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A Novel WSFD Model to Facilitate the Identification of Promising Locations and Appropriate Specifications of WECS in Egypt

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Abstract: In this paper a novel model for wind speed frequency distribution (WSFD) is proposed and tested using the Egyptian Atlas wind data for 29 areas. The accuracy of this model, named 3-M model, is proved to be the same as Weibull model accuracy but with less complexity and lower calculation time. The capacity factor and the cost/kWh generated are derived as function of rated speed of the wind turbine, from which the optimum rated speed of the wind turbine that leads to minimum cost/kWh generated is derived. The results of this analysis can be applied for any country at any site with known wind profile.
Keywords: *Wind Energy, Wind modelling, Capacity factor and Cost factor***.**

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I. INTRODUCTION

Electric power systems around the world are experiencing great changes including the retirement of coal and nuclear power plants, along with the rapid increase in the use of natural gas-fired turbines and variety of renewable energy technologies, such as wind, solar, biomass and geothermal energies [1]. The installed wind energy conversion systems (WECS) represent more than 60% of all the installed renewable energy systems (wind, solar, biomass and geothermal), not counting the hydropower resources. The rate of development of WECs is high compared with the other renewable energy systems. The global installed WECS increased from about 432GW in 2015 to about 487 GW in 2016 [2]. Egypt's role emerged during the past few years as a leader in the field of utilizing wind energy for electrical power generation in the Middle East and Africa. Egypt's declared strategy aims to increase the grid-connected WECS to reach 12% of the national power grid total installed capacity by the year 2020. This means that the installed WECS will reach 7200 MW by 2020 [3]. This will be achieved through state-owned projects (about 2375 MW) and private sector projects (about 4825 MW). The Egyptian government issued several laws to encourage the private sector to invest in WECS installations and to sell the generated energy to the national grid authority with competitive prices, declared by the governmental sectors responsible for electric power transmission and distribution.

This paper is an effort to assist the governmental institutions and the private sector investors in selecting the appropriate areas in Egypt where the installation of WECS can be economically viable. Egypt, with its one million square meters area and about 95 million population lies between latitude 22-32 North and longitude 25-35 East. Its north borders are mainly long coasts extending 1000 km along the Mediterranean sea, its east borders extend 1000 km along the Red sea and about 600 km along the east side of Gulf of Suez and west side of Gulf of Aqaba. The areas along the 2600 km- long coast are characterized by high wind potential, and many of these areas are suitable for wind farm installations. In the first section of this paper a novel simple model is proposed to configure the wind speed frequency distribution for several sites in Egypt depending on two parameters; namely, the prevailing wind speed and its frequency. This novel model is tested for several sites in Egypt and the results compared with those calculated by Weibull algorithm. The obtained results proved the accuracy of the proposed novel simple equation with lower calculation time. This model can be utilized for other sites in different countries by applying the wind speed pattern in these sites. To easy follow this paper, the proposed model is named "3M-model". The second section of this paper utilizes the 3-M model to calculate the expected capacity factor in 29 areas within Egypt. The capacity factor for each area, as its name implies, determines the amount of yearly electrical energy generated (kWh) per kilo-watt WECS installed in this area. In the third section of this paper an estimation of the optimum rated speed of the wind turbine that lead to the minimum cost per kWh generated in the specified area is done.

II. A NOVEL WIND SPEED FREQUENCY DISTRIBUTION MODEL FOR EGYPT

The Weibull probability density function (PDF) has mostly been used to fit wind speed distributions for wind energy applications. The goodness of fit of the results depends on the estimation method that was used and the wind type of the analyzed area. Characterizing the wind speed at a specific location or area is extremely important. This task is complex due to the random nature of the wind, which does not exactly follow any known statistical distribution. The importance of identifying the wind speed distribution is due to its reflection on in the power delivered by a wind turbine generator. The complexity and the long time taken in calculating the wind speed frequency distribution (WSFD) using the Weibull model are avoided in the proposed model in this paper, keeping the same, if not a better, accuracy of the Weibull model.

The proposed model was firstly introduced by the authors of this paper as [4]:

$$\frac{f}{f_p} = \exp\left(\frac{1}{n}\right).\ x\ \exp\left(-\frac{x^n}{n}\right) \qquad (1)$$

where

- n a positive integer of (3,4,5,6,..etc.)
- f frequency of the wind speed
- f_p the frequency of the prevailing wind speed
- x relative wind speed ($x=W/W_p$)
- W wind speed
- W_p the prevailing wind speed

Several versions of the proposed model are compared with the histograms of the measured wind speed distribution for 29 sites published in the wind Atlas of Egypt, [5]. The most accurate model to the majority of sites is when n=6, i.e.

$$\frac{f}{f_p} = \exp\left(\frac{1}{6}\right).\ x\ \exp\left(-\frac{x^6}{6}\right) \qquad (2)$$

Therefore, this model is adopted by the authors in this paper and given the name "3M-model" to distinguish it from other wind speed frequency distribution models. This model can be utilized for other country by applying the wind data available in this country. The simplicity of the 3M model lies in that it deals with only two measured parameters, the prevailing wind speed and its frequency ,and has only one standard shape as shown in Fig. (1).

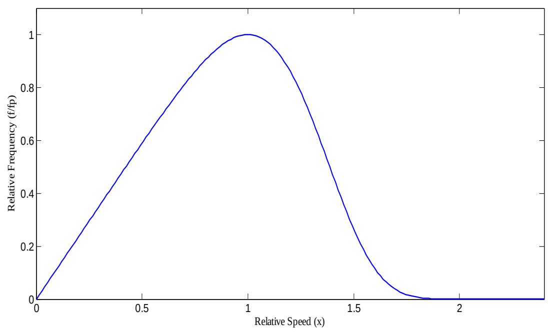
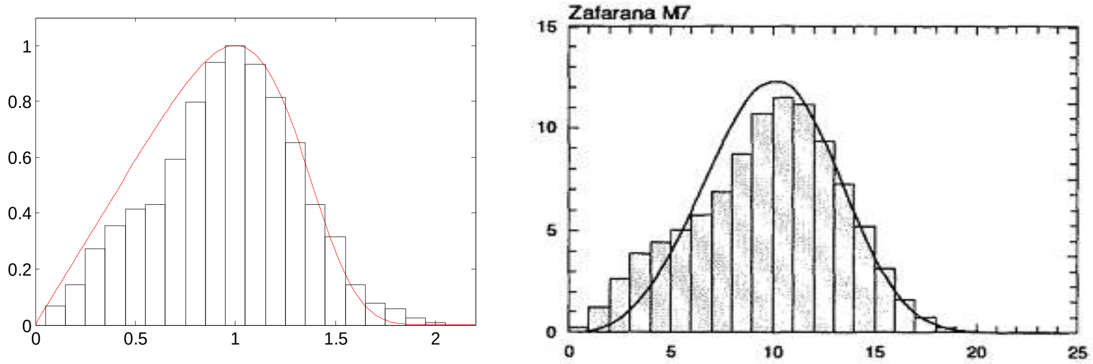


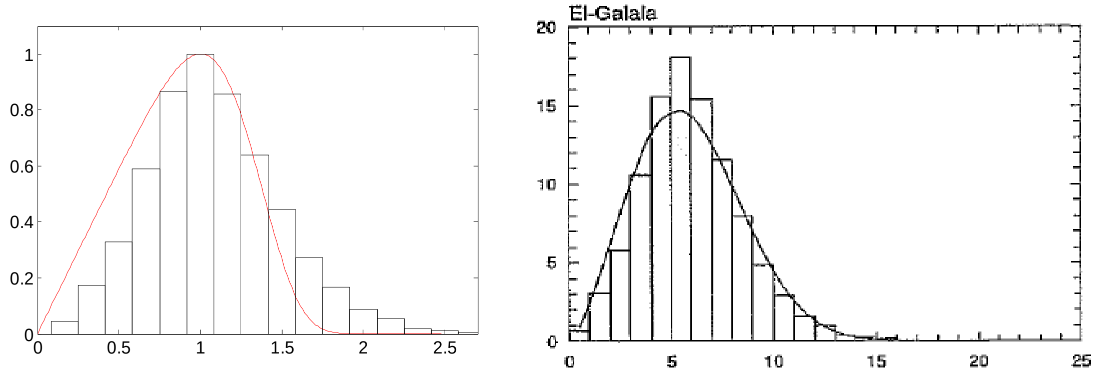
Fig. 1, the relative speed with frequency

A comparison between the 3M model and the Weibull model is shown in the group of figures from Fig. (2) to Fig.(6). The group of figures from Fig. (2a) to Fig. (6a) compare the measured histogram of WSFD with the 3M-model, while the group of figures from Fig. (2b) to Fig. (6b) compare the histogram with the Weibull model. The comparison is in favour with the 3-M model.



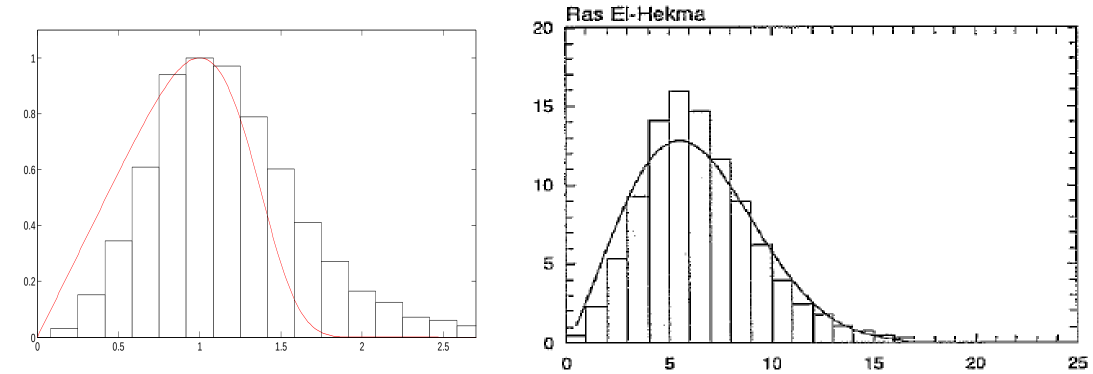
(a) 3 M-model (b) Weibull-model

Fig. 2, the curves of Zafarana



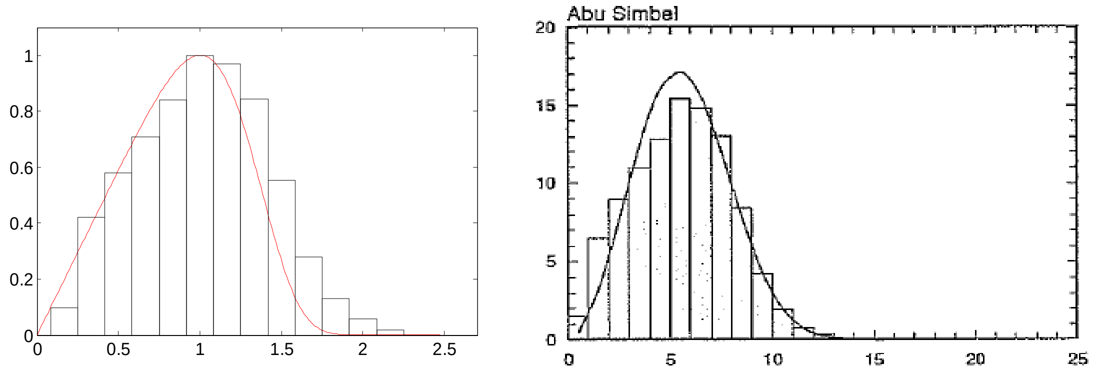
(a) 3 M-model (b) Weibull-model

Fig. 3, the curves of El Galala.



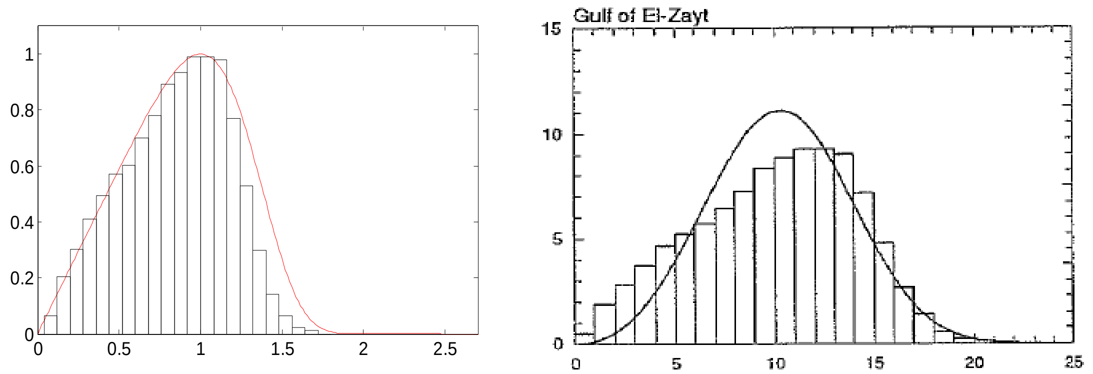
(a) 3 M-model (b) Weibull-model

Fig. 4, the curves of Ras EL Hekma.



(a) 3 M-model (b) Weibull-model

Fig. 5, the curves of Abu Simbal.



(a) 3 M-model (b) Weibull-model

Fig. 6, the curves of Gulf of Zayt.

III. THE CAPACITY FACTOR

The Capacity Factor C_f indicates the amount of energy generated by a specified wind turbine in a site with specific wind pattern. Hence C_f depends on the wind turbine specifications, mainly its rated speed, and the WSFD curve. The wind power converted to mechanical power by the wind turbine at any wind speed W (or the relative speed x) is represented by the wind power curve shown in Fig. (7), and expressed as:

$$P=P_r.(x^2/x_r^2) \quad \text{for } x_r>x \quad (3)$$

and $$P=P_r \quad \text{for } x \geq x_r \quad (4)$$

Where

P= the power at wind speed W (relative speed x)

P_r= rated output power of the wind turbine

x_r is the relative rated speed (W_r/ W_p)

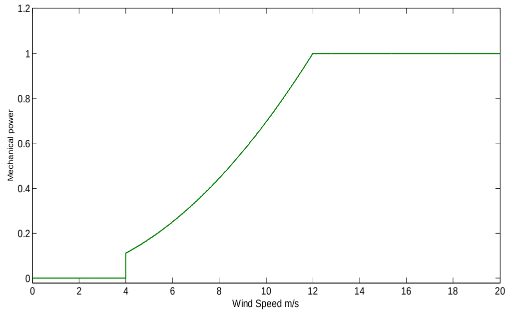


Fig. 7, the mechanical power with wind speed.

The energy generated for a period of time "f.T", were T is the total number of hours per year, is:

$$dE= P.f.T.dW \quad (5)$$

The annual amount of wind energy converted to mechanical energy is:

$$E = \int_{x_c}^{x_o} P.f.T.dW \quad \text{..........} \quad (6)$$

Manipulating equations (2) to (6), the annual total energy generated by the wind turbine is expressed as:

$$E = 1.184\, P_r T f_p W_p \left[\int_{x_c}^{x_r} \frac{x^3}{x_r^2} \exp\left(-\frac{x^6}{6}\right) dx + \int_{x_r}^{x_o} x \exp\left(-\frac{x^6}{6}\right) dx \right] \quad (7)$$

Where,

x_c, x_r, and x_o are the relative cut-in, and cut-out speeds respectively

W_c, W_r, and W_o are the actual cut-in, relative and cut-out speeds respectively.

The annual energy generated by the wind turbine can also be written as:

$$E=P_r.C_f\, T \quad (8)$$

Equating equations (7) and (8), thus:

$$\left(\frac{C_f}{f_p.W_p}\right) = \left[\int_{x_c}^{x_r} \frac{x^3}{x_r^2} \exp\left(-\frac{x^6}{6}\right) dx + \int_{x_r}^{x_o} x \exp\left(-\frac{x^6}{6}\right) dx \right] \quad (9)$$

The function ($C_f/f_p.W_p$) is calculated numerically for different values of xr (0.7 ≤ xr ≤ 1.6), as shown in Fig. (8).The relative value of the cut-in speed is taken as 0.3, which is an acceptable value practically, and the function is calculated for three values of the cut-out speed (xo=2, 2.5, and 3). There are no significant differences between these curves.

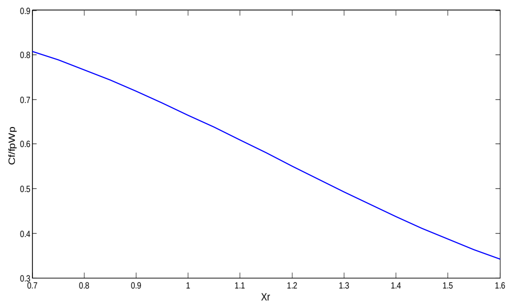


Fig. 8, ($C_f/f_p.W_p$) versus x_r.

Examining the function $(C_f/f_p.W_p) = f(x_r)$ from Fig. (8), it can be approximated as a linear function with reasonable accuracy. Using curve fitting algorithm, it is expressed as:

$$\left(\frac{C_f}{f_p.W_p}\right) \cong -0.53x_r + 1.186$$

And the capacity factor can be written as:

$$C_f \cong f_p.W_p(-0.53x_r + 1.186) \qquad (10)$$

IV. OPTIMUM RATED SPEED

The cost per installed kilowatt of the wind turbine manufactured by the same company, differ with the variation of the wind turbine rated speed. Obviously, the price of wind turbines manufactured by different companies cannot be compared due to variety of reasons, e.g. design of the wind turbine, material of different parts, cost of labour, and the country of manufacturing.

The authors of this paper examined a number of wind turbines manufactured by several companies regarding the cost per installed kW and the rated speed. It is concluded that, to a certain extent, the cost per installed kW multiplied by the rated speed is approximately the same. Therefore, with increase in rated speed, the cost per installed kW will decrease and the capacity factor will decrease also. i.e. the total annual amount of energy generated by the wind turbine will decrease. Therefore, the existence of an optimum value for the rated speed giving the lowest cost of the kWh generated by the wind turbine is expected. The cost per kWh in mills (10^{-3} USD) generated can be expressed as [6]:

$$\text{cost/kWh} \cong \frac{I}{C_f}(0.084r + 0.114\,m + 0.0066) \quad \text{mills} \qquad (11)$$

where

I the total capital investment in the WECS in USD per installed kW

r the annual interest rate

m the fraction of the capital investment needed per year for operation and maintenance of the WECS

As previously mentioned, the cost per installed kW of the wind turbine, which is the main component of the WECS, can be considered inversely proportional to the rated speed. Consequently the total capital investment per installed kW is also inversely proportional to the rated speed, therefore equation (11) can be written as:

$$\text{cost/kWh} = \frac{k}{W_r C_f} \qquad (12)$$

Where k is a constant

Combining equations (10) and (12) the cost/kWh is expressed as:

$$\text{cost/kWh} = \frac{k}{(-0.53W_r^2 + 1.186\,W_r)f_p} \qquad (13)$$

Differentiating eq. (13) and equating the derivative to zero, the minimum value of the cost/kWh is obtained at:

$$W_{rop} = 1.12\,W_p \qquad (14)$$

$$(\text{cost/kWh})_{min} = \frac{k}{0.664W_p^2 f_p} = k_i C_i \qquad (15)$$

Where $$C_i = \frac{1}{W_p^2 f_p} \qquad (16)$$

C_i is considered as cost indicator when comparing different sites for installation of WECS. The lower value of C_i indicates a lower cost of the kWh generated in the site, provided that the wind turbine rated speed is properly chosen.

The capacity factor corresponding to the optimum rated speed can be expressed from equations (10) and (14) as follows:

$$C_{fop} \cong 0.59 f_p.W_p \qquad (17)$$

V. THE PROMISING AREAS FOR WIND ENERGY UTILIZATION IN EGYPT

The optimum rated speed of the wind turbines, the corresponding capacity factor, and the cost indicator for 29 areas in Egypt are calculated using equations (14), (16), and (17). These areas are classified in three categories, namely; high, reasonable, and low potential sites. The calculated results are given in Tables (1), (2), and (3). The areas within the same category are ordered according to their economic viability, i.e. the least cost of the kWh generated by the wind turbine. The tabulated indicators are viable for comparison between different areas. However, for each chosen area, deeper analysis and calculations are needed for each site within this area. The tables are of help to investors for preliminary selection of the most appropriate location for WECS installation. These tables are also useful for comparison between different locations based on the annual generated kWh, on the relative cost of each kWh generated (C_i), as well as other factors such as the cost of land, the distance to the national grid,..etc. Also regarding the optimum rated speed of the wind turbine, it is clear that no manufacturers will tailor the wind turbine to have its rated speed at its optimum value, but the rated speed of the selected wind turbine should be the nearest to the optimum value, according to what is available on the market. The minimum cost of the kWh generated by the wind turbine can be calculated, when needed, from equations (11) and (17) as follows:

$$\text{cost/kWh} \cong \frac{I}{0.59\, f_p \,.W_p}(0.084r + 0.114\, m + 0.0066) \qquad (18)$$

For any rated speed W_r, the cost /kWh may be calculated from equations (10) and (11) as follows:

$$\text{cost/kWh} \cong \frac{I}{f_p}\,\frac{(0.084r + 0.114\, m + 0.0066)}{(1.186 W_p - 0.53\, W_r)} \qquad (19)$$

The cost /kWh generated by the WECS and delivered to the national grid will be 5%-10% higher due to the losses in WECS components (gearbox, generator, and converter) and due to the transmission line connecting it to the national grid.

Table 1: High wind potential areas

No.	Site	Location N/E	W_p m/s	f_p %	$W_{r\,op}$	$C_{f\,op}$	$C_{i\,op}$
1	Jabal El-Zeyt NW	27^{0}54’21.5’’/ 33^{0}20’10.5’’	12	11.1	13.44	0.7859	0.0626
2	Jabal El-Zeyt	27^{0}47’23.9’’/ 33^{0}28’23.3’’	12.5	9.25	14	0.6822	0.0692
3	Zafarana M7	29^{0}10’22.2’’/ 32^{0}37’44.9’’	11	11.4	12.32	0.7399	0.0725
4	Abu DaragNW	29^{0}17’15.0’’/ 32^{0}34’53.4’’	10	12.9	11.2	0.7611	0.0775
5	Saint Paul	28^{0}48’12.6’’/ 32^{0}44’23.5’’	10	12.1	11.2	0.7139	0.0826
6	Abu Darag	29^{0}16’49.4’’/ 32^{0}36’3.3’’	10	12	11.2	0.708	0.0833
7	Ras Ghareb	28^{0}20’25.7’’/ 33^{0}1’37.0’’	10	11.2	11.2	0.6608	0.0893
8	Zafarana	29^{0}6’48.7’’/ 32^{0}36’38.9’’	10	10.9	11.2	0.6431	0.0917

Table 2: Reasonable wind potential areas

No.	Site	Location N/E	W_p m/s	f_p %	$W_{r\,op}$	$C_{f\,op}$	$C_{i\,op}$
1	Shark El-Ouinat	22^{0}27’31.2’’/ 28^{0}41’51.1’’	8	15.6	8.96	0.7363	0.1002
2	Dakhla South	24^{0}37’19.0’’/ 29^{0}6’22.8’’	7	18.1	7.84	0.7475	0.1128
3	Ras Sedr	29^{0}25’57.8’’/ 32^{0}47’25.5’’	8	13.2	8.96	0.623	0.1184
4	Hurghada	27^{0}11’5.1’’/ 33^{0}48’7.9’’	7	16	7.84	0.6608	0.1276
5	El-Suez	29^{0}52’27.8’’/	6	20.8	6.72	0.7363	0.1335

		32^{0}28'18.8''					
6	Kharga	25^{0}46'20.3''/ 30^{0}39'40.1''	7	13.7	7.84	0.56.58	0.149
7	El-Galala	31^{0}1'43.6''/ 28^{0}10'59.7''	6	18	6.72	0.6372	0.1543
8	Nuweiba	28^{0}58'53.2''/ 34^{0}41'6.8''	6	17.4	6.72	0.616	0.1596
9	Alexandria	31^{0}10'55.2''/ 29^{0}57'7.2''	6	17.4	6.72	0.616	0.1596
10	El-Mathany	31^{0}23'25.9''/ 26^{0}48'2.5''	6	17.2	6.72	0.6089	0.1615
11	Hurghada WETC	27^{0}18'59.3''/ 33^{0}42'3.5''	7	12.6	7.84	0.5204	0.162
12	Katamaya	29^{0}54'21.2''/ 31^{0}46'8.4''	6	16.8	6.72	0.5947	0.1653
13	Ras El-Hekma	31^{0}12'21.4''/ 27^{0}52'0.3''	6	16	6.72	0.5664	0.1736
14	Abu Simbel	22^{0}25'49.1''/ 31^{0}33'25.7''	6	15.4	6.72	0.5452	0.1804
15	Sidi Barrani	31^{0}37'36.5''/ 25^{0}54'29.8''	6	15.1	6.72	0.5345	0.184

Table 3: Low wind potential areas

No.	Site	Location N/E	W_p m/s	f_p %	$W_{r\ op}$	$C_{f\ op}$	$C_{i\ op}$
1	Port Said	31^{0}10'5.8''/ 32^{0}18'4.6''	5	22.2	5.6	0.6549	0.1802
2	Kosseir	27^{0}3'29.3''/ 27^{0}59'20.7''	5	14.6	5.6	0.4307	0.274
3	Kosseir (62465)	26^{0}6'44.0''/ 34^{0}15'21.5''	4	20.5	4.48	0.4838	0.3049
4	Nabq	28^{0}7'45.2''/ 34^{0}25'46.3''	5	12.8	5.6	0.3776	0.3125
5	Asswan	23^{0}57'55.1''/ 32^{0}49'30.4''	4	19.1	4.48	0.4508	0.3272
6	Farafra	29^{0}25'57.8''/ 32^{0}47'25.5''	3	24.5	3.36	0.4337	0.4535

VI. CONCLUSION

A novel wind speed frequency distribution model (3M-model) is proposed in this paper. This model is a function of only easily measurable parameters of the wind data, namely; the prevailing wind speed and its frequency over a year. The 3M-model is tested using the measured data represented on histograms of 29 areas in Egypt, covering most of the Egyptian territory. The 3M-model showed, if not better, at least the same accuracy as the Weibull model. The 3M-model gives a unified curve, and it can be tested and verified for the wind data available for other countries.

1- The capacity factor and the cost per kWh generated by wind turbines, to be installed in any of these areas, are given as functions of the rated speed of these turbines. The optimum rated speed that leads to minimum cost /kWh generated is derived, which can be used as a guide in selecting the wind turbine for a selected site.

2- The optimum rated speed and the corresponding capacity factor for wind turbines that can be installed in 29 areas scattered on the Egyptian territory, are calculated and presented in three tables for the high, reasonable, and low wind potential areas. The selected areas are ordered in the tables according to their economic viability, i.e. the area of the least cost of generated kWh followed by the higher cost area.

3- All the indicators resulting from this analysis are beneficial as a guide for comparison between different areas in Egypt for wind energy utilization. Once the area is chosen and the specific site within this area is selected, according to the above mentioned contributions of this paper, more detailed analysis has to be done.

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