Wind turbine selection for case A

Following Fig. 3 and using Eq. (11) and Eq. (12), the amount of energy a wind turbine will generate in a year can be calculated corresponding to the wind speed distribution and the turbine's power curve. Fifty five wind turbines from many manufacturers, such as Alstom, Vestas, Enercon and Gamesa were used to select the highest annual energy production turbine at a given site. The turbine power curves data was entered to the computer program in the form of a matrix. According to case A specifications, annual energy produced by all the 55 wind turbines at the hub height was calculated. The highest annual energy production turbine belongs to Enercon, type "E-126 EP4", as illustrated in Fig. 14 with rotor diameter of 127 m with nominal power of 4200 kW and annual energy production of $1.39 \times 10^7\ kWh$.

4.4. Wave-power estimates for case A

As illustrated in Fig. 15, the monthly mean wave height varies between 0.54-1.2 m with an annual average of 0.8 m. The figure indicates that the highest wave height value occurs in August while the lowest wave height value occurs in January. For the period of wave equal to 6.54 s in this site, the calculated power density of a sea surface wave was 187.1 Wm^{-2}.

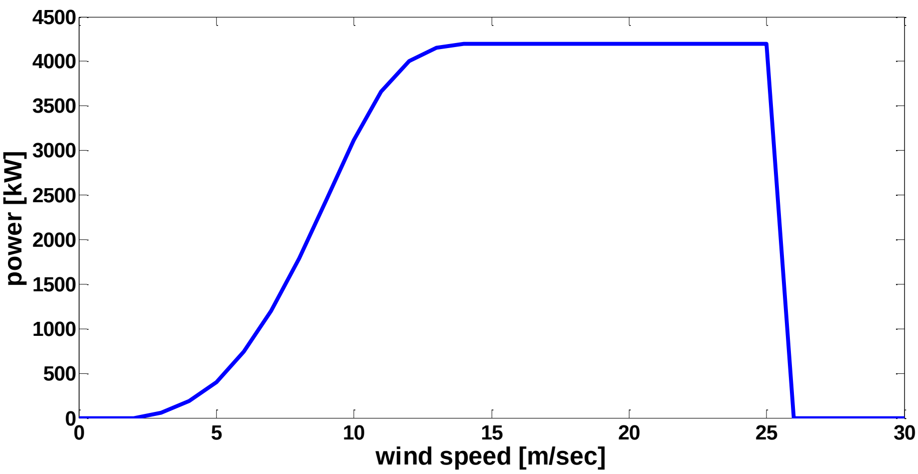

Fig. 14. Power curve of selected turbine for case A

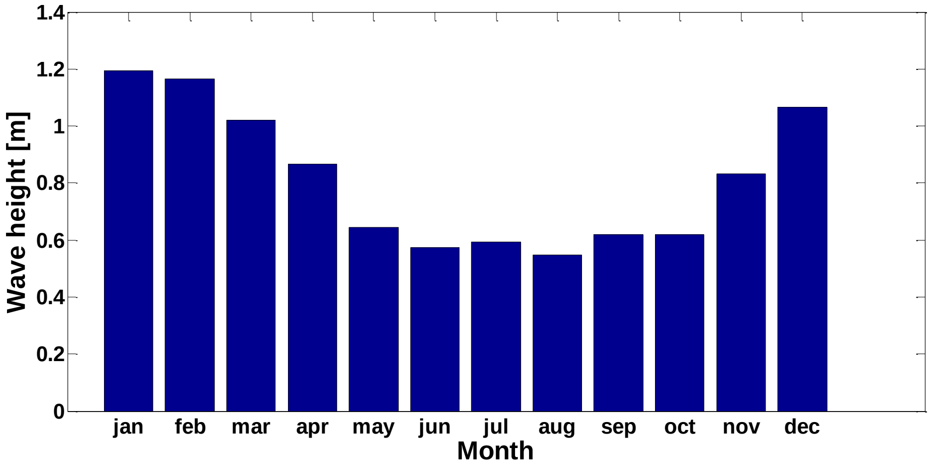

Fig. 15. Monthly mean wave height for case A

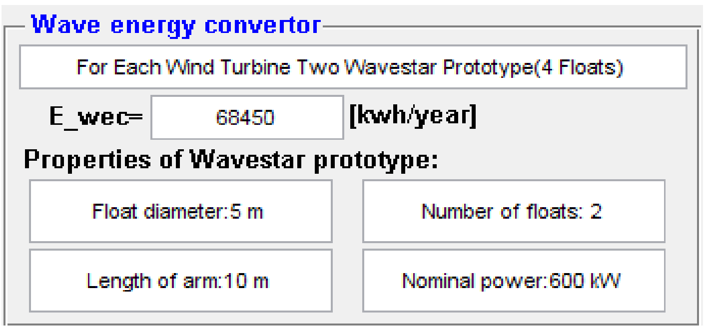

Fig. 16. Annual energy produced by wave energy converter system for each hybrid wind-wave device for case A

4.5. Wave energy convertor for case A

Since four floating (two Wavestar prototype for each wind turbine) on the same foundation were used in the proposed design, the WEC annual energy production system for each hybrid wind-wave device equals twice the annual energy produced by each Wavestar prototype. This annual energy and properties of Wavestar prototype are shown in Fig. 16.

4.6. Hybrid wind-wave device for case A

Knowing water depth in the region of study, fixed or floating foundation for hybrid wind-wave device is selected. Therefore, using Eq. (18), the annual energy production from hybrid device is calculated.

For water depth equal in mean to 40 m for case A, fixed hybrid wind-wave device is more appropriate. The annual energy production from the hybrid wind-wave device is $1.4 \times 10^7\ kWh$.

4.7. Hybrid wind-wave farm for case A

As the required electrical capacity for the case is 150 MW, the number of wind-wave hybrid devices and the annual energy production are calculated. The number of required wind-wave hybrid devices for the farm are 28 with an annual energy production of $3.9 \times 10^8\ kWh$.

4.8. Calculation of offshore wind speed from onshore meteorological measurements for case B

Figure 17 shows the values of monthly onshore wind speed at 10 m height with an annual average of 5.3 m/s. Figure 18 shows offshore wind speed at the 10 m reference height after substituting the onshore wind's data in Eq. (3). From Fig. 18, the highest wind speed value (10.7 m/s) occurs in December while the lowest wind speed value (5.6 m/s) occurs in October and the annual mean offshore wind speed at the reference height is 7.9 m/s. Figure

19 shows a comparison between the annual mean onshore and offshore wind speed at different heights. As we can see, the same remark related to Fig. 11 is valid and also applies to Fig. 19 of case B.

4.9. Offshore wind-power estimates for case B

Table 4 summarizes the monthly offshore wind speed at 10 m and 90 m altitude which is the most common height used for offshore wind turbines.

As can be seen from Table 4, it is obvious that the monthly mean wind speed for case B at hub height of 90 m varies between 7.7-14.6 m/s with an annual mean of 10.8 m/s. Figure 20 shows the offshore wind speed distribution at hub height of 90 m. Figure 21 shows the annual mean wind power density at hub height for case B. It also shows that the annual mean wind power density is 1425.6 Wm^{-2}.

Table 4. Calculated monthly mean offshore wind speed (m/s) at 10 m and 90 m height for case B

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
V_{10}	8.9	7.9	8.9	7.6	8.6	7.4	7.6	6.5	5.7	5.6	9.1	10.7	7.9
V_{90}	12.2	10.8	12.2	10.4	11.8	10.1	10.4	8.9	7.8	7.7	12.4	14.6	10.8

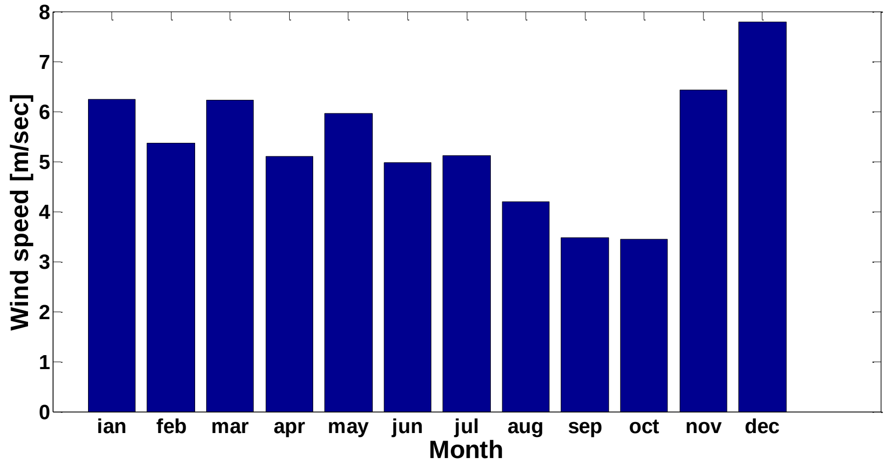

Fig. 17. Monthly mean onshore wind speed at the 10 m reference height for case B

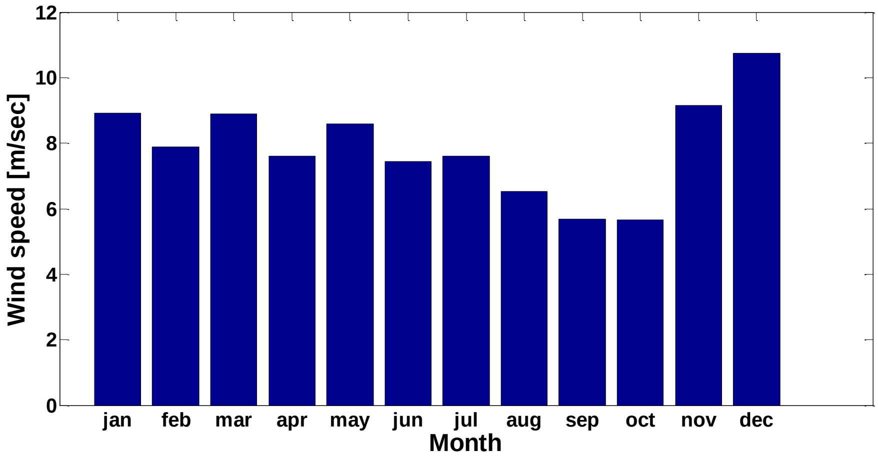

Fig. 18. Monthly mean offshore wind speed at the 10 m reference height for case B

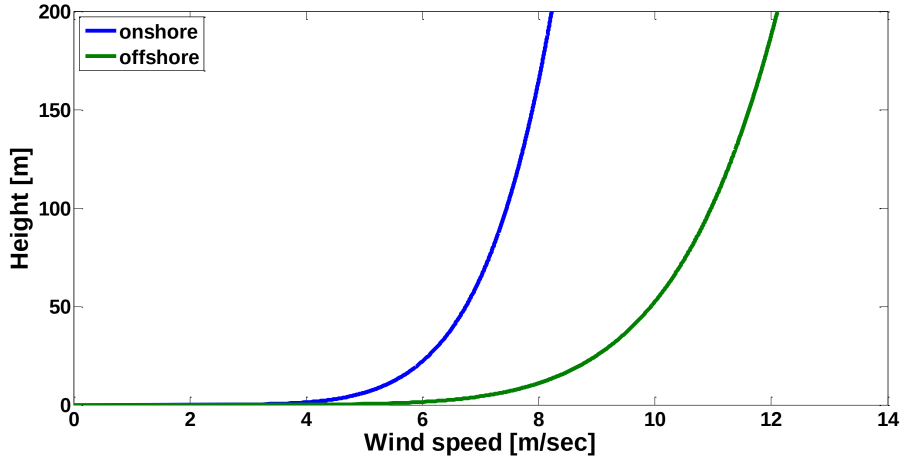

Fig. 19. Annual mean onshore and offshore wind speed at different heights for case B

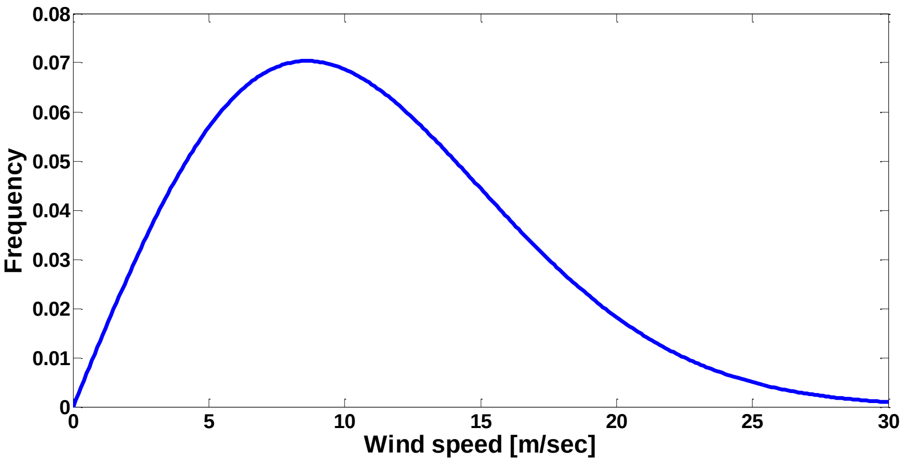

Fig. 20. Offshore wind speed distribution at hub height for case B

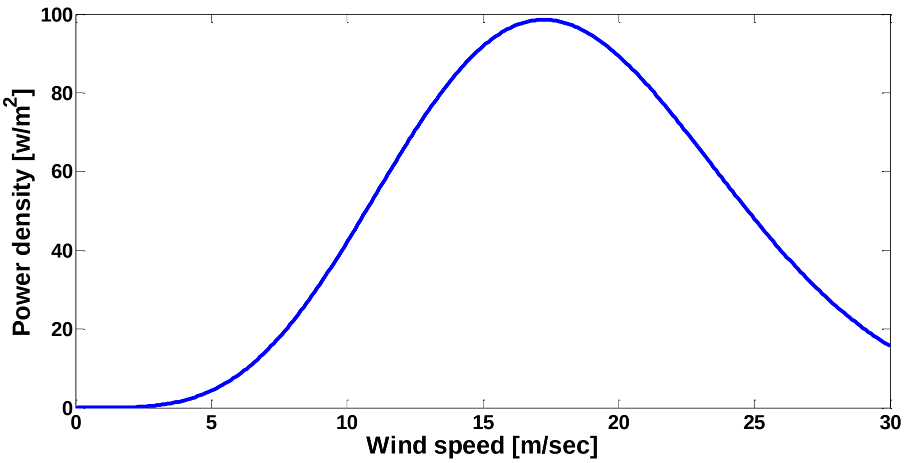

Fig. 21. Offshore annual mean wind power density at hub height for case B

4.10. Wind turbine selection for case B

The appropriate turbine power curve is selected as illustrated in Fig. 22. The annual energy produced by the "Enercon" turbine, type "E-126 EP4" with rotor diameter of 127 m is 2.25×10^7 kWh and nominal power of 4200 kW.

4.11. Wave-power estimates for case B

Figure 23 shows the monthly mean wave height for case B with an annual average of 1.5 m. For the period of wave equal to 6 s in the North Sea for case B, the calculated power density of a sea surface wave was 669.5 Wm^{-2}. Consequently, for case B, the annual mean offshore wind speed at the reference height is 7.9 m/s with annual mean wave height of 1.5 m. This is in line with the annual mean offshore wind speed of 17 knots (8.7 m/s) and the 4 Beaufort scale degree which equals an annual mean wave height of approximately 1.5 m obtained by the wind statistics. These statistics are based on real observations taken between 12/2008 - 08/2016 daily from 7am to 7pm local time from the weather station at Forties North Sea Platform [53].

4.12. Wave energy convertor for case B

The annual energy produced by WEC system for each hybrid wind-wave device for case B is 142×10^3 kWh. The specification of the Wavestar prototype is shown in Fig. 24.

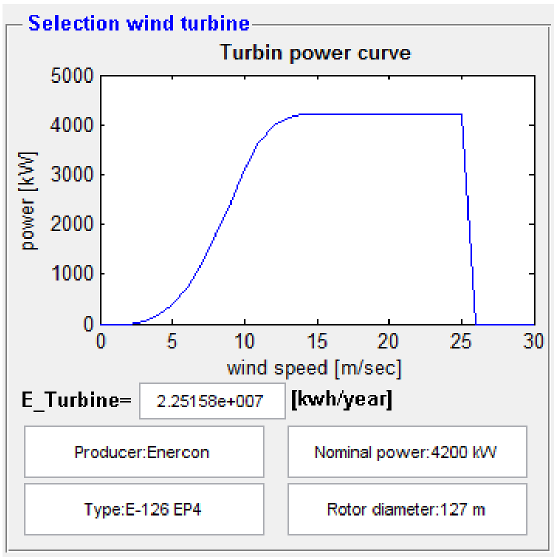

Fig. 22. The specification of the appropriate turbine for case B

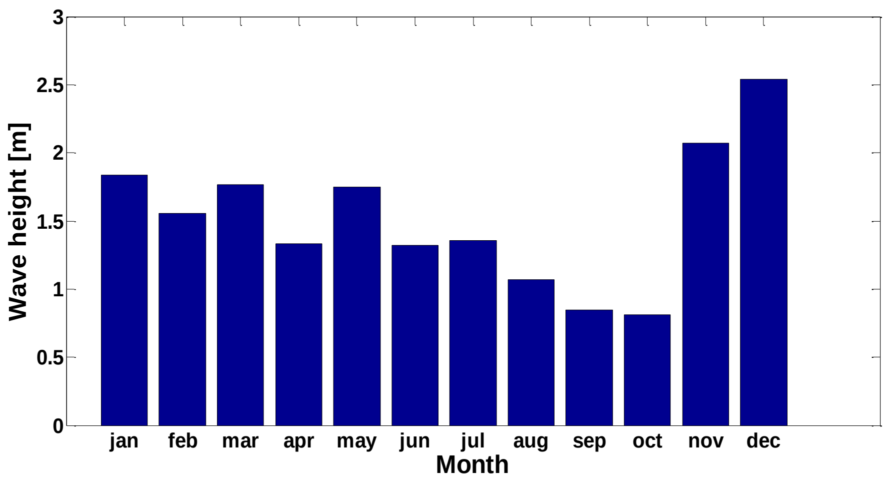

Fig. 23. Monthly mean wave height for case B

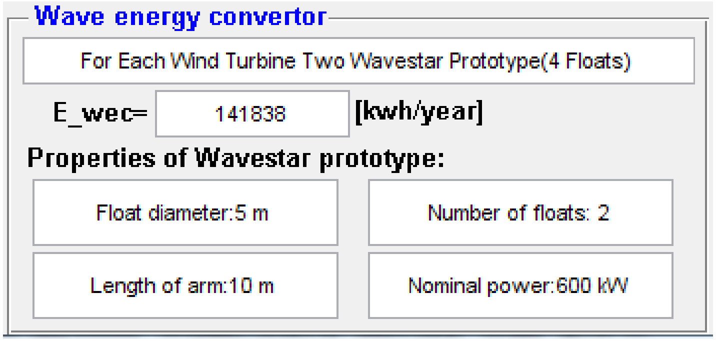

Fig. 24. Annual energy produced by wave energy converter system for each hybrid wind-wave device for case B

4.13. Hybrid wind-wave device for case B

For water depth of 50 m in mean, fixed hybrid wind-wave device is more suitable for this case. The annual energy production from hybrid wind-wave device was $2.3 \times 10^7\ kWh$ in the site.

4.14. Hybrid wind-wave farm for case B

For a capacity of 150 MW in the site for case B, twenty eight wind-wave hybrid devices are required in the farm with an annual energy production of $6.34 \times 10^8\ kWh$.

5. Conclusion

In this study, a mathematical model has been developed for the assessment of data collected from wind speed on the ground and modifying the data using a mathematical model, the data of wind speed at sea was calculated. This allowed the predicting of the potential of using offshore hybrid wind and wave energy. Moreover, this model is developed to assess a wind-wave hybrid system. In order to estimate offshore wind and wave energy resources and design the hybrid system, a computer code was developed in the programming environment MATLAB. The wind speed data was taken from the meteorological station for two regions: the first was Syria (Latakia) on the coast of the Mediterranean Sea and the second was United Kingdom (Hampstead) located close to the North Sea. Then, the data were corrected to calculate the wind speed above the sea. When comparing the annual mean onshore and offshore wind speed at different heights for the two cases, it was found that when v_{land} is negligible, it's not necessary that v_{sea} is zero. Table 5 summarizes the results obtained for two cases.

Table 5. Comparison between the results of case A and case B

	Syria (Latakia) Mediterranean Sea	United Kingdom (Hampstead) North Sea
Annual offshore mean wind speed at hub height [m/s]	7.3	10.8
Annual mean wave height [m]	0.8	1.5
Annual mean offshore wind power density [Wm^{-2}]	445	1425.6
Annual mean wave power density [Wm^{-2}]	187.1	669.5
Wind turbine manufacturer	Enercon	Enercon
Rotor diameter turbine [m]	127	127
Nominal power turbine [kW]	4200	4200
Annual energy production turbine [kWh]	1.39×10^7	2.25×10^7
Annual energy produced by wave energy converter [kWh]	68×10^3	142×10^3
Foundation for hybrid wind-wave device	fixed	fixed
Annual energy production from hybrid device [kWh]	1.4×10^7	2.3×10^7

The presented model of assessment has led to the conclusion that the annual average wind speed and the annual average wave height for case B was more than that calculated for case A. As a result, the area of Eastern Mediterranean Sea has a good wind potential but with lower wave potential. When comparing the annual energy production from hybrid wind-wave device for the two cases, it was found that the annual energy production in the North Sea is 64.3% more than its value in the Mediterranean Sea. Therefore, the energy in the offshore wind can be effectively harnessed and utilized for electric generation and the wave energy can an auxiliary role to the offshore wind energy. On the other hand, the site of the North Sea has good wind and wave potential for electric generation.

References

[1] Soleimani K., Ketabdari MJ., Khorasani F., Feasibility Study on Tidal and Wave Energy Conversion in Iranian seas, Sustain Energy Technol Assessments (2015) 11: 77–86.

[2] Prässler T., Schaechtele J., Comparison of the Financial Attractiveness Among Prospective Offshore Wind Parks in Selected European Countries, Energy Policy (2012) 45: 86–101.

[3] Pérez-Collazo C., Greaves D., Iglesias G., A Review of Combined Wave and Offshore Wind Energy, Renew Sustainable Energy Reviews (2015) 42: 141–53.

[4] European Wind Energy Association., The European Offshore Wind Industry - Key Trends and Statistics 2014 (2015) : 31.

[5] Kerkvliet H., Polatidis H., Offshore Wind Farms Decommissioning: A Semi Quantitative Multi-Criteria Decision Aid Framework, Sustain Energy Technol Assessments (2016) 18: 69–79.

[6] Dolores Esteban M., López-Gutiérrez J-S., Negro V., Matutano C., García-Flores FM., Millán MÁ., Offshore Wind Foundation Design: Some Key Issues, J Energy Resour Technol (2015) 137: 50801.

[7] Gupta A.K., Efficient Wind Energy Conversion: Evolution to Modern Design, J Energy Resour Technol (2015) 137: 51201.

[8] Ebuchi N., Graber H.C., Caruso M.J., Evaluation of Wind Vectors Observed by QuikSCAT/SeaWinds Using Ocean Buoy Data, Journal of Atmospheric and Oceanic Technology (2002) 19: 2049–62.

[9] Carvalho D., Rocha A., Gómez-Gesteira M., Silva Santos C., Offshore Wind Energy Resource Simulation Forced by Different Reanalyses: Comparison with Observed Data in the Iberian Peninsula, Appl Energy (2014) 134: 57–64.

[10] Soukissian T.H., Papadopoulos A., Effects of Different Wind Data Sources in Offshore Wind Power Assessment, Renew Energy (2015) 77: 101–14.

[11] Gallego C., Pinson P., Madsen H., Costa A., Cuerva A., Influence of Local Wind Speed and Direction on Wind Power Dynamics - Application to Offshore very Short-Term Forecasting, Applied Energy (2011) 88: 4087–96.

[12] Berge E., Byrkjedal Ø., Ydersbond Y., Kindler D., Modelling of Offshore Wind Resources, Comparison of a Meso-Scale Model and Measurements from FINO 1 and North Sea Oil Rigs, Eur Wind Energy Conf Exhib, EWEC (2009) 4: 2327–34.

[13] Jimenez B., Durante F., Lange B., Kreutzer T., Tambke J., Offshore Wind Resource Assessment with WAsP and MM5: Comparative study for the German Bight, Wind Energy (2007) 10: 121–34.

[14] Beaucage P., Glazer A., Choisnard J., Yu W., Bernier M., Benoit R., et al., Wind Assessment in a Coastal Environment Using Synthetic Aperture Radar Satellite Imagery and a Numerical Weather Prediction Model, Can J Remote Sens (2007) 33: 368–77.

[15] De Andres A., MacGillivray A., Roberts O., Guanche R., Jeffrey H., Beyond LCOE: A Study of Ocean Energy Technology Development and Deployment Attractiveness, Sustain Energy Technol Assessments (2017) 19: 1–16.

[16] Kallesøe B., Aero-Hydro-Elastic Simulation Platform for Wave Energy Systems and floating Wind Turbines (2011) ISBN 978-87-550-3883-7, Technical University of Denmark.

[17] Zheng S., Zhang Y., Sheng W., Maximum Wave Energy Conversion by Two Interconnected Floaters, The Journal of Energy Resources Technology (2016) 138: 32004.

[18] Karimirad M., Offshore Energy Structures: For Wind Power, Wave Energy and Hybrid Marine Platforms (2014) 301, ISBN 978-3-319-12174-1, Springer.

[19] Veigas M., Iglesias G., Wave and Offshore Wind Potential for the Island of

Tenerife, Energy Convers Manag (2013) 76: 738–45.

[20] Veigas M., Iglesias G., A Hybrid Wave-Wind Offshore Farm for an Island, International Journal of Green Energy (2015) 12: 570–6.

[21] Veigas M., Ramos V., Iglesias G., A Wave Farm for an Island: Detailed Effects on the Nearshore Wave Climate, Energy (2014) 69: 801–12.

[22] Fusco F., Nolan G., Ringwood J.V., Variability Reduction Through Optimal Combination of Wind/Wave Resources - An Irish Case Study, Energy (2009) 35: 314–25.

[23] Anderson M., Beyene A., Integrated Resource Mapping of Wave and Wind Energy, The Journal of Energy Resources Technology (2015) 138: 11203.

[24] Sheng W., Lewis A., Assessment of Wave Energy Extraction From Seas: Numerical Validation, The Journal of Energy Resources Technology (2012) 134: 41701.

[25] Lund H., Large-Scale Integration of Optimal Combinations of PV, Wind and Wave Power into the Electricity Supply, Renew Energy (2006) 31: 503–15.

[26] Stoutenburg E.D., Jenkins N., Jacobson MZ., Power Output Variations of Co-Located Offshore Wind Turbines and Wave Energy Converters in California, Renew Energy (2010) 35: 2781–91.

[27] Slocum A.H., Symbiotic Offshore Energy Harvesting and Storage Systems, Sustain Energy Technol Assessments (2015) 11: 135–41.

[28] Matha D., Model Development and Loads Analysis of a Wind Turbine on a Floating Offshore Tension Leg Platform, Eur Offshore Wind Conf (2010) : 129.

[29] http://www.deq.mt.gov/energy/wind_atlas/atlas/pdf/Chapter5.PDF. (accessed October 14, 2015).

[30] Chichester S.H., Grid Integration of Wind Energy Conversion Systems (1999) 385, Wiley.

[31] Hsu S.A., Models for Estimating Offshore Winds from Onshore Meteorological Measurements, Boundary-Layer Meteorol (1981) 20: 341–51.

[32] Hsu S.,A., Correction of Land-Based Wind Data for Offshore Applications: A Further Evaluation, The Journal of Physical Oceanography (1986) 16: 390–4.

[33] Fang H.F., Wind Energy Potential Assessment for the Offshore Areas of Taiwan West Coast and Penghu Archipelago, Renew Energy (2014) 67: 237–41.

[34] Murthy K.S.R., Rahi O.P., Preliminary Assessment of Wind Power Potential over the Coastal Region of Bheemunipatnam in Northern Andhra Pradesh, India, Renew Energy (2016) 99: 1137–45.

[35] Karthikeya B.R., Negi P.S., Srikanth N., Wind Resource Assessment for Urban Renewable Energy Application in Singapore, Renew Energy (2016) 87: 403–14.

[36] Mostafaeipour A., Sedaghat A., Ghalishooyan M., Dinpashoh Y., Mirhosseini M., Sefid M., Evaluation of Wind Energy Potential as a Power Generation Source for Electricity Production in Binalood, Iran, Renew Energy (2013) 52: 222–9.

[37] Bataineh K.M., Dalalah D., Assessment of Wind Energy Potential for Selected Areas in Jordan, Renew Energy (2013) 59: 75–81.

[38] Fagbenle R.O., Katende J., Ajayi O.O., Okeniyi J.O., Assessment of Wind Energy Potential of Two Sites in North-East, Nigeria, Renew Energy (2011) 36: 1277–83.

[39] Manwell J.F., McGowan J.G., Rogers A.L., Wind Energy Explained: Theory, Design and Application (2009) 577, ISBN 978-0-470-01500-1, John Wiley&Sons Ltd, UK.

[40] Mathew S., Wind Energy: Fundamentals, Resource Analysis and Economics (2007) 1-246, ISBN 3-540-30905-5, Springer.

[41] Derakhshan S., Tavaziani A., Kasaeian N., Numerical Shape Optimization of a Wind Turbine Blades Using Artificial Bee Colony Algorithm, The Journal of Energy Resources Technology (2015) 137: 51210.

[42] Carrillo C., Obando Montan ˜o A.F., Cidra´ s J., Dı´az-Dorado E., Review of Power Curve Modelling for Windturbines, Renewable and Sustainable Energy Reviews (2013) 21: 572–81.

[43] Mathew S., Philip, Susan G., Advances in Wind Energy Conversion Technology vol. 3. (2011) 806, ISBN 978-3-540-88257-2, Springer.

[44] Blackledge J., Coyle E., Kearney D., Norton B., Blackledge J., Coyle E., et al., Estimation of Wave Energy from Wind

Velocity Estimation of Wave Energy from Wind Velocity (2013) .

[45] Beaufort scale, http://www.metoffice.gov.uk/media/pdf/b/7/Fact_sheet_No._6.pdf. (accessed January 23, 2015).

[46] WaveStar., Wave Star Energy (2004), http://wavestarenergy.com/sites/default/files/nei-dk-4501.pdf. (accessed February 8, 2016).

[47] Kramer M.M., Marquis L., Frigaard P., S W.S. a., Allé P., Performance Evaluation of the Wavestar Prototype, 9th Eur Wave Tidal Energy Conf (2011) .

[48] Wavestar projects, http://wavestarenergy.com/projects/ (accessed May 12, 2017).

[49] Syrian Meteorological Departement, Archive data from 1990 to 2012.

[50] Syria Location, https://upload.wikimedia.org/wikipedia/commons/3/3f/Latakia_in_Syria_%28%2BGolan_hatched%29.svg (accessed February 5, 2017).

[51] Hampstead nw3 UK, http://nw3weather.co.uk/ (accessed April 12, 2016).

[52] UK Location, https://upload.wikimedia.org/wikipedia/commons/7/7d/Greater_London_UK_location_map_2.svg (accessed April 18, 2017).

[53] Wind, waves and weather for kitesurfers, windsurfers, surfers and sailors, https://www.windfinder.com/ (accessed March 7, 2016).