Theoretical investigation and mathematical modelling of a wind energy system
Case study for Mediterranean and Red Sea

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Abstract

Fossil fuel is getting more and more expensive every year, and is not readily available in some remote locations. Today, wind power can be harnessed to provide some or all of the power for many useful tasks such as generating electricity, pumping water and heating a house or barn.

Egypt has two coastal areas that show significant promise for wind energy exploitation; the north coast on the Mediterranean Sea and the east coast on the Red Sea. The wind energy is utilized along the coast of Mediterranean Sea in Egypt on few occasions, while from national programs for wind energy utilization in Egypt, at the Red Sea coast, the master plan calls for 600 MW which are expected to be achieved by the year 2005. The contribution of fossil fuels (oil and natural gas) to electricity production in Egypt accounts for about 79% of total production, while 21% is hydro-power. The demand is expected to grow rapidly to meet the large requirements of future projects. Studies showed that there is an additional need of annual electricity generation capacity around 1000 MW/year up to 2017 [14].

The purpose of this thesis is to present a new analytical method for the calculation of the wind energy potential available along the north coast of the Mediterranean Sea and the east coast of Red Sea in Egypt and moreover, it estimates the possible electrical power generated by large wind turbines and the expected cost in € cent/kWh for the power level of 2000 kW. It is hoped that the data analysis will help to identify good sites in Egypt for new wind turbine installations. This evaluation is hoped to trigger the use of large wind turbines at the selected sites along the coasts of Mediterranean Sea and Red Sea in Egypt.

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F(v)	Weibull cumulative distribution function
v	Wind speed (m/s)
k	Shape parameter
c	Scale parameter (m/s)
R(v)	Rayleigh cumulative distribution function
v_x	Long term average wind speed (m/s)
v_i	Observed mean monthly wind speed (m/s)
z_a	Desired height in meter
n	Power law exponent (coefficient)
ρ	Standard air density (kg/m^3)
$\overline{V}$	Mean wind speed (m/s)
$\overline{\rho}$	Corrected mean monthly air density (kg/m^3)
$\overline{P}$	Monthly average air pressure (N/m^2)
$\overline{T}$	Monthly average air temperature (K)
R_d	Gas constant for dry air (R_d = 287 J/kg.K)
$\mathbf{P}_{wind}$	Specific mean wind power available in the wind stream (W/m^2)
$\mathbf{P}_{10}$	Specific mean wind power available in the wind at a height of 10 meter (W/m^2)
$\mathbf{P}_{mo.}$	Specific mean wind power per month (kW/m^2. month)
$\mathbf{P}_h$	Specific mean wind power in the wind at any height (W/m^2)
V_h	Wind speed at any height (m/s)
V_{10}	Wind speed at the standard height of 10 meter (m/s)
α	Roughness factor

V_{ci} Cut-in wind speed (m/s)

V_{co} Cut-out wind speed (m/s)

V_r Rated wind speed (m/s)

P_r Rated power (kW)

PLF Plant load factor

WECS Wind energy conversion system

C_f Capacity factor

E_{out} Total energy delivered over a period (kWh/y)

PVC Present value of costs

I Turbine price plus 20% for the civil work (Euro)

C_{omr} Operation, maintenance and repair cost (Euro)

S Scrap value (Euro)

r Interest rate

i Inflation rate

t Lifetime of the wind machine (20 years)

Chapter 1

Introduction

1.1 General introduction

Wind is an abundant resource, available in nature that could be utilized by mechanically converting wind power into electricity using wind turbines [1]. Since earliest recorded history, man has been harnessing the energy of the wind. There is evidence that energy was used to propel boats along the Nile River in Egypt by the Egyptians 5000 years ago.

The new energy sources should of course be "clean and renewable". Solar and wind energy have these features and offer attractive alternatives. These sources are freely available, solar being limited only by latitude, time of year, cloud cover and atmospheric turbidity, while wind power is limited by season, time of day and the physical features of the area (topography) which may obstruct the flow of air. This means that it depends on the site characteristics, so its variability is stronger in a country such as Egypt with its long coastline. Wind energy is an indirect form of solar energy and meteorologists estimate that about 1% of the incident solar radiation is converted into wind energy which is a very competitive source of energy for many applications in many locations [2].

Wind power is one of the most attractive sources of renewable energy; it is also a potentially valuable source of energy in the Third World in general and in Egypt in particular as Egypt is totally dependent on exported energy. Egypt's energy resources are limited in oil and petroleum products and high limited in natural gas, however, is rich in renewable energy resources such as hydro, solar, geothermal and wind. Of these, wind seems to be the most suitable renewable energy resource for electricity production.

Wind energy in Egypt has not been studied thoroughly. Some attempts have been made to analyse the potential in Egypt [2–10,13,14] and some experimental work [11,12,17] has been conducted. A wind energy converter, industry and manufacturing of wind turbines blades are not available in Egypt. All the installed systems were imported.

A review study of the previous work and research activities in wind energy in Egypt and its field applications is done in the next section.

1.2 Previous work

D. S. Renne and Elliott (1986-1987) [3,4], The authors studied the wind energy resource assessment activities in Egypt. The study describes the wind resource assessment activities being conducted in Egypt as part of the "Renewable Energy Field Test Program". Historical wind data have been summarized and measurements that have been conducted as part of the program have been analyzed. The authors concluded the following: these studies confirm and further quantify the existence of high wind resource regions in Egypt. The highest resource appears to be the coastal regions of the Gulf of Suez. Much of the Mediterranean coastline also shows strong winds speeds or strong thermal/pressure gradients. With a measurement program this finding has been confirmed for the western coastal regions.

M. Rizk (1987) [5], He studied the wind characteristics and available wind energy in Egypt. For three sites in Egypt, differing in natural conditions but having almost the same wind characteristics. Daily wind-speed distribution for every month of the year is presented. The average wind speeds during the year were also presented. The research concluded that at three sites in Egypt, El-Khargha, El-Suez and Mersa Matruh the annual mean wind speed is between 4.6 and 5.5 m/s at a height of 20 m above ground level. These findings result in a mean annual specific energy is between 638 and 1127 kWh/m^2. Annual duration of wind speed of 4 m/s ranges between 5650 and 7700 h. With respect to this analysis and according to the natural conditions of each site, a small WEC-Farm is suggested for Mersa Matruh station. The energy should be used especially for water pumping, irrigation and small agricultural industries.

H. M. Abu El-Eizz et al. (1991) [6], They studied the wind characteristics and energy potentials of some selected sites in the Yemen Arab Republic and the Republic of Egypt. Wind regimes as observed in four meteorological stations in Yemen and eight stations in Egypt are presented in the form of speed and power duration curves as well as in the form of speed and power frequency curves. The study concluded that based on the analyzed data, the utilization of wind for power production purposes is promising particularly in the coastal stations of both countries. In the considered locations and allowing for aerodynamic imperfections and mechanical as well as electrical losses, the extracted annual amounts of wind energy (evaluated for a wind system conversion efficiency of 40%) range from 103 to 576 kWh/m^2. Also by using the correlation relation designers can optimize the selection of wind turbines by relating the mean wind speed of the location to the optimum rated wind speed (the speed at which annual output is maximum).

Al-Motawakel MK et al. (1991) [7], Studied the performance of different types of renewable power supply systems. The study is based on the three sites in the Republic of Egypt and three selected sites in the Yemen Arab Republic. Wind regimes are observed in three meteorological stations in Yemen and three stations in Egypt. This paper attempts to present the performance of a hybrid system formed by combining PV generators with wind energy systems. The authors tried to establish a reliable combined scheme based on both the complementary availability of the energy sources and the load demands. Dimensionless parameters are then developed for judging the performance of hybrid power generating systems compared with the performance of PV generating systems sized to meet the same load demand. Finally, the study describes the optimal system size as a function of weather conditions of the site, technical characteristics of the components involved in collecting and storing the generated electricity, and the load demands. The researcher concluded that the combination of PV and wind generators is, in the considered sites, very effective because of additional energy storage with batteries.

A.I. Salem et al. (1993) [8], Studied the effects of different heights, wind speeds and ventilation coefficients at some sites in Egypt. The study is based on data from three radio-stations Mersa Matruh (altitude of 25 m), Helwan (altitude of 139.3 m) and Aswan (altitude of 191.1 m). They studied the monthly average wind speeds, the mixing layers and the ventilations coefficients from a data set obtained from the Meteorological Authority of Egypt. They estimated the mixing heights directly from the temperature profiles. The study concluded that Mersa Matruh and Helwan regions are pollution prone areas in May during the early morning. Aswan region can have a high pollution potential during the afternoon all over the year. The wind speed has a pronounced effect on the ventilation coefficients especially in Winter and Autumn, at Mersa Matruh region. The study can be taken as a data base for planning the emission schedule at Mersa Matruh, Helwan and Aswan.

Laila Saleh (1994) [9], Studied the national programs for wind energy utilization in Egypt. The study presents energy policy and describes the frame work of energy utilization, with special emphasis on wind energy plans and programs, to illustrate the role wind energy can play in the sustainable energy development programs. Moreover the paper presents the national five year plan objectives that calls for 70 MW wind farms at the area of the Red Sea, based on national investment together with 150 MW wind farms in the same area based on private investment. The study concluded that based on the analyzed data from national programs for wind energy utilization in Egypt, at the Red Sea coast, the master plan calls for 600 MW to be achieved by the year 2005.

A. I. Salm (1995) [10], Studied the characteristics of surface wind speeds all over Egypt. He classified Egypt into six zones according to the climatic conditions and topography. Monthly and annual average of wind speed, the percentage frequency of occurrence, the diurnal variations were calculated and discussed in form of characteristic curves and diagrams that represent the different zones and seasons. Annual seasonal wind roses were also designed. The research concluded that the chances of having wind speeds less than 3.1 m/s is small all over Egypt. The Mediterranean Sea and Red Sea areas are the windiest regions.

Fouad Kamel (1995) [11], Investigated a small locally produced windmill for electric power generation as a model for small industry. The study used a 3-bladed 7 kW windmill which has been designed and implemented. This project is serving as a model for the local production of such technology in small industry. Electrical and mechanical design descriptions and general considerations were also presented. The researcher concluded that the Weibull and Rayleigh probability models are useful tools for wind energy density estimations but not quite appropriate to fit actual wind data with low mean speeds. The author suggested using actual wind data (histogram) or looking for a better fit by other models of the probability function.

N. G. Mortenson et al. (1996) [12], Studied the wind atlas for the Gulf of Suez, Arab Republic of Egypt. Measurements and modelling was related to the time interval 1991–95. The primary purpose has been to establish reliable and accurate wind atlas data sets for this area. With mean wind speeds and energy densities of 9–12 m/s and 600–1350 W/m^2, respectively, at a height of 25 m over roughness class 0 (water), the wind resources of the Gulf of Suez are comparable to those of the most favourable regions in NW-Europe. The wind atlas methodology has proven to be very useful in the extreme climatic conditions of the desert. Applied with care, it can provide accurate predictions of the wind climate sites for wind turbines along the Gulf of Suez. The research concluded that the inland potential in the Gulf of Suez near Zafarana is therefore twice as high as the inland potential close to Vindeby (Denmark).

A. B. Mayhoub et al. (1997) [2], Studied a survey of the assessment of the wind energy potential in Egypt. The study was based on wind data from 15 anemometer meteorological stations, distributed all over Egypt. For these stations the wind data are summarized. The analysis showed that in Egypt, it is not preferable to estimate wind power values by using a Weibull distribution. The research concluded that along the Red Sea coasts, the annual wind energy potential is found to be high, which indicates that these coastal stations are possible locations for wind energy utilization. On both the Mediterranean coast and in the interior parts of Egypt, some stations have a low wind energy level, while others are found to be rather high.

H. K. Ahmed et al. (2001) [13], Studied the utilization of wind energy in Egypt in remote areas. The study based on three costal and remote desert areas. The available wind energy data at the north coast, the Red Sea coast and east of Qweinat were collected, analyzed and are presented in a form useful wind energy study. Results have shown that there are two ways in which wind power may be used economically on a significant scale. The first is by means of turbines of medium size (100–200 kW capacity) used in conjunction with other forms of power generation plants for the supply of electricity to isolated communities on the north coast of Oweinat which can not be supplied economically from the main network. The second possibility lies in the employment of large wind-driven generators each having a capacity of at least 1000 kW. These units would be located at the Red Sea coast (from Zafarana to Hurghada), fairly close to supply networks, into which they feed their outputs.

M. N. El-Kordy et al. (2002) [14], Studied the economical evaluation of electricity generation considering externalities. A full analysis for the cost of the kWh of electricity generated from different systems actually used in Egypt is presented. Also renewable energy systems are proposed and their costs are analyzed. The analysis considers the external cost of emissions from different generation systems. A proposed large scale PV plant of 3.3 MW, and a wind farm 11.25 MW grid connected at different sites in Egypt are investigated. The research concluded that the comparison results showed that wind energy generation in Egypt has the lowest cost, followed by a combined cycle-natural gas fired system. A photovoltaic system still uses a comparatively expensive technology for electricity generation.

A. S. Ahmed Shata and R. Hanitsch (2006) [15], Studied the evaluation of wind energy potential and electricity generation at the coast of the Mediterranean Sea in Egypt. Wind data from 10 coastal meteorological stations along the Mediterranean Sea in Egypt have been used for statistical analysis to determine the wind characteristics. It found that three stations show annual mean wind speed greater than 5.0 m/s. Numerical estimations using measured wind speeds and frequencies to calculate the two Weibull parameters were carried and two methods were applied. Also the wind power densities for heights of 30–50 m were calculated for all stations. A technical assessment has been made of the electricity generation using two commercial turbines (300 kW and 1 MW) considering an installation at the three promising sites namely: Sidi Barrani, Mersa Matruh, and El Dabaa. The research concluded that the expected yearly energy gain from the turbine with 1 MW, at El Dabaa is 2718 MWh/y and the specific cost per kWh is 0.02 €, which was found to be very competitive compared with other stations along the coast of Mediterranean Sea in Egypt.

A. S. Ahmed Shata and R. Hanitsch (2006) [16], The potential of electricity generation at the east coast of Red Sea in Egypt was studied. Wind characteristics have been analyzed based on long-term measured data of monthly mean wind speed of 7 meteorological stations along the east coast of Red Sea in Egypt. It was found that the windiest stations (Region A) namely (Zafarana, Abu Darag, Hurghada and Ras Benas) have annual mean wind speeds (7.3, 7.2, 6.4 and 5.5 m/s) at 10 m height, respectively. In order to identify the Weibull parameters for all stations two different methods were applied. Also the corrected annual wind power density at heights (50–70) m was obtained for all stations. Moreover, calculations show that the four stations in (Region A) have a huge energy potential available (430–1000 W/m^2) at 70 m height, while Quseir and Suez stations (Region B) have good wind power density (170–190 W/m^2) at 50 m height. The yearly energy output, capacity factor and the electrical energy cost of kWh produced by the two different turbines (1 MW and 600 kW) considered in two regions (A&B) were estimated. The authors concluded the following: The expected electricity generation costs of 1 kWh in four stations of (Region A) along the Red Sea in Egypt is less than 2 € cent/kWh, which is very competitive compared to the actual tariff system.

Mohammed G. Khalfallah et al. (2007) [17], Studied the wind turbines power curve variability. A comprehensive measurement programme was carried out at a 300 kW Nordtank stall-regulated horizontal axis wind turbine. This turbine was erected at the test station for windmills by «Hurghada Wind Energy Technology Centre». To the extent necessary to understand the measurement carried out, all experimental set up systems must be described. This paper describes the annual wind speed variability in Hurghada city for the period 1973–2001. The wind speed and direction were measured at the latitude of masts as 10, 24.5, and 31 m. These stations operated since 1981. The wind data were recorded from the instruments with a scanning rate of about 2 Hz and the data were subsequently stored as consecutive 1–h average values. Simultaneously, various types of monthly statistics were accumulated. Also the effect of the wind variability on the power curve at Hurghada farm wind turbines is discussed. The research concluded that if the annual mean wind speed varies by ±10% around a long-term value the corresponding natural variability of the available wind energy is about ±25%.

A. S. Ahmed Shata and R. Hanitsch (2007-2008) [18,70], Studied the application of electricity generation along the western coast of Mediterranean Sea in Egypt. The aim of the study was to identify suitable sites for large wind turbines in the extreme northwest of Egypt along the Mediterranean Sea. A technical and economic assessment has been made of the electricity generation using wind turbines located at three promising potential wind sites: Sidi Barrani, Mersa Matruh and El Dabaa. These contiguous stations along the coast have an annual mean wind speed greater than 5.0 m/s at a height of 10 m. Weibull parameters and the power law coefficient (n) for all seasons have been estimated and used to describe the distribution and behaviour of seasonally wind speed at these stations. The three stations have a high wind power density which are in the range from 340–425 to 450–555 W/m^2, at the heights of 70–100 m, respectively. In this paper an analysis of the cost of the kWh of electricity generation from two different systems was made one using a relatively large single wind turbine of capacity of 2 MW and the other by using 25 small wind turbines of 80 kW arranged in a wind farm of 2 MW total power. The yearly energy output of each system at each site was determined and the electricity generating costs in each case was also determined and compared with the generating costs of generating electricity using diesel oil, natural gas and photovoltaic system furnished by the Egyptian Electricity Authority. The authors concluded the following: these studies confirm that the single wind turbine 2 MW was found to be more effective than the wind farm. For all three envisaged stations the electricity production cost was found be less than 2 € cent/kWh which is about half the specific cost of the wind farm. Moreover, the expected cost of electricity generation by using a single 2 MW wind turbine at the three stations was found to be very competitive with the cost of kWh produced by the "Egyptian Electricity Authority".

A. S. Ahmed Shata and R. Hanitsch (2008) [19], Studied the electricity generation and wind potential assessment at Hurghada, Egypt. The main aim of this paper was to present a new analytical method to choose suitable large wind turbines with low-rated wind speed and high capacity factor at Hurghada city and to estimate the expected cost in € cent/kWh for the power level of 2000 kW. The WASP program was used to calculate the values of wind speed frequency for the station, their seasonally values have been estimated and compared with measured data over 23 years for this site. Weibull parameters and the power law coefficient (n) for all seasons at different heights (10–70 m) have been estimated and used to describe the distribution and behavior of seasonal wind speed and their frequencies at Hurghada. Also, the monthly plant load factor (PLF) has been estimated of a 1000 kW turbine considered for this site. The variation of the annual capacity factor with rated wind speed for 10 different wind turbines has been studied. The research concluded that the use of wind turbines with lower rated speeds will produce more energy in a year than wind turbines with higher rated speeds, also the capacity factor is greater than with wind turbines characterized by lower rated wind speeds. The important result derived from this study encourages the construction of wind farms at Hurghada for electricity generation using large wind turbines each having a capacity of greater than 1000 kW and they recommend usage of the wind turbine model "Repower MM82" with a capacity 2 MW at 100 m hub height. It has a rated speed of 13 m/s and is competitive with other commercial wind turbines of 2000 kW capacity. The expected electricity generation costs of 1 kWh using this turbine was found to be 1.26 € cent, which is a very competitive price compared to the actual tariff system.

Chapter 2

Mathematical modeling

2.1 Wind speed frequency distribution

2.1.1 Weibull distribution

It is one of the most flexible distribution that can be used to represent various types of physical phenomena. It is important to know the number of hours per month or per year during which the given wind speeds occurred, i.e. the frequency distribution of the wind speeds. When the percentage frequency distribution (F%) is plotted against the wind, the frequency distribution emerges as a curve. The top of this curve being the most frequent wind speed. This frequency distribution is used also to identify the most suitable site for the wind turbine. The Weibull distribution (named after the Swedish physicist W. Weibull, who applied it when studying material strength in tension and fatigue in the 1930s) provides a close approximation to the probability laws of many natural phenomena [20, 21].

As mentioned above, the Weibull distribution gives a good match with the experimental data. This is also mentioned in many references [22–28]. This distribution is characterized by two parameters: the shape parameter k (dimensionless) and scale parameter c (m/s). A typical wind distribution is presented in annex **A**. The effect of the shape parameter k on the distribution is given in annex **B**.

Recently Justus, Lysen, Darwish, Som, Jamil, Shabbaneh and Vogiatzis, references [22–28], have shown four different methods for the estimation of

k and c parameters. The Weibull cumulative distribution function is written mathematically as [25, 29]

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2–1}$$

Where F(v) is the Weibull cumulative distribution function,

v denotes the wind speed (m/s),

k is the shape parameter and c is the scale parameter (m/s).

2.1.2 Rayleigh distribution

One should note that the Rayleigh distribution is a special case of Weibull distribution, which has found to typically represent the wind speed frequency distributions at most cases. In the Rayleigh distribution, the shape factor k is assumed to have a value of 2 (i.e. k=2). So the Rayleigh cumulative distribution function is expected mathematically as [22]

$$R(v) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{v}{v_x}\right)^{2}\right] \tag{2–2}$$

Where R(v) is the Rayleigh cumulative distribution function,

v_x is the long term average wind speed (m/s).

2.1.3 Estimation of Weibull parameters

In this study to estimate the Weibull parameters from the obtained data the following methods are applied [30]:

(a) *Method 1*: Weibull probability paper.

(b) *Method 2*: Maximum likelihood estimation.

In Method 1, with a double logarithmic transformation, Equation (2–1) can be written as

$$\ln\left[-\ln\left(1-F(v)\right)\right] = k \ln v - k \ln c \tag{2–3}$$

Plotting ln v against ln [– ln (1 – F(v))] should yield a straight line. The gradient of the line is k and the intercept with the y–axis is $-k \ln c$.

In Method 2, we apply the principle of maximum likelihood. Recently [31] a simple estimating procedure has been introduced to estimate the parameter k by the following formula:

$$k = \frac{\pi}{\sqrt{6}}\left[\frac{n(n-1)}{n(\sum \ln^2 v_i) - (\sum \ln v_i)^2}\right]^{0.5} \tag{2–4}$$

Then the parameter c is found by using this estimate of k in the following equation:

$$c = \left(\frac{\sum \ln v_i^{\;k}}{n} \right)^{1/k} \qquad (2\text{–}5)$$

Where v_i (i = 1, 2, 3, …….., n) are the observed mean monthly wind speeds.

2.2 Power law coefficient

Justs and Mikhail [24] recommended usage of the following equations when the Weibull's parameters (say c_a and k_a) can be evaluated at any desired height (z_a) in meter height, based on the records at the standard anemometer height of 10 m by the following equation [32]:

$$k_a = k_{10}[1–0.0881 \ln (z_a/10)]^{-1} \qquad (2\text{–}6)$$

$$c_a = c_{10}(z_a/10)^n \qquad (2\text{–}7)$$

$$n = [0.37–0.0881 \ln c_{10}] \qquad (2\text{–}8)$$

Where n is the power law exponent (coefficient).

2.3 Wind power estimation

The average specific power available in a cross-sectional area (A) perpendicular to the wind stream moving at speed V (m/s) is calculated and expressed per unit area as follows [33,34]:

$$\mathbf{P}_{wind} = \frac{1}{2}\,\rho\,\overline{V}^{3} \qquad (\mathrm{W/m^2}) \qquad (2\text{–}9)$$

Where ρ is the standard air density (ρ = 1.225 kg/m^3 dry air at 1 atm and 15 ^{0}C),

$\overline{V}$ is the mean wind speed (m/s).

On the other hand, the density of the air is an important parameter related with pressure and temperature, which changes the efficiency of the wind turbines. Then the corrected mean monthly air density $\overline{\rho}$ (kg/m^3) is estimated as follows [35]:

$$\overline{\rho} = \frac{\overline{\mathrm{P}}}{\mathrm{R_d}\overline{\mathrm{T}}} \qquad (2\text{–}10)$$

Where, $\overline{\mathrm{P}}$ is the monthly average air pressure (N/m^2),

$\overline{\mathrm{T}}$ is the monthly average air temperature (K),

R_d is the gas constant for dry air (R_d = 287 J/kg.K).

Once the corrected power available in the wind at a height of 10 m, can be calculated as follows:

$$\mathbf{P_{10}} = \frac{1}{2}\bar{\rho}\bar{V}^{3} \quad (\text{W/m}^2) \tag{2–11}$$

In addition, for calculating the mean power density over a long time T for one month. If we take 30 days per month we end up with the following equation, where the available mean power at 10 m per month is given by [36]:

$$\mathbf{P_{mo.}} = \frac{720}{1000}\,\frac{1}{2}\bar{\rho}\bar{V}^{3} \ (\text{kW/m}^2\text{. month}) \tag{2–12}$$

However, for a height less than 100 m, to estimate the wind speed at any height (h) by using the wind speed at the standard height, recommended by the World Meteorological Organization (WMO), is 10 m above the ground level, Justus recommended the usage of the Hellman’s exponential law under two important conditions: the stability of the atmosphere and modest roughness of the site [37–41] as follows:

$$\text{V}_{\mathbf{h}} = \text{V}_{\mathbf{10}}\left(\frac{\text{h}}{10}\right)^{\alpha} \tag{2–13}$$

Where α is the roughness factor, this parameter is the wind speed power law index, which is considered to be 1/7 or 0.14, for surfaces with low roughness, as given by the one-seventh power law [24].

The value of the coefficient varies from less than 0.10 over the tops of steep hills to over 0.25 in sheltered locations [29,44]. Table (2–1) presents this constant for different roughness classes according to the European Wind Atlas.

Table (2–1): Correction constant α for speed adjustment [26].

Roughness class	**α**
0	4.247
1	1.976
2	1.307
3	0.170

In addition, the value of α in Eqn. (2–13) depends on the time of the day, the wind speed level, the wind stability and the surface roughness. This value varies from 0.10 to 0.40.

In this analysis, α is chosen to be 0.25 which presents a suitable value for Egyptian terrain and wind conditions [5,15].

Whereas, the effect of height on air density for the elevations under consideration is negligible, the power density of the wind above the ground level will be mainly affected by the increase in wind speed with height [42]. Hence,

$$\mathbf{P_h} = \mathbf{P_{10}} \left(\frac{h}{10}\right)^{3\alpha} \qquad (2\text{–}14)$$

2.4 Plant load factor and capacity factor

An important wind energy parameters is the plant load factor (**PLF**). This factor is used in determining the monthly and annual energy output of wind energy conversion system (**WECS**). The **PLF** is defined as the ratio between the actual power available in the wind and the rated power of the **WECS** [32]. i. e.

$$\mathbf{PLF} = \frac{\text{Power available in wind}}{\text{Rated power for WECS}} = \frac{P_h}{P_r} \qquad (2\text{–}15)$$

However, the capacity factor $\boldsymbol{C_f}$, is a very significant index of productivity of a wind turbine. It represents the fraction of the total energy delivered over a period, $\boldsymbol{E_{out}}$, divided by the maximum energy that could have been delivered if the turbine was used at maximum capacity over the entire period of one year, $\boldsymbol{E_r}$ = 8760 $\mathbf{P}_{\boldsymbol{r}}$.

The capacity factor $\boldsymbol{C_f}$ of a wind turbine can be calculated as [43,44]:

$$\boldsymbol{C_f} = \frac{E_{out}}{E_r} \qquad (2\text{–}16)$$

2.5 Economic analysis

In this study the present value of money method has been used to estimate the cost of a kWh of energy produced by the chosen wind energy conversion system (**WECS**). In order to calculate the present value of costs (**PVC**) of electricity produced per year, following expression, given by Lysen [22] and referred by Habali [45,46], Sarkar [47], Alnaser [48], Türkosy [49] and by Rehman [50] is used in the present study under the following assumptions:

(1) Investment (**I**) includes the turbine price plus its 20% for the civil work and connection cables to the grid (other connections).
(2) Operation, maintenance and repair cost ($\mathbf{C}_{omr}$) was considered to be 25% of the annual cost of the turbine (machine price/life time).
(3) The interest rate (**r**) and inflation rate (**i**) were taken to be 15% and 12%, respectively.
(4) Scrap value (**S**) was taken to be 10% of the turbine price and civil work.
(5) The lifetime of the machine (**t**) was assumed to be 20 years.

The present value of costs (**PVC**) is [45–50]:

$$\mathbf{PVC} = \mathbf{I} + \mathbf{C}_{omr}\left[\frac{1+\mathbf{i}}{\mathbf{r}-\mathbf{i}}\right]\times\left[1-\left(\frac{1+\mathbf{i}}{1+\mathbf{r}}\right)^{t}\right]-\mathbf{S}\left(\frac{1+\mathbf{i}}{1+\mathbf{r}}\right)^{t} \qquad (2\text{–}17)$$

Chapter 3

Evaluation of wind energy potential and electricity generation on the coast of Mediterranean Sea in Egypt

3.1 Introduction

In this chapter an evaluation of wind energy along the coast of Mediterranean Sea in Egypt is done. It is hoped that the data analysis will help to identify good sites for new wind turbine installations at the selected sites.

Egypt occupies a geographical zone between 22^0 and 32^0N latitude and 25^0 and 36^0E longitude. The Egyptian area is about 998,000 km^2, only 3.5% of it can be said to be permanently settled, while the remainder being desert. The orography of the region has an important role in accelerating and deflecting the wind. Fig. (3–1) shows the orography of the Egyptian region.

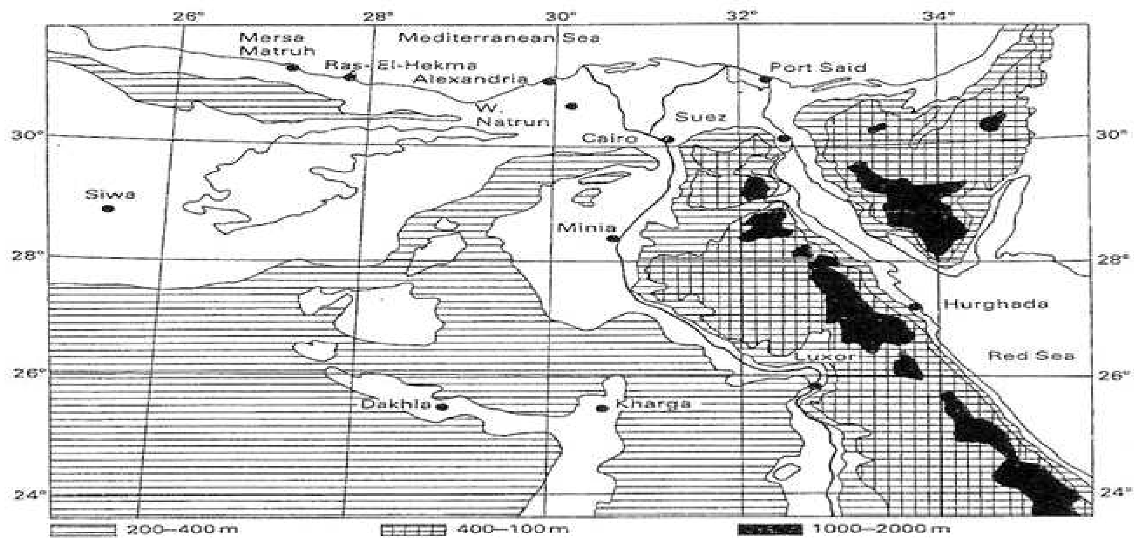


Fig. (3–1). Orography of the Egyptian Region (obtained from Ref. [5]).

3.2 Wind characteristics

3.2.1 Analysis of wind data

Fig. (3–2) shows the location of 10 chosen stations along the coast of Mediterranean Sea zone in Egypt. The present study is based on measurements of monthly wind speed, air temperature and air pressure data were taken at a height of 10 m above ground level, in open areas and over roughness class 0 (water). The Egyptian Meteorological Authority provided the data for a period of more than 10 years. Table (3–1), shows the physical features of the meteorological stations.

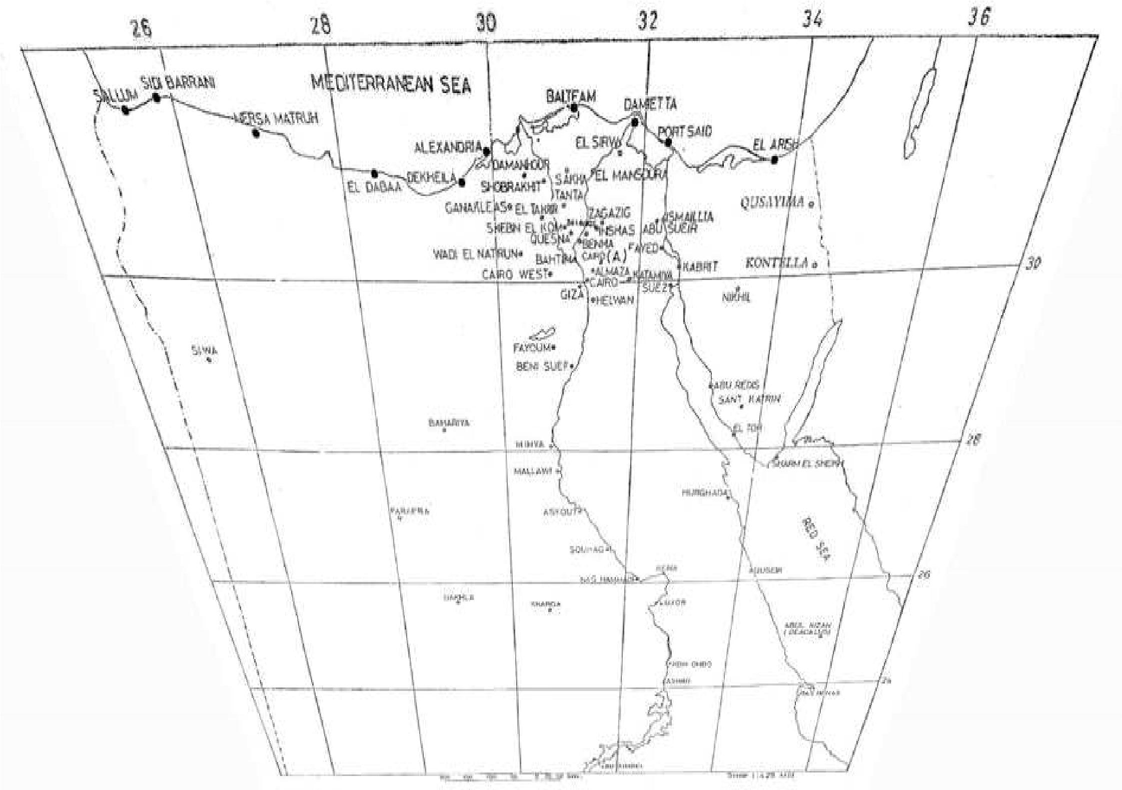


Fig. (3–2). Distribution of meteorological stations over Egypt.

● *indicates the location of stations under study.*

Table (3–1): Physical features of the meteorological stations.

Name of Station	coordinates		
	Latitude Deg. Min.	Longitude Deg. Min.	Elevation (m)
Sallum	31 32	25 11	4.0
Sidi Barrani	31 38	25 38	21.0
Mersa Matruh	31 20	27 13	28.3
El Dabaa	30 56	28 28	17.0
Dekheila	31 08	29 48	3.1
Alexandria	31 12	29 57	-3.4
Balteam	31 33	31 06	1.0
Damietta	31 25	31 49	1.9
Port Said	31 16	32 17	1.0
El Arish	31 16	33 45	15.0

Table (3–2): Mean monthly and annual wind speed (m/s) and its direction (at a height 10 m).

Station	Month												Annual	Wind
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Mean	direction
Sallum	5.4	4.8	5.2	4.3	3.6	4.1	4.7	4.2	3.4	3.6	4.2	5.2	4.4	330 NW
Sidi Barrani	5.6	5.7	5.9	5.7	4.7	4.6	5.2	4.5	4.0	4.2	4.6	5.6	5.0	330 NW
Mersa Matruh	6.1	6.1	6.3	5.7	4.9	5.2	5.2	4.7	4.4	4.3	4.8	5.9	5.3	330 NW
El Dabaa	5.5	5.8	6.1	5.8	5.1	6.0	6.0	5.7	5.0	4.2	4.5	5.5	5.4	330 NW
Dekheila	4.5	4.6	4.9	4.8	4.3	4.5	4.6	4.5	4.2	3.7	3.8	4.1	4.4	360 N
Alexandria	4.4	4.4	4.6	4.3	4.0	4.0	4.4	4.0	3.7	3.1	3.4	4.1	4.0	330 NW
Balteam	3.6	3.5	4.2	4.0	3.5	3.7	3.9	3.6	2.8	2.3	2.6	3.3	3.4	330 NW
Damietta	2.8	3.1	3.7	3.6	3.1	3.1	2.8	2.5	2.3	2.5	2.5	2.9	2.9	330 NW
Port Said	4.8	5.2	5.8	5.4	4.8	4.6	4.3	3.8	3.8	4.1	4.3	4.3	4.6	360 N
El Arish	2.5	2.9	3.0	2.5	2.4	2.4	2.3	2.1	2.2	2.0	2.1	2.4	2.4	330 NW

The analysis of this region showed that the typical features of Mediterranean coasts are strong winds aloft or strong thermal/pressure gradients [3]. The Mediterranean zone is characterised by a wide flat coastal area along the sea and existence of Maryout plateau in the northwest area [34] (see Fig. (3–1)). So the roughness factor in this study will be taken as constant, because the coast of the Mediterranean Sea in Egypt is flat and homogenous.

The mean monthly averages of wind speed and wind directions beside the annual means are listed in Table (3–2). The table indicates that most stations have an annual mean wind speed more than 3.1 m/s expect Damietta and El Arish and the main wind direction over the Mediterranean Sea is north and northwest.

Fig. (3–3) illustrates the monthly mean of wind speed for all stations. It clear from the figure that the Mediterranean zone is windy. The wind speed has a maximum value of 6.3 m/s at Mersa Matruh in March, and a minimum value of 2.0 m/s at El Arish in October. This zone characterized by sea-land winds. Also from Fig. (3–3), it can be taken that high wind speeds occur in the winter and spring seasons. This may be a result of the Mediterranean Sea secondary depressions [10].

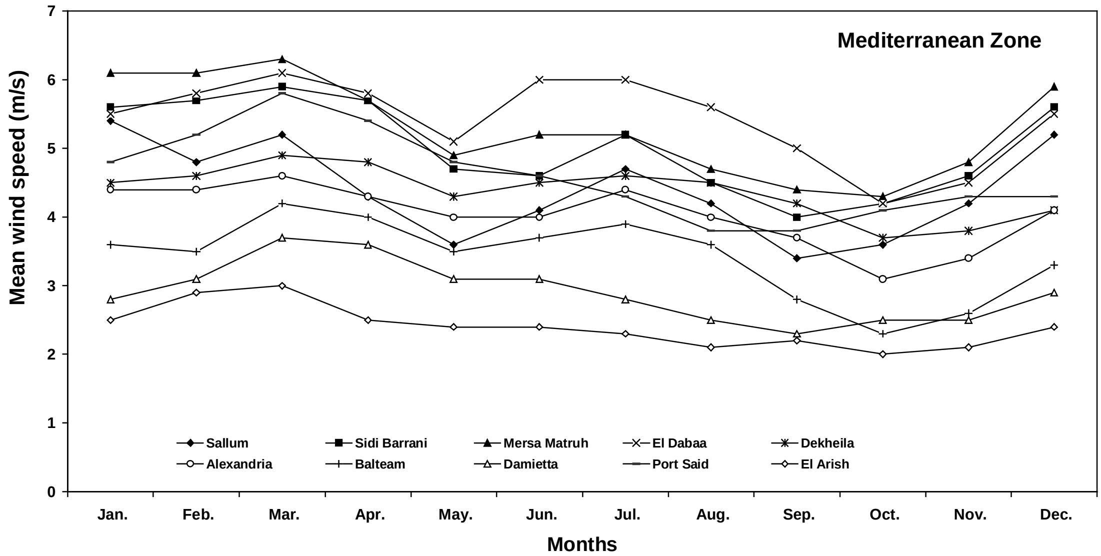


Fig. (3–3). Monthly variation of wind speeds of the year for selected stations.

Mean monthly wind speeds for different seasons of the year are plotted in Fig. (3–4). During ***winter season***, the wind speed level at three stations Sidi Barrani, Mersa Matruh and El Dabaa reaches high values of 5.5–6.1 m/s. The maximum mean wind speed occurs at Mersa Matruh during January and February with 6.1 m/s. In ***spring season***, four stations (Sidi Barrani, Mersa Matruh, El Dabaa and Port Said) have high values of wind speed 4.8–6.1 m/s, where the maximum value is recorded in Mersa Matruh with 6.3 m/s during March. In ***summer season***, the wind speed level reaches 6.0 m/s at El Dabaa during June and July. For ***autumn season***, the maximum mean wind speed is recorded as 5.0 m/s at El Dabaa in September.

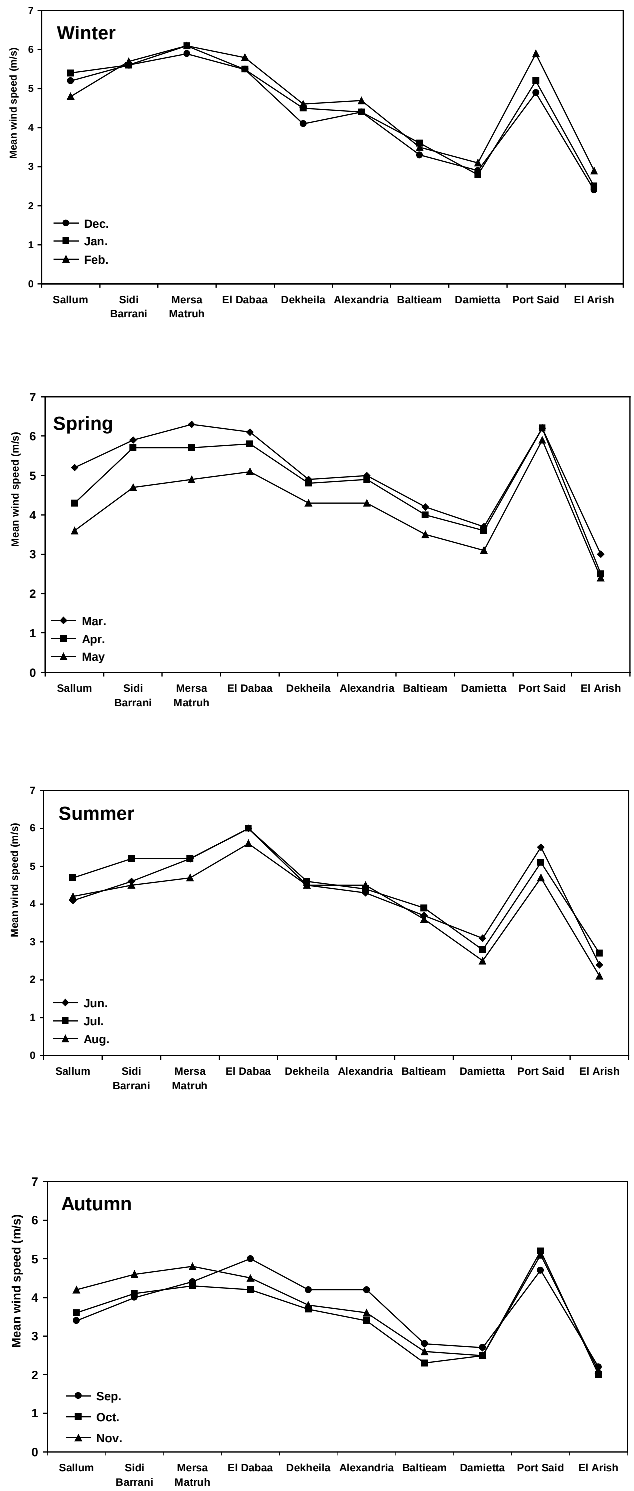


Fig. (3–4). Mean monthly wind speeds at different seasons of the year for all stations.

From Fig. (3–4) the following findings can be derived:

(1) The highest values of mean monthly wind speed of all stations occurred during winter and spring seasons. This can be explained by the decease of the temperature during winter and spring. Such decrease causes thermal convection so that some of momentum of the upper air, which is moving at higher velocity, is transmitted to the surface layers causing the noticed increase in the mean monthly wind speeds [6].

(2) For all seasons, we noticed that El Arish has the minimum values of monthly wind speed.

(3) The monthly wind speed, for all seasons, has the same trend and has pronounced peaks, which decrease from west along the Mediterranean coast especially from El Dabaa to El Arish, except in Port Said.

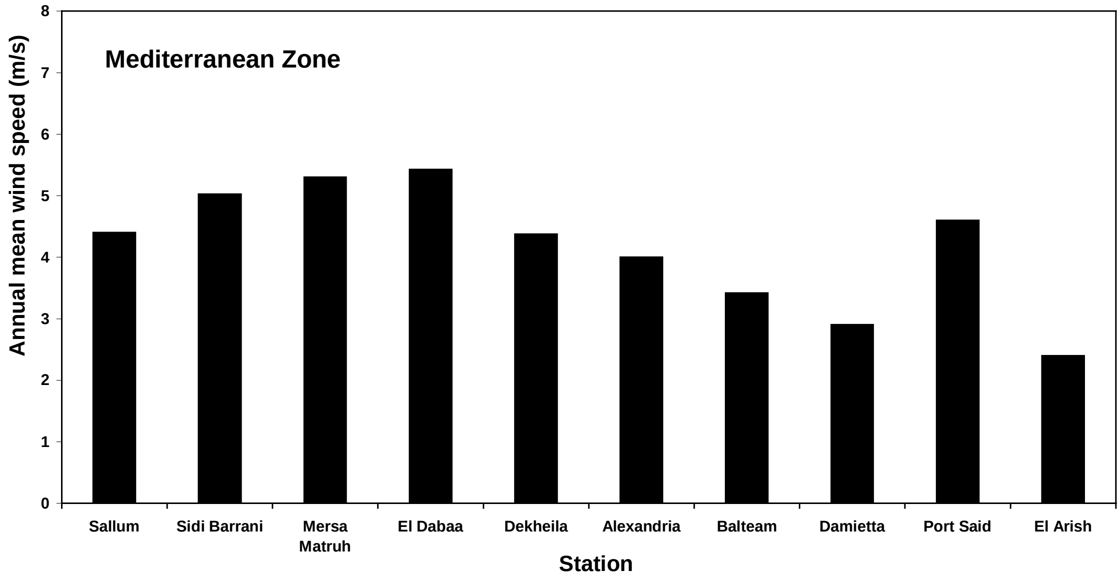


Fig. (3–5). Annual monthly averages of wind speed for selected stations.

Fig. (3–5) illustrates the annual mean wind speeds for all stations. The wind speeds decrease along the Mediterranean coast from El Dabaa to El Arish, with exception Port Said. The relative increase of the wind speed at Port Said may be due to the broad coast of Suez Canal–Mediterranean intercept. In general, from the Fig. (3–5) it can be taken that Sidi Barrani, Mersa Matruh and El Dabaa are the windiest stations with wind speeds greater than 5.0 m/s.

3.2.2 Annual mean frequency distribution

The Weibull distribution shows its usefulness when the wind data of one reference station are being used to predict the wind regime in the surroundings of that station. The idea is that only annual or monthly average wind speeds are sufficient to predict the complete frequency distribution of the year or the month [22].

The annual values of the monthly average wind speeds for the stations under study are estimated and have been analyzed using the Wind Atlas Analysis Application Program (WASP) to predict the complete annual mean frequency distribution of the year for all stations, as shown in Fig. (3–6).

It is clear from the Fig. (3–6) that:

(1) All the frequencies have the same trend and have pronounced peaks, which, are located in the neighbourhood of the mean wind speed.

(2) In all stations, the peak frequencies are shifted towards the higher values of mean wind speeds. For example, El Dabaa has annual mean wind speed of 5.4 m/s (see Table (3–2)) and peak frequency value of 14%.

(3) In general, all stations have peak frequencies in the range from 15 to 24% except for Damietta and El Arish. For these sites peak frequencies in the range from 30 to 35% occur. This is due to the stability of weather condition at these stations and the fact that Damietta and El Arish are not windy sites.

(4) For the investigated stations in the Mediterranean zone, no frequencies occurred for a mean wind speed of 13 m/s.

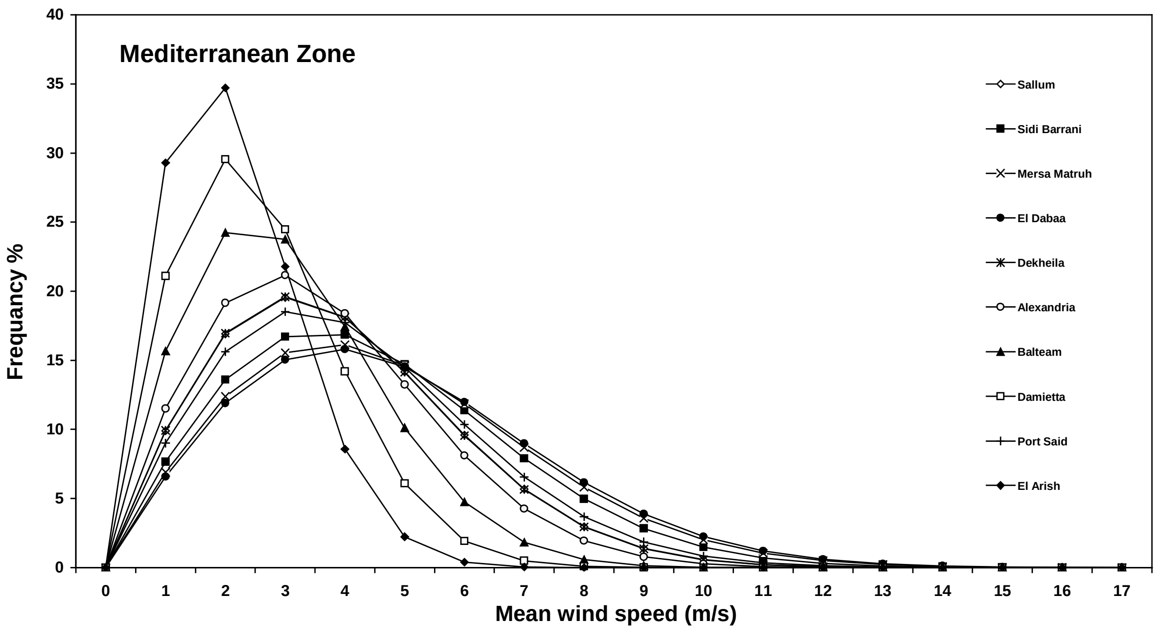


Fig. (3–6). Wind speed frequency distribution throughout the year selected stations.

One important characteristic which we note from Fig. (3–6) is that: there are no frequencies for mean wind speed of zero speed (calm winds). This is discussed by Vogiatzis et al. [23] as follows, wind speed frequencies based directly on measurements and those computed through Weibull distribution formula (theoretical), the comparison indicates a good agreement except for the range of wind stillness. Where the mathematical formula of Weibull distribution imposes zero probability, while the frequency computed directly through the measurements attains significant values.

3.2.3 Weibull's parameters

As mentioned above, the Weibull distribution gives a good match with the experimental data. This is also mentioned in many references [22–28]. This distribution is characterized by two parameters: the shape parameter *k* (dimensionless) and scale parameter *c* (m/s).

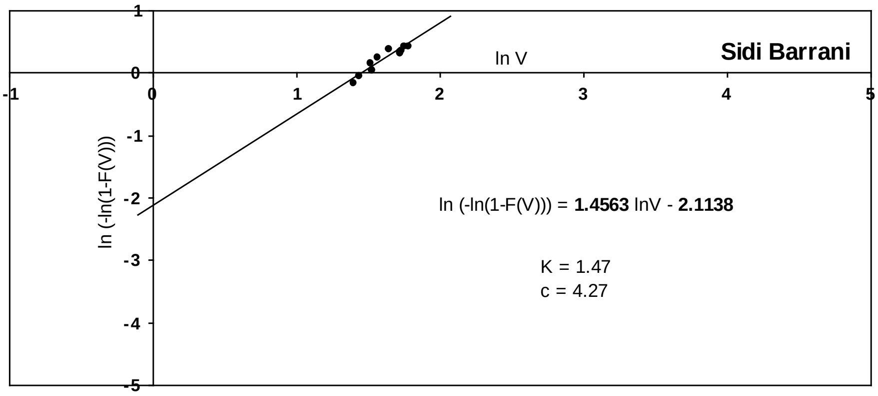
Table (3–3), gives the Weibull parameters: yearly shape parameter *k*, and scale parameter *c*, at a height 10 m. They are estimated by two methods as mentioned in chapter 2, from Eqns. (2–1) to (2–5). We calculated the monthly observed values of ln [– ln (1– F(V))] and plotted it against ln V, where V is the mean monthly wind speed, as shown in Fig. (3–7) (as example). Using the least square method, a straight line is fitted to the above mentioned data which is also drawn in the same figure in order to obtain the parameters *k* and *c*. Where *k* is the slope of the straight line, while (– *k* ln *c*) is the intercept on the vertical axis.

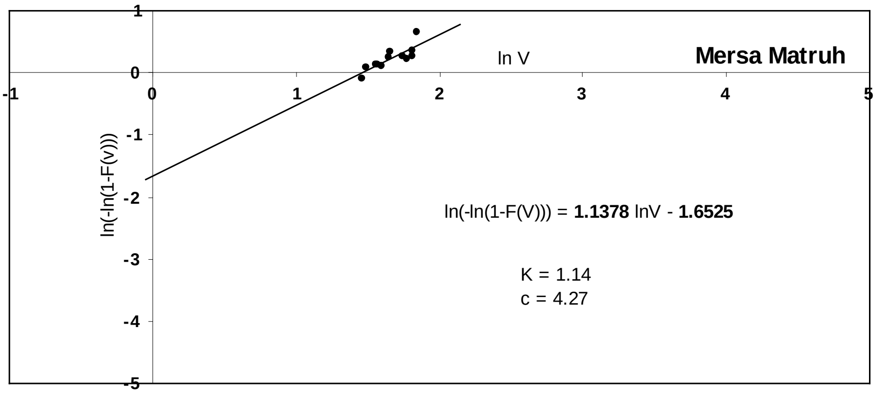
It is clear from results in Table (3–3), that both methods give identical estimates of the parameter *c* (m/s), but different values of *k*, although in Method 2: estimation of *c* (m/s) depends on estimated values of *k* firstly. The parameter *c* is then found by the using this estimate of *k* in Eqn. (2–4). This may be due to the fact that, Method 2: maximum likelihood estimation, leads to large errors in some individual cases and is useful only for ensemble averages [15,31].

Table (3–3): Estimates of the constants c and k of Weibull distribution by two methods.

Name of Station	Method (1)		Method (2)	
	c	*k*	*c*	*k*
Sallum	4.88	1.46	4.68	8.20
Sidi Barrani	4.27	1.47	5.29	9.79
Mersa Matruh	4.27	1.14	5.60	9.75
El Dabaa	4.02	1.19	5.64	11.05
Dekheila	--	--	4.53	14.37
Alexandria	4.36	1.49	4.21	11.09
Balteam	--	--	3.62	7.19
Damietta	--	--	3.12	8.39
Port Said	4.77	1.71	4.93	9.74
El Arish	4.56	2.39	2.58	10.12
Mean	4.45	1.55	4.42	9.97

(--) Monthly percentage frequency not available.





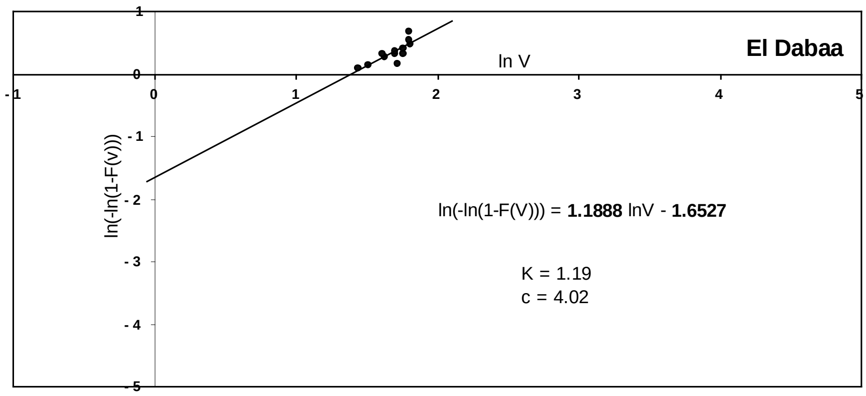


Fig. (3–7). Monthly observed values of ln (– ln (1–F(V))) plotted against ln V, for three stations, through which the Weibull parameters are estimated.

3.3 Wind power estimation and analysis

3.3.1 Analysis wind power and air density corrections

Wind power density, expressed in Watt per square meter (W/m^2), takes into account the frequency distribution of the wind speed and the dependence of wind power on air density and the cube of the wind speed. Therefore, wind power density is generally considered to be a better indicator of the wind resource than the wind speed itself [1].

The monthly corrected and uncorrected wind power ($\mathbf{P_{10}}$, $\mathbf{P}_{\boldsymbol{wind}}$) were calculated using Eqns. (2–9) – (2–11) and the results lead to Fig. (3–8).

From Fig. (3–8) it can be taken that the mean corrected specific power available $\mathbf{P_{10}}$ for El Dabaa station is higher than 100 W/m^2 for 8 months during the year (nearly in all seasons except in autumn). Whereas for both Mersa Matruh and Sidi Barrani, they have only 5 months a specific power higher than 100 W/m^2 during the year.

Annual values of corrected wind power, $\mathbf{P_{10}}$, is always smaller than the uncorrected wind power, $\mathbf{P}_{\boldsymbol{wind}}$ (see Table (3–4)). This deviation is important, because sizing and costing of any technical wind system depends mainly on the wind power.

The annual average corrected wind power values at a height 10 m for all stations are given in Fig. (3–9). It can be seen that over the year El Dabaa has the highest mean power followed by Mersa Matruh and Sidi Barrani. These stations may be utilized as wind power sites. El Dabaa was chosen for this purpose and an analysis of the costs was done.

To confirm the validity of our results, the greatest negative bias (the ratio of difference between corrected and uncorrected air density to the standard air density) [35], was calculated and listed in Table (3–4), as bias ($\bar{\rho}$, ρ). For additional confirmation, bias (**P_{10}**, **P_{wind}**) was also calculated. From Table (3–4), it is evident that the corrected air density values are almost stable and the shift from the standard air density (ρ=1.225 kg/m^3) is very small for the selected sites.

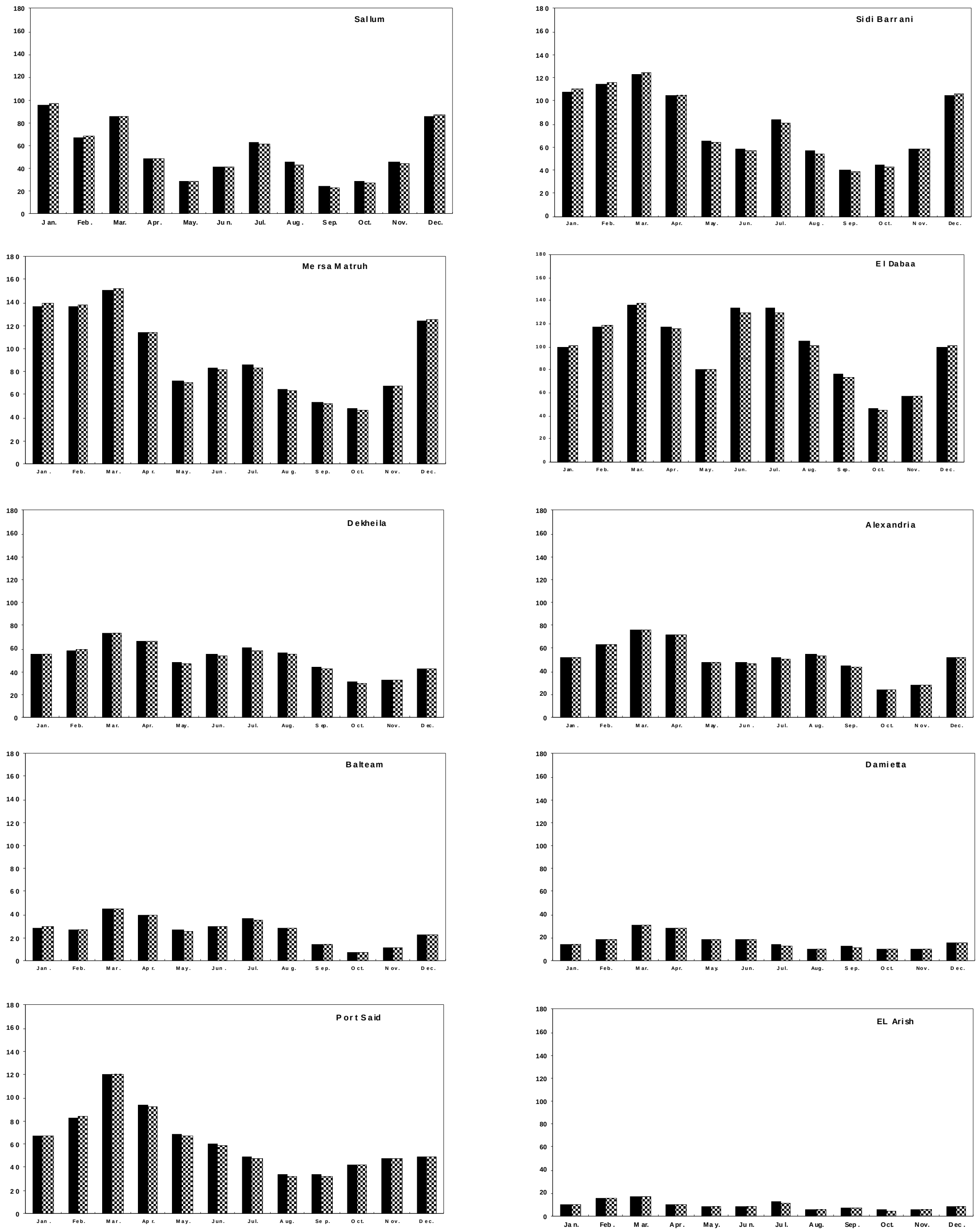


Fig.(3–8). Monthly corrected and uncorrected wind power P_{10} ▒, P_{wind} █ (W/m^2) respectively, throughout the year at a height 10 m for all stations.

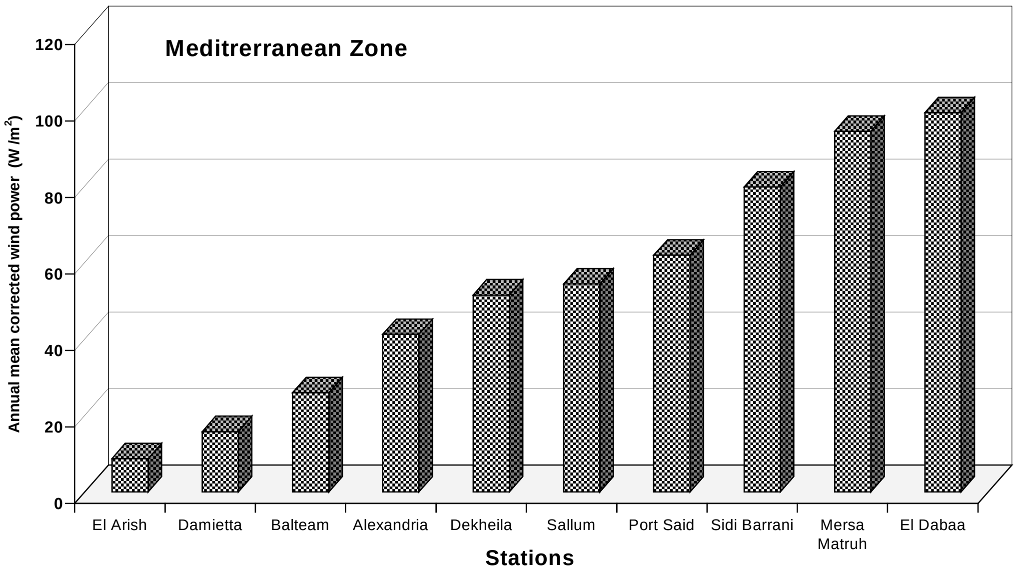


Fig. (3–9). Annual average corrected wind power through the year at a height 10 m for all stations.

Table (3–4): Annual corrected air density, corrected and uncorrected specific wind power and bias for all stations beside annual values of air temperature and pressure.

Name of Station	T (K)	P x10^2 (N/m^2)	P_{Wind} (W/m^2)	P_{10} (W/m^2)	$\bar{\rho}$ (kg/m^3)	Bias ($\bar{\rho}$, ρ)	Bias (P_{10}, P_{Wind})
Sallum	293.0	1014.6	54.70	54.39	1.207	-0.015	-0.006
Sidi Barrani	292.4	1014.1	80.12	79.76	1.209	-0.013	-0.005
Mersa Matruh	292.3	1014.7	94.6	94.32	1.210	-0.012	-0.003
El Dabaa	292.2	1013.3	100.08	99.17	1.209	-0.013	-0.009
Dekheila	293.2	1014.3	52.07	51.49	1.206	-0.016	-0.011
Alexandria	293.2	1014.1	41.60	41.20	1.206	-0.016	-0.010
Balteam	293.5	1013.4	26.26	25.93	1.203	-0.018	-0.013
Damietta	292.6	1013.8	15.89	15.77	1.208	-0.014	-0.007
Port Said	294.0	1013.4	62.57	61.89	1.201	-0.019	-0.011
El Arish	293.5	1013.5	8.78	8.71	1.204	-0.017	-0.009

For simplicity, when considering the calculation of monthly corrected wind power, $\mathbf{P_{10}}$, from the monthly uncorrected values, $\mathbf{P}_{\boldsymbol{wind}}$, a correlation between $\mathbf{P_{10}}$ and $\mathbf{P}_{\boldsymbol{wind}}$ has been investigated and illustrated in Fig. (3–10). A strong linear fit has been found between $\mathbf{P_{10}}$ and $\mathbf{P}_{\boldsymbol{wind}}$, where we obtain a correlation coefficient of CC = 0.99.

The recommended correlation equation is:

$$\mathbf{P_{10}} = \mathbf{P}_{\boldsymbol{wind}} - 0.5414 \qquad (3\text{–}1)$$

Equation (3–1) is quite practical to calculate $\mathbf{P_{10}}$, along the coast of Mediterranean Sea in Egypt.

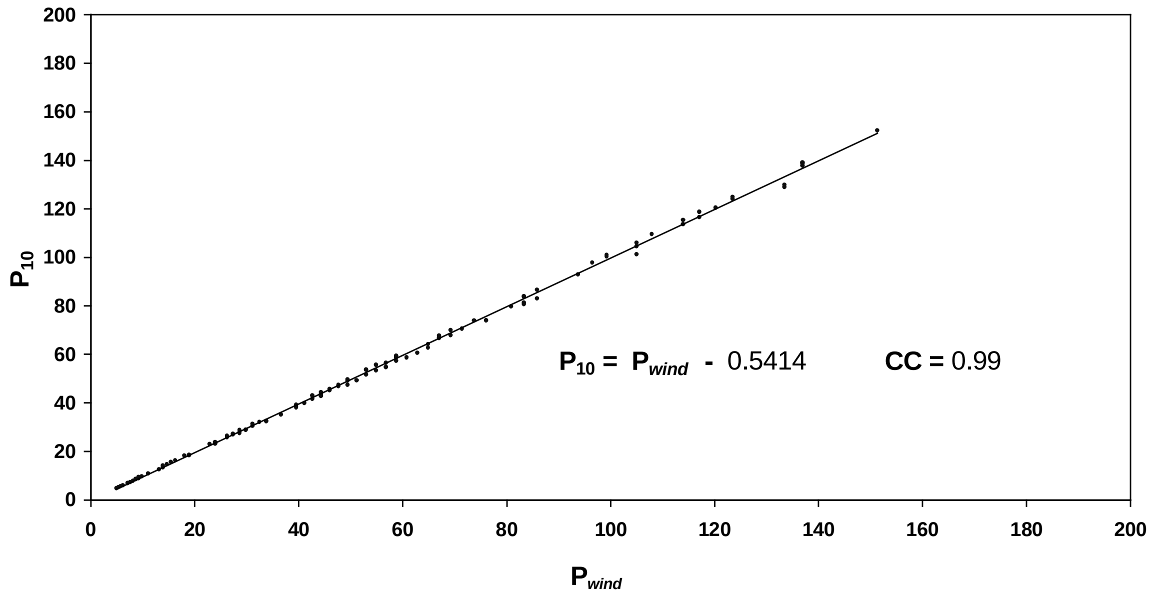


Fig. (3–10). Correlation between monthly values of corrected $\boldsymbol{P_{10}}$ and uncorrected $\boldsymbol{P_{wind}}$ wind power (W/m^2) of the selected stations.

3.3.2 Extrapolation of wind power with height

The vertical extrapolation of wind speed and mean wind power density has been subject to numerous investigations in recent years. The common expression for calculating the wind speed at any height (h) based on the measured wind speed at the standard height (10 m) is given by the equation (2–13). Because the effect of height on air density for the elevations under consideration is negligible, the power density of the wind above the ground level will be mainly affected by the increase in wind speed with height [42].

Justus [24] recommended usage of Eqn. (2–13) in the range of heights 0–100 m above the ground level, under two important conditions: stability of the atmosphere and modest roughness of the site.

As mentioned in the beginning of this chapter, from the wind atlas analysis the roughness factor is kept constant. And from the results in Table (3–4), we concluded that, the values of corrected air density are almost stable and the shift from the standard air density (ρ =1.225 kg/m^3), is very small. This confirms the stability of the atmosphere along the coast of Mediterranean Sea in Egypt. For this analysis we use, α = 0.25, which is the standard value for the Egyptian terrain and wind conditions [5]. Also due to the common heights of wind turbines from 30 to 50 m above the ground level, Table (3–5) is prepared by using Eqn. (2–14) and the results for all stations are plotted in Fig. (3–11).

Table (3–5): Annual mean corrected wind power at heights of 10, 30, 50 m.

Name of Station	P_{10} (W/m^2)	P_{30} (W/m^2)	P_{50} (W/m^2)
Sallum	54.4	124.0	181.9
Sidi Barrani	79.8	181.8	266.7
Mersa Matruh	94.3	215.0	315.4
El Dabaa	99.2	226.0	331.6
Dekheila	51.5	117.4	172.2
Alexandria	41.2	93.9	137.8
Balteam	25.9	59.1	86.7
Damietta	15.8	35.9	52.7
Port Said	61.9	141.1	207.0
El Arish	8.7	19.9	29.1

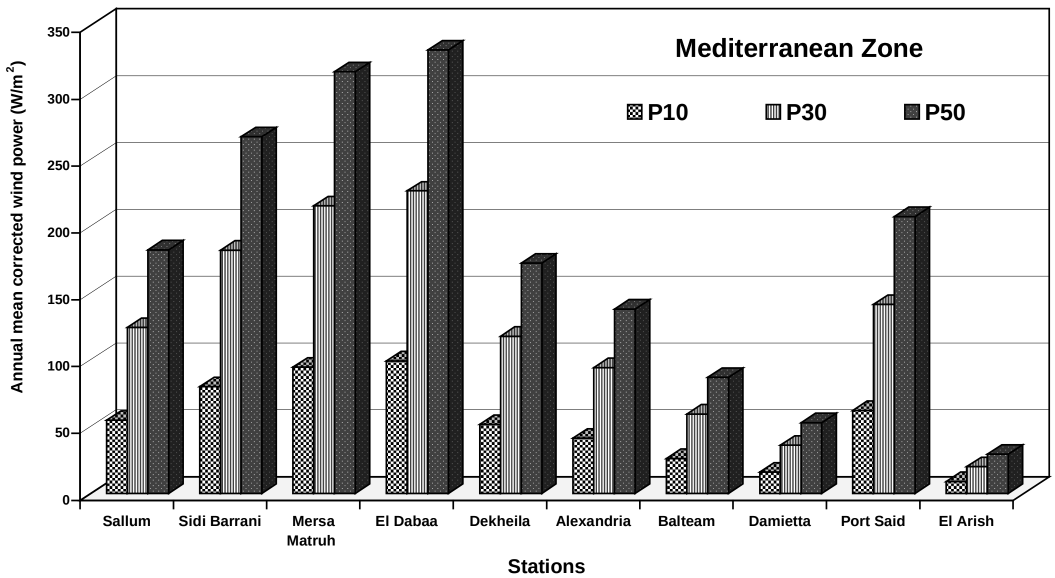


Fig. (3–11). Annual mean wind power throughout the year at the heights 10, 30, 50 m, respectively.

Based on Fig.(3–11), a classification into two different groups can be done.

Group A, which contains ***Sidi Barrani, Mersa Matruh and El Dabaa***, has annual mean specific wind power in the range from 180 to 230 W/m^2 at a height 30 m above ground level. It has annual mean specific wind power in the range from 260 to 330 W/m^2 at a height 50 m. This group **A** is ideal for electricity generation using large wind turbines.

Group B, which contains the stations ***Sallum, Dekheila, and Port Said***, has annual mean specific wind power between 120–140 W/m^2 and 180–210 W/m^2 at the heights of 30 and 50 m, respectively. This group **B** is suitable for special wind turbines because it has only annual mean wind speed between 3.5 and 5 m/s (at a height 10 m, see Table (3–2)). A special wind conversion system, with simple technology, like it was designed and implemented by Foaud Kamel in Port Said city (Egypt), see Ref. [11], is suitable for the stations of group **B**. Application fields might be: lighting of small areas, irrigation, water pumping and desalination plants in rural areas like in Sallum and Dekheila areas.

3.4 Electricity generation and cost analysis

3.4.1 Turbines wind power

In this section, we focus on three stations namely: ***Sidi Barrani, Mersa Matruh and El Dabaa***. These selected sites are suited for generation of electricity, using two turbines with different rated power: Turbine (1), 300 kW and Turbine (2), 1000 kW. Table (3–6), lists the characteristic properties of the selected wind turbines. With respect to the wind characteristics, the two machines are similar in the values of cut-in wind speed (V_{ci}) and cut-out wind speed (V_{co}) and the difference in the value of rated wind speed (V_r).

Fig. (3–12) shows the power curve for the two selected wind turbines. It is clear from the figure that at wind speed below 3 m/s, threshold value, there is no power produced. A saturation power of 300 kW, Turbine (1), corresponds to a wind speed of 14 m/s, while for Turbine (2) the corresponding wind data for 1000 kW is 15 m/s.

Table (3–6): Characteristics of the selected wind turbines [15].

Characteristics	***Turbine (1)***	**Turbine (2)**
Turbine model	AN Bonus 300/33	AN Bonus 1MW/54
Rated Power (P_r)	300 kW	1000 kW
Hub height	30 m	50 m
Rotor diameter	33.4 m	54.2 m
Swept area	876 m^2	2300 m^2
Number of blades	3	3
Cut-in wind speed (V_{ci})	3 m/s	3 m/s
Rated wind speed (V_r)	14 m/s	15 m/s
Cut-off wind speed (V_{co})	25 m/s	25 m/s
Price / Euro	305,000	828,000

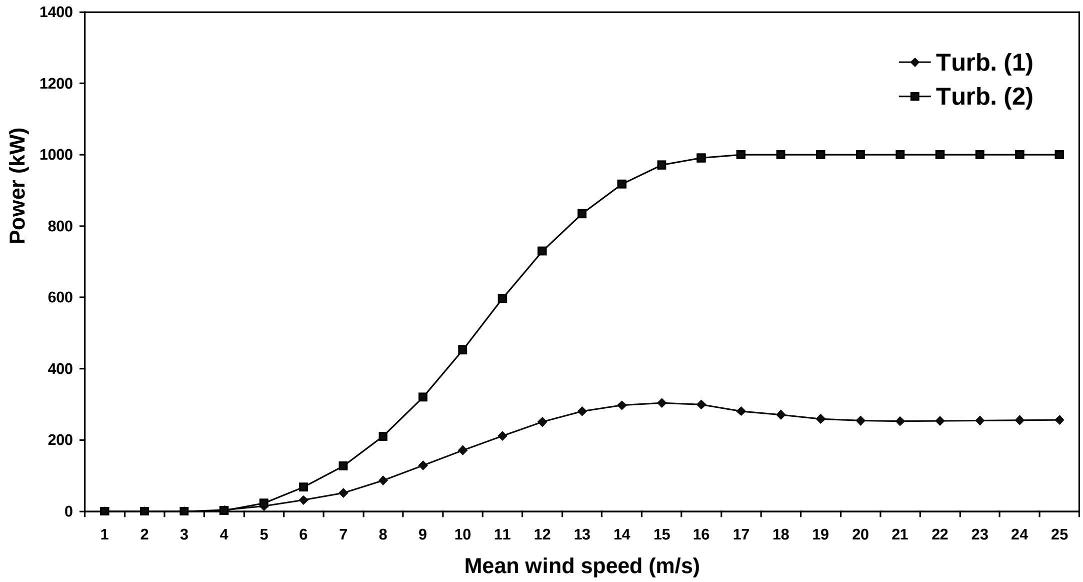


Fig. (3–12). Power curve for the selected wind turbines [15].
http://www.anwind.de/1MWe.htm

3.4.2 Wind speed adjustment

The wind speed changes with height and the available wind data at different sites are normally measured at a height 10 m above ground level. So it is necessary to know the wind speed at wind turbine hub height. The wind power law has been recognized as a useful tool to transfer the anemometer data recorded at certain levels to the desired hub center [51]. This is done using Eqn. (2–13) for the three selected stations. The annual mean wind speed for Sidi Barrani will be: 6.57 and 7.47 m/s at the heights of 30 m and 50 m, respectively. For Mersa Matruh the annual mean wind speed will be: 6.98 and 7.93 m/s at the heights of 30 m and 50 m, respectively. Also for El Dabaa the wind speed is calculated to be 7.12 and 8.09 m/s at the heights of 30 and 50 m, respectively.

3.4.3 Wind turbine energy output

The annual energy output, $\boldsymbol{E_{out}}$ (kWh/y), is estimated by using the WASP program for the given turbines and selected stations and the results are summarized in Table (3–7). Fig. (3–13) has been prepared for illustration of the relation between the annual energy output as a function of mean wind speed for the two considered turbines and for the selected stations.

From Fig. (3–13) we can derive:

(1) Very little wind energy exists below a wind speed of 3 m/s (a typical cut-in wind speed for the Turbines (1) and (2)).

(2) In case of Turbine (1), the accumulated annual wind energy in the considered stations ranges from 96 MWh (Sidi Barrani station) to a maximum of 108 MWh (El Dabaa station) per year.

(3) In case of Turbine (2), the range is from 312 MWh/y to 346 MWh/y for the stations Sidi Barrani and El Dabaa, respectively.

(4) The bulk of the annual energy (in all stations) is obtained for wind speeds between 4 and 16 m/s for Turbine (1), and from 4 to 20 m/s for Turbine (2).

(5) The annual energy distribution curves show the maximum annual energy is derived from a wind speed of 9 m/s for Turbine (1) and 10 m/s for Turbine (2).

It is noted that from Table (3–7), the maximum yearly energy gain from the wind Turbines (1) and (2) are 769 MWh/y and 2718 MWh/y, for El Dabaa station.

Table (3–7): Yearly energy gain from Turbines (1) and (2).

Name of Station	E_{out} (MWh/year)	
	Turb. (1) / H= 30m	Turb. (2) / H=50m
El Dabaa	769	2718
Mersa Matruh	740	2614
Sidi Barrani	653	2313

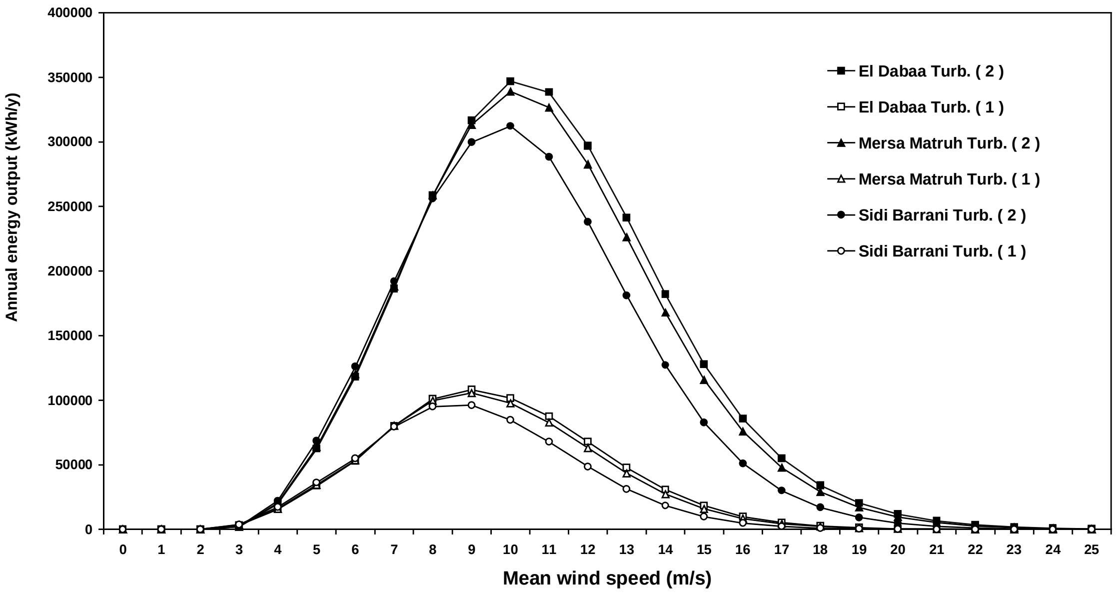


Fig. (3–13). Annual energy output by Turbines (1) and (2) as function of mean wind speed for the selected three stations in Egypt.

3.4.4 Cost analysis

The estimation of the costs for one kWh of energy produced by the Turbine (2), (AN Bonus 1 MW/54), to operate at El Dabaa station has been done under the mentioned assumptions with using Eqn. (2–17).

For the Turbine (2), the price is taken to be EURO 828,000, and the cost of civil work (20% of the price) = €165,600. Therefore investment **I** = € 993,600, $\mathbf{C}_{omr}$ = € (828,000/20) x 0.25 = € 10,350 and **S** = € (993,600 x 0.1) = 99360, where **r** = 0.15 and **i** = 0.12.

Using all these values in Eq. (2–17), we get:

$$\mathbf{PVC} = 1{,}093{,}679.9$$

From Table (3–7), the annual output of Turbine (2) at El Dabaa is 2,718,251 kWh. So the total output over 20 years = (20 x 2,718,251) kWh. Therefore, the specific cost per kWh = (1,093,679.8/(20 x 2,718,251)) = 0.02 €.
Where 1 EURO ≈ 7.5 Egyptian pounds, (one Pound = 100 Piaster). Then, the cost will be 15 Piaster per kWh.

3.5 Conclusions

From the statistical data and the calculations in this chapter, we can conclude the following:

(1) The wind energy potential along the cost of Mediterranean Sea in north Egypt is quite promising, because the chances of having wind speeds less than 3.1 m/s are small, see Table (3–2).

(2) Because the wind speed range for electricity generation is (5–6) m/s [52], the following contiguous sites are suitable for electricity generation: ***Sidi Barrani, Mersa Matruh and El Dabaa***.

(3) The shift of the values of air density, see Table (3–4), from the standard air density (ρ=1.225 kg/m^3) along the coast Mediterranean Sea is very small.

(4) Investigation of available wind power density at the heights of 30–50 m indicates that, there are six stations which have good wind power densities.

(5) Group A, which included the three contiguous stations: ***Sidi Barrani, Mersa Matruh and El Dabaa***. They have high wind power density ranging from 180–230 W/m^2 and 260–330 W/m^2 at the heights of 30–50 m, respectively. So wind farms can be installed in these regions to supply a reasonable amount of energy using a number of wind turbines, like the selected Turbine (2) with, 1 MW.

(6) Group B, included the stations: ***Sallum, Dekheila and Port Said***. They have moderate wind power densities ranging from 120–140 W/m^2 to 180–210 W/m^2 at the heights of 30–50 m above ground level. The two foreseen applications of these stations, which are faraway from the Nile River in Egypt, are water pumping for storage

and electricity generation using small wind machines with installed capacities of less than 100 kW.

(7) An estimation of the cost of installing a wind Turbine (2), 1 MW, at El Dabaa station for the generation of electricity is carried out. The expected yearly energy gain from Turbine (2), at El Dabaa is 2718 MWh/y and the specific cost per kWh is 0.02 €, which was found to be very competitive with another stations along the coast of Mediterranean Sea in Egypt [15].

Chapter 4

Applications of electricity generation on the western coast of Mediterranean Sea in Egypt

4.1 Introduction

About 85% of Egypt's electricity is produced in power plants predominantly operated with natural gas, while the remaining 15% are produced through water and wind energy. The increase in demand of energy is mainly due to rapid expansion of industrial projects and the economic growth, particularly, in the extreme northwest of Egypt along the coast of Mediterranean Sea.

In the previous chapter, a technical assessment of the wind energy potential in Egypt was made. The assessment entailed studies of 10 coastal sites from west to east along the coast of the Mediterranean Sea in Egypt. The contiguous stations: Sidi Barrani, Mersa Matruh and El Dabaa were the three most promising sites along the western coast of Mediterranean Sea. In this chapter, we will focus on these sites.

In this chapter, the possible applications of electricity generation produced by using two different systems at these three stations and the cost analysis of kWh at each of them are discussed and compared with the generating costs by the Egyptian Electricity Authority. They use diesel oil and natural gas in the power plants. This evaluation is hoped to trigger the use of large wind turbines in Egypt.

4.2 Analysis of wind data

Fig (4–1) shows the location of the three selected stations along the western coast of Mediterranean Sea in Egypt. Table (4–1) shows the mean monthly averages of wind speed and wind directions beside the annual means of ***Sidi Barrani, Mersa Matruh and El Dabaa*** stations. The table indicates that these stations have an annual mean wind speed greater than 5.0 m/s at a height of 10 m and the main wind direction is northwest. These wind data were taken from Table (3–2). These three contiguous stations are suitable for electric wind applications. Because the wind speed range for electricity generation is (5–6) m/s [52].

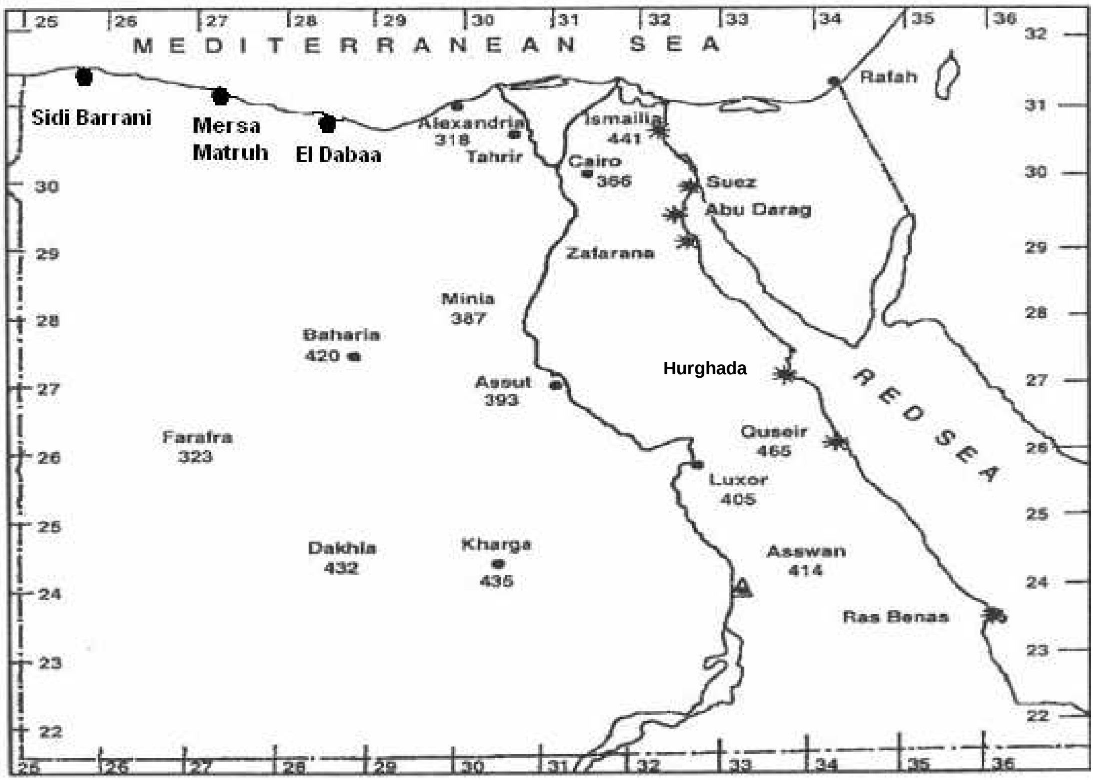


Fig. (4–1). Distribution of some meteorological stations over Egypt.

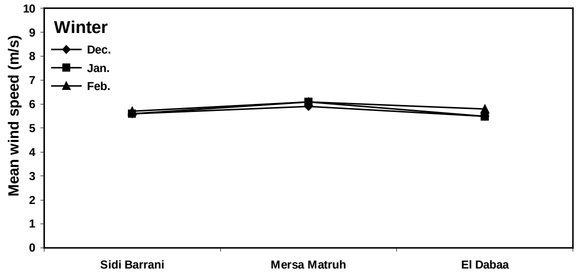
● indicates the location of stations under study.

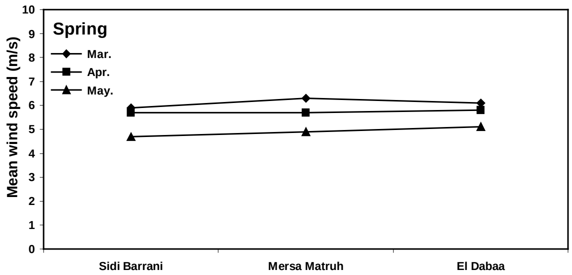
Table (4–1): Mean monthly and annual wind speed (m/s) and its direction (at a height 10 m).

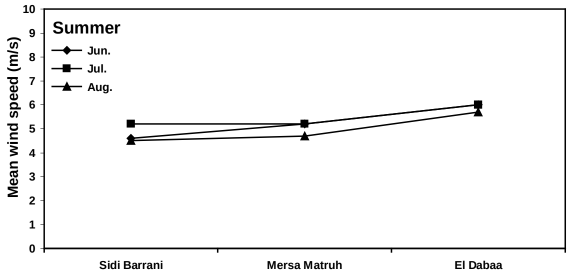
Station	***Month***												**Annual mean (m/s)**	**Wind direction**
	Jan.	***Feb.***	***Mar.***	***Apr.***	***May.***	***Jun.***	***Jul.***	***Aug.***	***Sep.***	***Oct.***	***Nov.***	***Dec.***		
Sidi Barrani	5.6	5.7	5.9	5.7	4.7	4.6	5.2	4.5	4.0	4.2	4.6	5.6	5.0	330 NW
Mersa Matruh	6.1	6.1	6.3	5.7	4.9	5.2	5.2	4.7	4.4	4.3	4.8	5.9	5.3	330 NW
El Dabaa	5.5	5.8	6.1	5.8	5.1	6.0	6.0	5.7	5.0	4.2	4.5	5.5	5.4	330 NW

The mean monthly wind speeds for different seasons of the year are plotted in Fig. (4–2). It can be taken that high wind speeds occur in the winter and spring seasons. This may be due to the Mediterranean Sea secondary depression [10]. During ***winter season***, the wind speed level at the three stations reaches high values of 5.5–6.1 m/s. The maximum mean wind speed occurs at Mersa Matruh during January and February with 6.1 m/s. *In* ***spring season***, the three sites have high values of wind speed 4.8–6.1 m/s, where the maximum value is recorded in Mersa Matruh with 6.3 m/s during March. During ***summer season***, the wind speed level reaches 6.0 m/s at El Dabaa during June and July. *For* ***autumn season***, the maximum mean wind speed is recorded as 5.0 m/s at El Dabaa in September.

One important characteristic which can be derived from Fig. (4–2) is that: the curves of mean monthly wind speeds for all seasons of the year are very similar at the three sites and the variation of their values is very small. This confirms the stability of weather condition at these contiguous sites throughout the year.







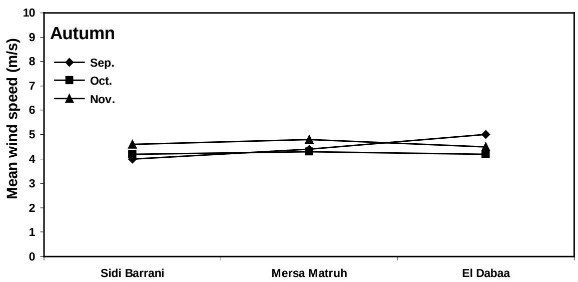


Fig. (4–2). Mean monthly wind speeds at different seasons of the year for three stations.

4.3 Result and discussion

4.3.1 Seasonal power law coefficient and Weibull parameters

Table (4–2) gives the Weibull parameters: Seasonal shape parameter *k* and scale parameter *c*, at 10 m height beside the values of *c* and *k* over the whole year as shown in Fig. (3–7). They are calculated by using Eqn. (2–3), and using the monthly percentage frequency of the mean monthly wind speeds from Ref. [10] of the three stations: Sidi Barrani, Mersa Matruh and El Dabaa. Also the power law coefficient *n* of all seasons is calculated by Eqn. (2–8) and the results are given in Table (4–2). From this table we can derive the following:

(1) The values obtained of *n* in all seasons at the three stations have low values for high speeds c_{10}. These findings agree with Justus et al. [24], who concluded that at high wind speeds, the exponent *n* would equal about 0.15, closely corresponding to 1/6 (0.17) or 1/7 (0.14) power coefficient law often assumed for neutral stability (high wind) cases. This argument breaks down above 100 m.

(2) Small values of *k* obtained at *spring and autumn* seasons indicate widely dispersed data, i.e. the data tend to be distributed uniformly over a relatively wide range wind of speeds [1]. This has a positive implication on wind power generation because this means that the three stations experience a high wind speed enough to operate a wind turbine for at least a short period.

(3) For large values of *k* at *winter and summer* seasons at the three sites, the majority of the wind speed data tend to fall around the mean wind speed, and if the mean wind speed is high, then the wind would be useful for power generation for a large part of time.

(4) El Dabaa station at *summer* season has a large value of the mean wind speed (v_{10}= *5.9 m/s*) and (c_{10}= *5.4 m/s*) and the value of k is high (see Tables (4–1) and (4–2)). Hence, the wind speed is sufficient during this season for high power generation.

Table (4–2): Seasonal power law coefficient and Weibull parameters at 10 m height.

Station	Winter			Spring			Summer			Autumn			Annual mean		Whole year	
	n x10^{-2}	c m/s	k	n x10^{-2}	c m/s	k	n x10^{-2}	c m/s	k	n x10^{-2}	c m/s	k	c m/s	k	c m/s	k
Sidi Barrani	22.61	5.12	4.00	25.88	3.53	0.82	24.06	4.34	2.31	23.94	4.40	1.38	4.35	2.13	4.27	1.47
Mersa Matruh	22.27	5.32	2.40	23.36	4.70	2.00	23.94	4.40	1.81	24.02	4.36	1.74	4.70	1.99	4.27	1.14
El Dabaa	21.82	5.60	0.37	24.78	4.00	1.16	22.14	5.40	5.67	24.85	3.97	1.33	4.72	2.22	4.02	1.19

4.3.2 Extrapolation of wind power density with height

By using the corrected monthly values of available wind power $\mathbf{P_{10}}$ at Sidi Barrani, Mersa Matruh and El Dabaa stations at a height of 10 m from chapter 3 and then by substituting these values in Eqn. (2–14), we obtain the annual wind power at the heights of 70–100 m. The results are given in Table (4–3). We can conclude that the power density obtained from the wind is ranging from 340 to 425 W/m^2 and 450 to 555 W/m^2 at the heights of 70–100 m, respectively. This result is similar to the power density in some European countries [12].

Also at these contiguous stations along the western coast of Mediterranean Sea in Egypt the power density is equally as high as the inland potential close to Vindeby (Denmark). So the foreseen applications at these sites should use large wind turbines with a capacity at least 1000 kW or more for electricity generation [15].

Table (4–3): Annual mean corrected wind power at height of 10, 70 and 100 m.

Name of Station	**P_{10} (W/m^2)**	**P_{70} (W/m^2)**	**P_{100} (W/m^2)**
Sidi Barrani	***79.8***	***343.4***	***448.7***
Mersa Matruh	***94.3***	***405.8***	***530.3***
El Dabaa	***99.2***	***426.9***	***557.8***

4.4 Applications of electricity generation

The typical applications of wind energy at these stations are electricity generation and water pumping using wind turbines, where they are farway the Nile River, see Fig. (4–1). Whereas a technical and economic assessment of electricity generation from two turbines machines having capacity of 300 and 1000 kW considered at these three sites was made in the last chapter 3.

Therefore, in this section, the possibility of generating electricity from wind power at Sidi Barrani, Mersa Matruh and El Dabaa is given using two different systems. The first approach is the installation of a single wind turbine “*Repower MM82*” of high rated power (i.e., 2000 kW). The second approach is by installing an equivalent 25 small wind turbines “*Lagerwey LW 18/80*”, each of 80 kW rated power, arranged in a wind farm of 2 MW total power. The characteristics of these different wind turbines are shown in Fig. (4–3) and Table (4–4).

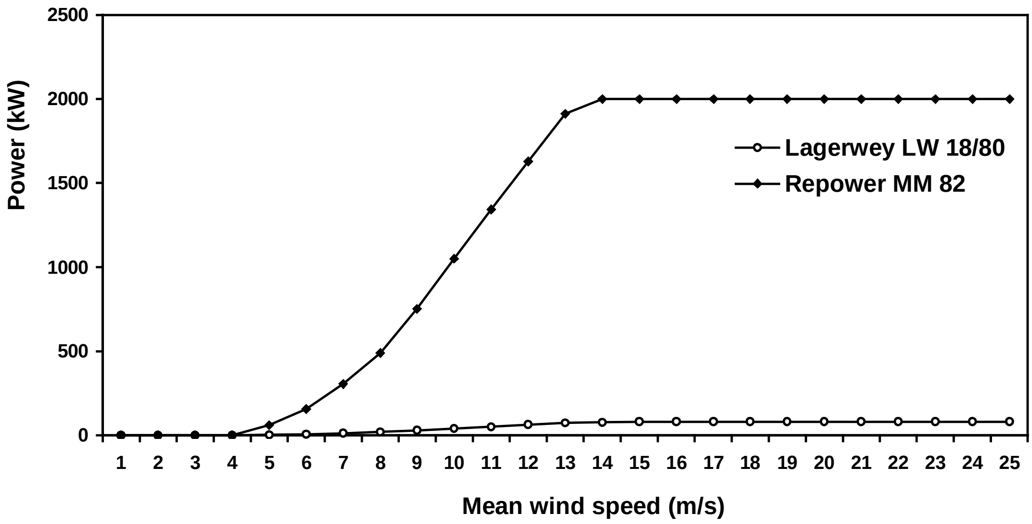


Fig. (4–3). The power curve for the two chosen wind turbines [70].

http:// www.repower.de

Table (4–4): Characteristics of the selected wind turbines.

Characteristics	***Turbine (3)***	***Turbine (4)***
Turbine model	***Lagerwey LW 18/80***	***Repower MM82***
Rated Power (P_r) (kW)	***80***	***2000***
Hub height (m)	***40***	***100***
Rotor diameter (m)	***18***	***82***
Swept area (m^2)	***254***	***5281***
Number of blades	***2***	***3***
Cut-in wind speed (V_{ci}) (m/s)	***3***	***4***
Rated wind speed (V_r) (m/s)	***14***	***13***
Cut-off wind speed (V_{co}) (m/s)	***25***	***25***
Price / Euro	***97,145***	***1,850,000***

4.4.1 *Estimation of the energy output from the single turbine "Repower MM82"*

Recently, in this calculation process we introduce both the power output curve of the wind turbine and the wind velocity distribution of the wind regime, and combine them to calculate the output of the chosen wind turbine and also the availability of the output [20].

We must calculate the wind speed at the hub height of this turbine. This is done by using Eqn. (2–13). In doing so, the annual mean wind speed for Sidi Barrani, Mersa Matruh and El Dabaa will be : 8.89, 9.42 and 9.60 m/s at 100 m height, respectively. Given the power curve of the turbine "*Repower MM82*", the WASP program was used to estimate the actual yearly energy production at the three stations [53–55]. The yearly energy output, $\boldsymbol{E_{out}}$ (kWh/year), for these stations is summarized in Table (4–5). The annual energy production was found to be (7118.2, 7765.5 and 7975.3 MWh/year), respectively.

Table (4–5): The annual energy production from the two different systems at the three selected sites.

Name of Station	E_{out} (kWh/year)	
	Wind farm (2 MW) / H= 40 m	Single machine (2 MW) / H= 100 m
	Lagerwey LW 18/80	Repower MM82
Sidi Barrani	4,726,226.3	7,118,226.2
Mersa Matruh	5,318,903.6	7,765,541.5
El Dabaa	5,510,702.2	7,975,302.9

4.4.2 Estimation of the energy output from the 2 MW–wind farm

The wind farm to be installed at the three sites consist of 25 wind turbines having the power curve as shown in Fig. (4–3). For Sidi Barrani, Mersa Matruh and El Dabaa, the annual mean wind speed is calculated to be : 7.07, 7.50 and 7.64 m/s at 40 m height, respectively. This is done by using Eqn. (2–13) at the hub height of the turbine "*Lagerwey LW 18/80*". Using these data in combination with WASP program, the annual energy production was found to be (472.6, 531.8 and 551.0 MWh/year) for the three stations, respectively, see Table (4–5).

Fig. (4–4) shows the relation between the yearly energy output as a function of mean wind speed for the two cases (single turbine and wind farm) at the three sites. From this figure we can derive:

(1) The maximum yearly energy is derived from a wind speed of 11 m/s in case of single 2 MW wind turbine and 10 m/s in case of wind farm. Where the bulk of the annual energy (in all stations) is obtained for wind speeds between 4 to 24 m/s for single 2 MW turbine, and from 4 to 18 m/s for the wind farm.

(2) In the case of a single 2 MW turbine, the accumulated annual wind energy in the considered stations ranges from 839 MWh (in Sidi Barrani station) to a maximum of 917 MWh (in El Dabaa station) per year. However, in the case of the wind farm, the range is from 639 MWh/y to 703 MWh/year for the stations Sidi Barrani and El Dabaa, respectively.

(3) Very little wind energy is available below a wind speed of 3 m/s in the two cases.

(4) The use of a single 2 MW wind turbine at the three stations will produce more energy per year than the wind farm of 2 MW. The maximum yearly energy gain from the wind turbines for the two cases studies is found to be 5510 MWh/y and 7975 MWh/y at El Dabaa station, see Table (4–5).

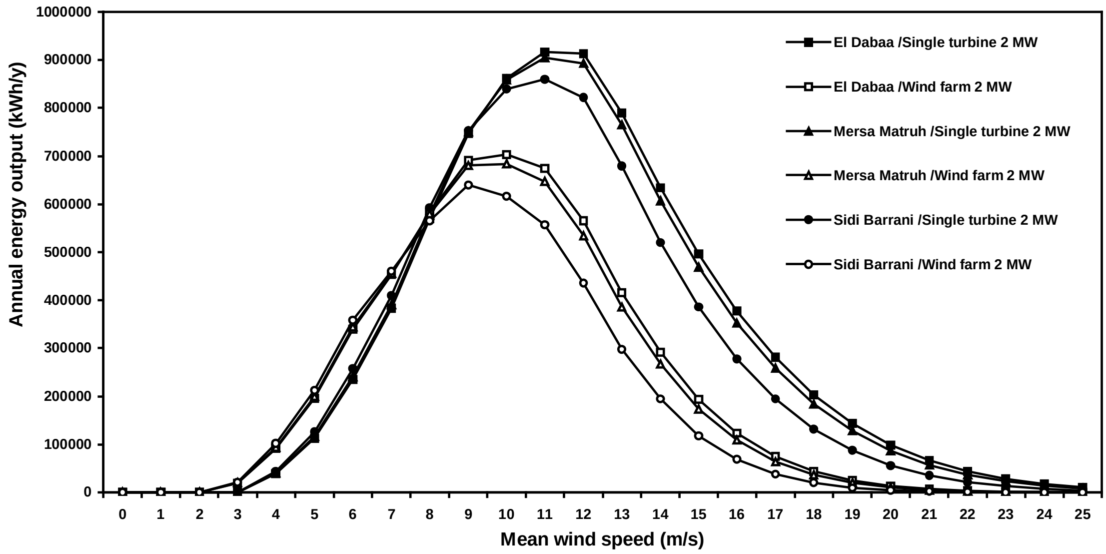


Fig. (4–4). Annual energy output from the two different WEC systems: single turbine of 2 MW and wind farm of 2 MW total power, as a function of mean wind speed at three stations in Egypt.

4.5 Economic and cost analysis

In this section, an analysis of the cost of the kWh of electricity generation from the two different systems will made, one using a large single wind turbine with a capacity of 2 MW and the other using 25 small wind turbines of 80 kW each arranged in a wind farm of 2 MW total power. The yearly energy output of each system at each site will be determined, and the electricity generating costs in each case will also be calculated and compared with the generating costs of generating electricity using diesel oil, natural gas and photovoltaic system furnished by the Egyptian Electricity Authority.

For estimation the cost of one kWh produced by the chosen wind energy conversion systems (**WECS**), the method of the present value of money is employed. In order to calculate the present value of costs (**PVC**) of electricity produced per year, Equation (2–17), given by Lysen [22] and referred by Rehman et al. [50], is used in the present study under assumptions as mentioned in chapter 2.

The price of the wind turbine and civil works for each of the investigated systems were substituted, and in case of the *wind farm*, the capital investment, **I**, is taken as the number of units multiplied by the unit price, from which the **PVC** for each system was obtained [45]. Dividing this value by the total energy produced during the life time of the machines of each system. The present value of the cost for one kWh was obtained for each system at each of the three sites. The results are given in Table (4–6). From this table we can derive:

(1) In the case of a single 2 MW wind turbine, the cost of each kWh electricity produced varies between (1.5–1.7) € cent/kWh. However in the case of the wind farm, the cost of electricity production was found to between (2.9–3.4) € cent/kWh. Hence, the single 2 MW wind turbine was found to be more effective than the wind farm.

(2) These results are in line with the information in chapter 3, where it was concluded that the expected cost of electricity generation was found to be 2 € cent/kWh at El Dabaa station, where another wind turbine with 1000 kW capacity (AN Bonus 1MW/54) had been used. Also, these results agree with El-Kordy et al. [14], who concluded that WECS have the lowest cost in Egypt with 1.8 US cent/kWh, see Table (4–7).

(3) Furthermore, by comparing these results of expected cost of electricity generation by using a single 2 MW wind turbine at Sidi Barrani, Mersa Matruh and El Dabaa stations with the cost of 1 kWh produced by the Egyptain Electricity Authority using diesel oil, natural gas and photovoltaic system, which was found to be very competitive with the actual tariff system in Egypt as shown in Table (4–7).

Table (4–6): The expected cost of kWh of electricity generated using two different WEC systems at the three stations.

Name of Station	Cost (€ cent/kWh)*	
	Wind farm (2 MW)	Single machine (2 MW)
Sidi Barrani	3.4	1.7
Mersa Matruh	3.0	1.6
El Dabaa	2.9	1.5

*** 1 Euro ≈ 7.5 Egyptian pounds; 1 Pound = 100 Piaster.***

Table (4–7): The cost of kWh of electricity generated from different systems actually used in Egypt [14].

System	Cost ($ cent/kWh)
1- WEC system	1.8
2- Combined cycle system	2.4
3- Conventional steam-fuel oil fired	5.4
4- Gas turbine diesel oil fired	5.4
5- Photovoltaic system	14.0

4.6 Conclusions

In this chapter, we found that:

(1) The prevailing wind direction was north–west during the year at the three sites: ***Sidi Barrani, Mersa Matruh and El Dabaa***.

(2) At these contiguous stations along the western coast of Mediterranean Sea in Egypt the power density obtained from the wind, is ranging from 340 to 425 W/m^2 and 450 to 555 W/m^2 at the heights of 70–100 m, respectively, at the three stations. This power density is ***equally*** as high as the inland potential close to Vindeby (Denmark) and is similar to the power density in European countries.

(3) The use of a single wind turbine with 2 MW capacity at the three sites will produce more energy per year than the wind farm of 2 MW total power. The maximum yearly energy gain from the wind turbines in the two cases are 5510 MWh/y and 7975 MWh/y at El Dabaa station.

(4) The single wind turbine 2 MW was found to be more effective than the wind farm. For all three envisaged stations the electricity production cost was found to be ***less than 2 €*** cent/kWh which is about ***half*** the specific cost of the wind farm.

(5) The important result derived from this study encourages the construct-ion of large wind turbines with a power level of 2000 kW at the three stations, where the expected cost of electricity generation was found to be very competitive with the cost of one kWh produced by the Egyptian Electricity Authority as shown at the actual tariff system in Egypt [70].

Chapter 5

The potential of electricity generation on the east coast of Red Sea in Egypt

5.1 Introduction

Egypt has two coastal areas that show significant potential for wind energy exploitation; the north coast on the Mediterranean Sea and the east coast on the Red Sea. It has long been recognized that the wind potential along the coast of Red Sea is markedly higher than in other parts of Egypt–and most other parts of North African deserts as well. However, early estimates of the mean wind speed–based on the existing network of meteorological stations in Egypt–range about 6 m/s in the northern Red Sea. These values which we today know are far too low [12]. In recent 10 years not much work is reported in the literature on wind energy related topics for the Red Sea coast in Egypt. A few studies [2,9,12,13,17] presented the wind energy analysis for some locations. From national programs for wind energy utilization in Egypt, at the Red Sea coast, the master plan calls for 600 MW are expected to be achieved by the year 2005 [9].

The purpose of this chapter is to present an analytical method for the calculation of the wind energy available along the east coast of Red Sea in Egypt. Again the energy yield for two different turbines with a power of 600 kW and 1000 kW will be analyzed. Also the specific cost will be calculated. This evaluation is hoped to be interest for study the effectiveness of the wind machines for assessing the feasibility of using large wind turbines in Egypt.

5.2 Wind characteristics

5.2.1 Wind data analysis

Deserts have a number of characteristics that make them almost ideal for wind energy applications: the pressure on the land is low, access is easy, and construction work is relatively simple. Furthermore, the surface roughness tends to be done low and uniform, so siting of wind turbines can be done primarily with optimization of the energy production–and minimization of cost–in mind. Large desert regions exist with a very promising wind potential. One region with these features is the coast along the Red Sea in Egypt [12], see Fig. (3–1).

Knowledge of the characteristics of the wind regimes in any location is important in the exploitation of wind resources. It is essential in designing or selecting wind conversion systems for any applications [56]. The present study is based on measurements of monthly wind speed, air temperature and air pressure data were taken at a height of 10 m above ground level, in open areas and over roughness class 0 (water). These wind data were obtained from seven meteorological stations along the coast of Red Sea. These locations have been chosen to cover the whole eastern Red Sea coast in Egypt.

Fig. (5–1) shows the locations of these seven stations along Red Sea zone in Egypt. The period of observations that was used equal more than 10 years except two stations (Abu Darag and Zafarana), 5 years. Data was obtained from the Egyptian Meteorological Authority and New & Renewable Energy Authority in Egypt. Table (5–1) shows the physical features of the meteorological stations.

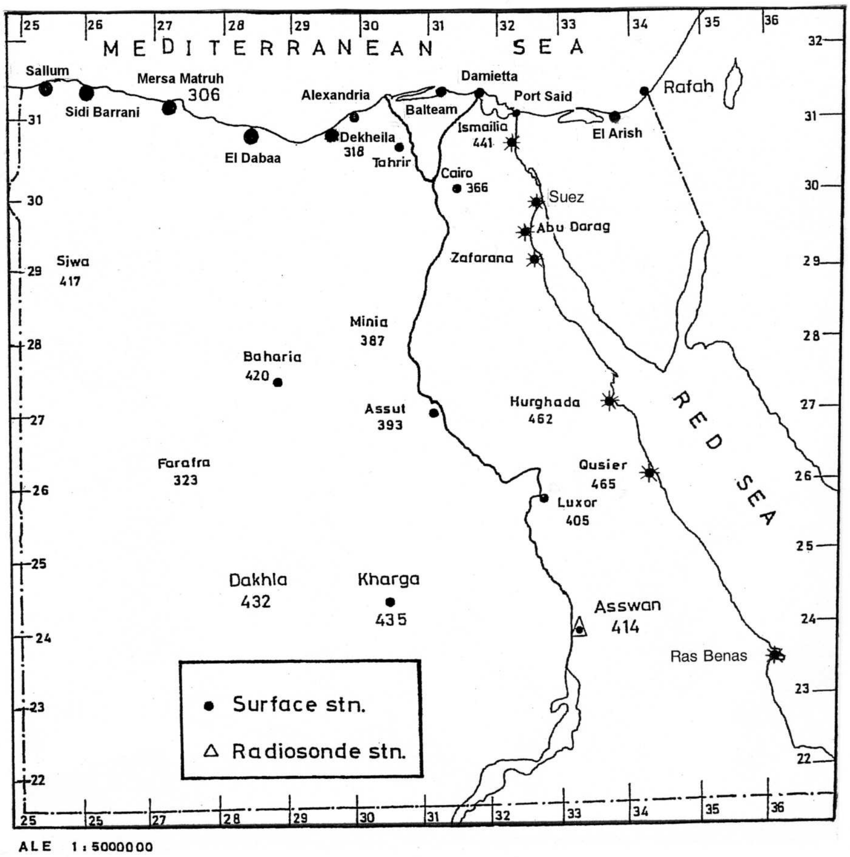


Fig. (5–1). Distribution of some meteorological stations over Egypt [2].

☀ indicates the location of stations under study.

Table (5–1): Physical features of the meteorological stations.

Name of Station	***coordinates***		
	Latitude ***Deg. Min.***	***Longitude*** ***Deg. Min.***	***Elevation*** ***(m)***
Ismailia	30 35	32 14	12.5
Suez	29 52	32 28	2.5
Abu Darag	29 16	32 35	10.0
Zafarana	29 06	32 36	25.0
Hurghada	27 17	33 46	1.0
Quseir	26 08	34 18	8.7
Ras Benas	23 58	35 30	3.7

Table (5–2): Mean monthly and annual wind speed (m/s) and its direction (at a height 10 m).

Station	Month												Annual	Wind
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Mean	direction
Ismailia	2.9	2.6	3.7	3.6	3.4	3.4	3.5	2.8	2.8	2.3	2.2	2.6	3.0	330 NW
Suez	3.0	3.5	4.3	4.7	4.8	4.8	5.4	4.8	5.4	4.5	3.8	3.2	4.4	330 NW
Abu Darag	5.8	6.0	6.6	7.0	8.6	8.1	7.6	8.2	8.7	7.5	6.2	5.8	7.2	360 N
Zafarana	6.2	6.2	6.8	7.1	8.0	8.3	7.6	8.4	8.5	7.4	6.3	5.9	7.3	360 N
Hurghada	5.8	6.3	6.5	6.4	6.9	7.4	6.6	6.6	7.0	5.8	5.3	5.5	6.4	330 NW
Quseir	4.7	4.6	4.8	4.4	4.6	4.8	3.8	3.8	4.7	4.4	5.1	5.1	4.6	360 N
Ras Benas	4.8	4.8	5.4	5.6	6.3	7.1	5.3	5.5	6.4	4.8	5.1	4.7	5.5	360 N

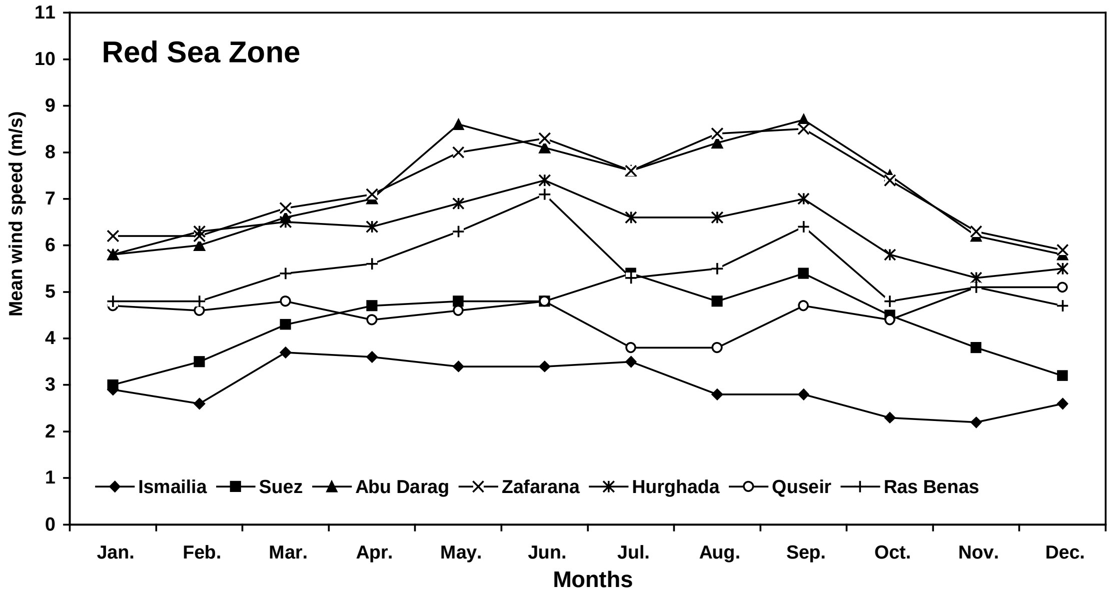


Fig. (5–2). Monthly variation of wind speeds of the year for selected stations.

The mean monthly averages of the wind speed and directions beside the annual means are listed in Table (5–2). The table indicates that the main wind direction over the Red Sea region is north and northwest. Fig. (5–2) illustrates the monthly mean of wind speeds for all stations. It is clear from the figure that the Red Sea zone is windy; it has a maximum value of 8.7 m/s, at Abu Darag in September, and a minimum value of 2.2 m/s, at Ismailia in November. The richness of wind at these stations is due to the fact that Red Sea mountain series in the west side (Egypt) and Asser & Hegaz series (Sudia Arabia) in the east side guide the wind [16].

Mean monthly wind speeds for different seasons of the year are plotted in Fig. (5–3). From this figure, in ***winter season***, it can be seen that the wind speed level at three stations (Abu Darag, Zafarana and Hurghada) reaches high values of 5.5–6.3 m/s. The maximum mean wind speed is 6.3 m/s at Hurghada during February. ***In spring season***, four stations (Abu Darag, Zafarana, Hurghada and Ras Benas) have high values of wind speed 5.4–8.6 m/s, where the maximum value is recorded in Abu Darag with 8.6 m/s during May. ***In summer season***, the wind speed level at (Abu Darag, Zafarana, Hurghada and Ras Benas) reaches the high value of 5.3–8.4 m/s, where the maximum mean wind speed is 8.4 m/s during August at Zafarana. ***In autumn season,*** the last four stations have high values of wind speed 4.8–8.7 m/s, the maximum value is recorded in Abu Darag with 8.7 m/s during September.

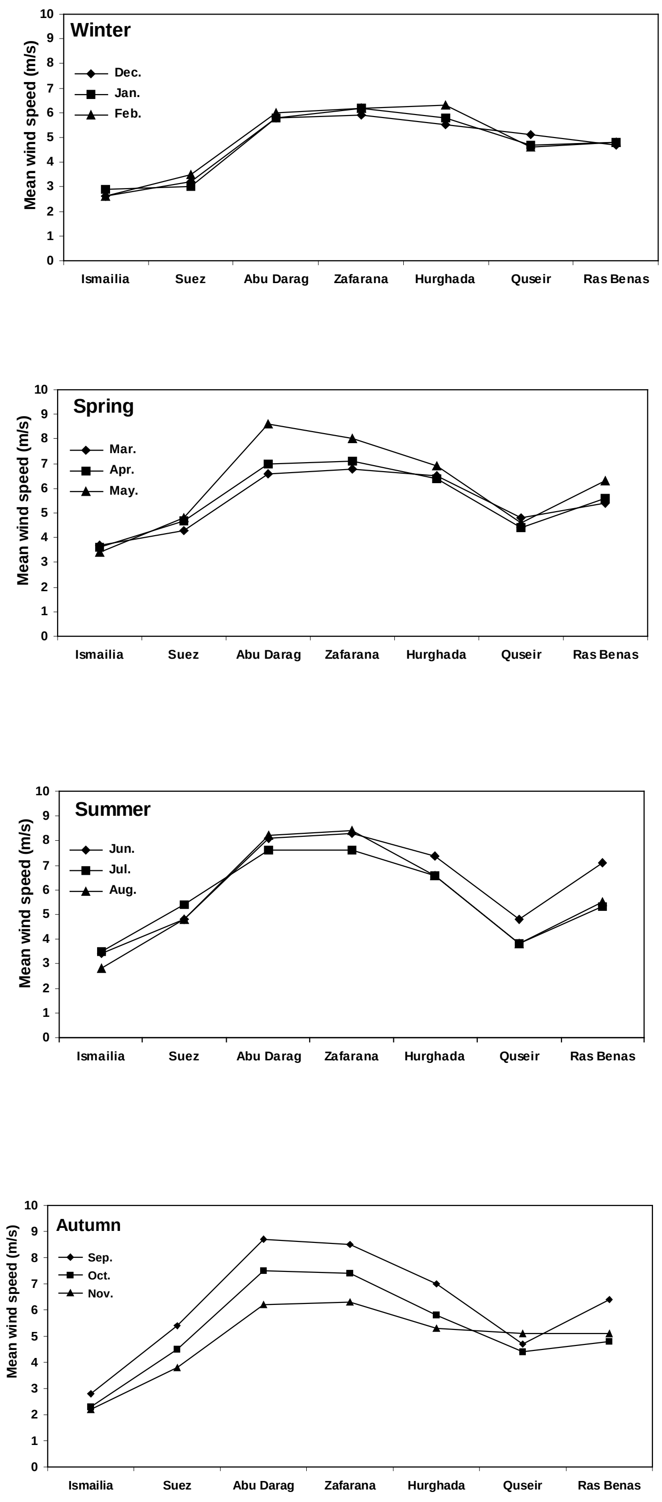


Fig. (5–3). Mean monthly wind speeds at different seasons of the year for all stations.

An integral view of Fig. (5–3) gives the following findings:

(1) The highest values of mean monthly wind speed of all stations occurred in summer and autumn seasons. This can be explained by the weather phenomena of land and sea breezes which are the famous on the coasts of Red Sea.

(2) Also the monthly wind speeds, for all seasons, has the same trend and has pronounced peaks.

(3) In all seasons, we noticed that Ismailia has the minimum values of monthly wind speed.

With respect to the annual mean wind speeds, Fig. (5–4) illustrates such data for a collective view. From this figure it is clear that all stations have an annual mean wind speed more than 3.1 m/s except Ismailia has 3.0 m/s. Indeed, there is an increase of annual mean wind speeds when going from north to south along the Red Sea coasts in Egypt, i.e. from Ismailia to Ras Benas, except in Quseir. These strongly preferred wind direction, however, is not only due to the general pressure gradient from north to south, but also caused by channeling of the wind flow between the mountain ranges that border the Red Sea zone in Egypt on both sides–reaching heights of 1000 m or more above sea level [16]. In general, from the Fig. (5–4) the most promising wind sites are: ***Zafarana, Abu Darag, Hurghada and Ras Benas,*** which have annual mean wind speeds of 7.3, 7.2, 6.4 and 5.5 m/s, respectively.

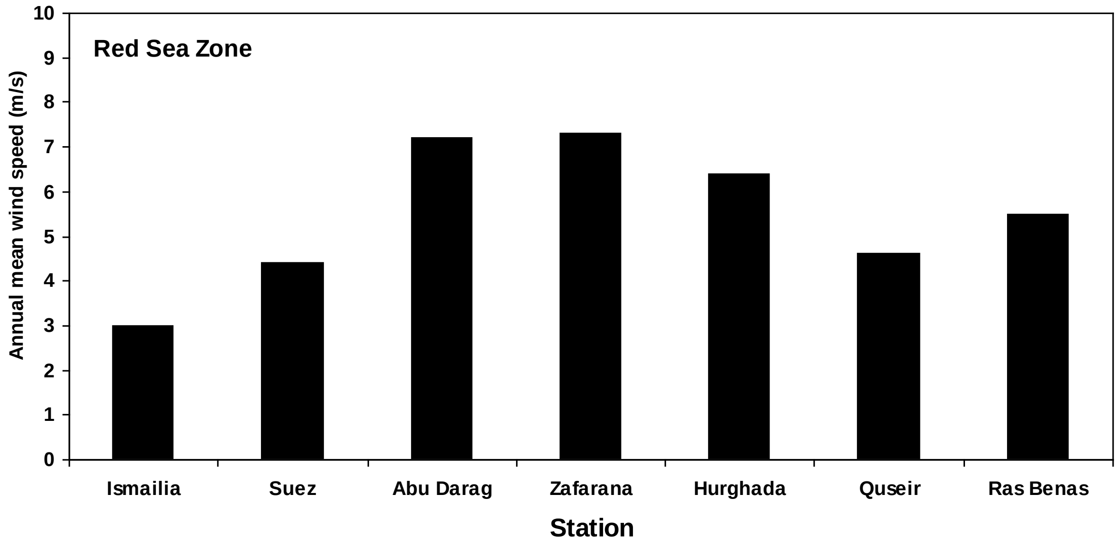


Fig. (5–4). Annual monthly averages of wind speed at a height 10 m for all stations.

5.2.2 Frequency distribution

The wind speed frequency distribution at a given location is either tabulated from wind speed data as a function of time or is approximated by a probability distribution function based on measured data or assumed wind resources characteristics. It is important to know the number of hours per month or per year during which the given wind speeds occurred [57].

Weibull distribution is a good match with the experimental data. The idea is that only annual or monthly average wind speeds are sufficient to predict the complete frequency distribution of the year or the month [22]. The Wind Atlas Analysis Application Program (WASP) is used with the annual values of the monthly average wind speeds for all stations under study. The estimated annual wind speed frequencies of seven stations under this study obtained using WSAP program are shown in Fig. (5–5). The frequency curves in this figure show the most frequent wind speed and number of hours per year can be easily determined for each station [58].

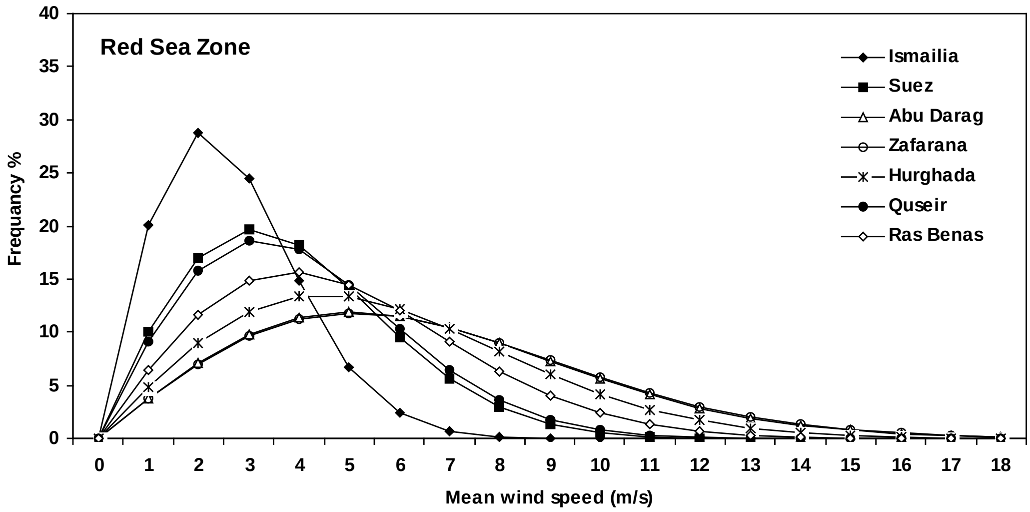


Fig. (5–5). Estimated annual frequency distribution of wind speeds at a height 10 m for all stations.

From Fig. (5–5) the following information can be derived:

(1) All the frequencies have the same trend and have pronounced peaks, which are located in neighbourhood of the mean wind speed.

(2) The peak frequencies of all stations are shifted towards the higher values of mean wind speed. For example: Zafarana has an annual mean wind speed value of 7.3 m/s, see Table (5–2), and a peak frequency value of 11%, where Ismailia has an annual mean wind speed of 3.0 m/s and a peak frequency of 28%.

(3) All stations except Ismailia exhibit a similar trend. Ismailia station has a low relatively constant wind speed.

(4) All stations have peak frequencies in the range between 12% to 20%, except Ismailia station, which has a peak frequency of 28%. This is due to stability of the weather condition at Ismailia.

(5) The considered interval of mean wind speeds varies from 0 to 18 m/s. The representative wind speed curves for (Abu Darag, Zafarana, Hurghada and Ras Benas) stations are spread and they show frequencies from 12 m/s to 17 m/s.

(6) The important characteristic which we note from Fig. (5–5) is that, there are no frequencies for mean wind speed of zero speed (calm winds). This is due to Weibull distribution function is not taken into account calm frequencies, where the mathematical formula of Weibull distribution imposes zero probability [16].

5.2.3 Weibull's parameters

Weibull function is usually used to describe the wind speed distribution of a given location over a certain period of time, typically monthly or annually [59]. In the present study the annual Weibull function and its two parameters are derived from the available data. The results are shown in Table (5–3) and Fig. (5–6).

Table (5–3) gives the Weibull parameters: yearly shape parameter *k*, and scale parameter *c*, at a height 10 m. They are calculated by two methods as mentioned in chapter 2, from Eqns. (2–1) to (2–5). The observed monthly values of ln [– ln (1– F(V))] are plotted against ln V, where V is the mean monthly wind speed, as shown as example in Fig. (5–6). Using the least square method, a straight line is fitted to the above mentioned data which is also drawn in the same figure in order to obtain the parameters *k* and *c*.

It is obvious from results in Table (5–3), that both methods gives identical estimates of the parameter *c* (m/s), but different values of the *k*, although in Method 2: estimation of *c* (m/s) depend mainly on the estimated values of *k* firstly from Eqn. (2–4), the parameter *c* found by the using the estimate of *k* in Eqn. (2–5). This may be due to the fact that, Method 2 (maximum likelihood estimation) leads to large errors in some individual cases and is useful only for ensemble averages [16].

Table (5–3): Yearly shape parameter, k, and scale parameter, c, estimated by two methods at 10 m height.

Name of Station	Method (1)		Method (2)	
	c	*k*	*c*	*k*
Ismailia	--	--	3.19	7.25
Suez	4.45	1.78	4.66	6.59
Abu Darag	8.23	3.00	7.64	8.52
Zafarana	8.23	2.70	7.64	9.86
Hurghada	6.60	2.03	6.63	12.84
Quseir	4.66	2.53	4.73	13.56
Ras Benas	5.67	1.20	5.93	9.75
Mean	6.31	2.21	5.77	9.77

(--) Monthly percentage frequency not available.

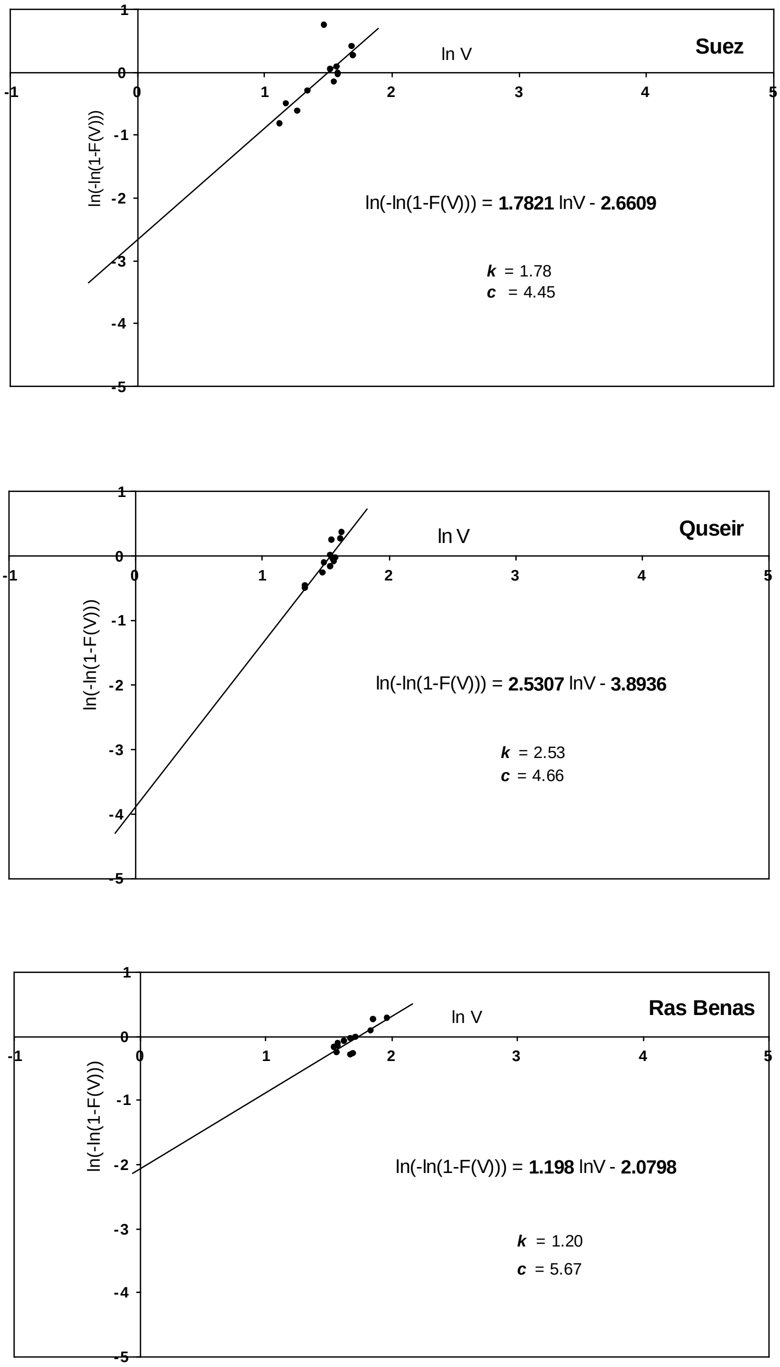


Fig. (5–6). Monthly observed values of ln (– ln (1– F(V))) plotted against ln V, for three stations, through which the Weibull parameters are estimated.

5.2 Wind power density

5.3.1 Wind power and air density estimations

Mayhoub et al. [2], concluded that, for Egypt it is not preferable to estimate wind power values by using a Weibull distribution. However, by applying the available wind data for all stations under study with the Eqns. (2–9)–(2–11), the values of monthly corrected and uncorrected wind power ($\mathbf{P_{10}}$, $\mathbf{P}_{\boldsymbol{wind}}$) throughout the year for all stations were calculated and plotted. The results lead to Fig. (5–7).

From this figure, we found that $\mathbf{P_{10}}$ for Abu Darag and Zafarana stations, is between 200 W/m^2 and 400 W/m^2 for 7 months during the year (nearly in all seasons except in winter). Whereas for both Hurghada and Ras Benas, they have specific power available $\mathbf{P_{10}}$ higher than 100–220 W/m^2 during the year, where Hurghada has $\mathbf{P_{10}}$>100 W/m^2 during the all months of the year except in November, but Ras Benas has $\mathbf{P_{10}}$ >100 W/m^2 during 6 months only.

With respect to the annual mean corrected air density, $\bar{\rho}$, corrected and uncorrected wind power $\mathbf{P_{10}}$ and $\mathbf{P}_{\boldsymbol{wind}}$, were calculated and presented in Table (5–4). The corrected wind power, $\mathbf{P_{10}}$, is always lightly smaller than the uncorrected wind power, $\mathbf{P}_{\boldsymbol{wind}}$ (see Table (5–4)). This deviation is important, since sizing and costing of any technical wind system depend mainly on the wind power. Also from Table (5–4), one can notice that the absolute maximum highest corrected wind power, $\mathbf{P_{10}}$, was recorded at Zafarana (233.72 W/m^2), and the absolute minimum of $\mathbf{P_{10}}$ was recorded at Ismailia (17.20 W/m^2). Also over the year Abu Darag and Zafarana stations have the highest specific power of $\mathbf{P_{10}}$≥232 W/m^2 followed by Hurghada and

Ras Benas. These four locations are suitable for installing large wind energy conversion systems.

To confirm the validity of the results, the greatest negative bias (the ratio of difference between corrected and uncorrected air density to the standard air density) [35], was calculated and listed also in Table (5–4), as bias ($\bar{\rho}$, ρ). For additional confirmation, bias (**P_{10}**, **P_{wind}**) was also calculated for **P_{10}** and **P_{wind}**. From Table (5–4), it is evident that the corrected air density values are almost stable and the shift from the standard air density (ρ = 1.225 kg/m^3) is very small along the Red Sea zone in Egypt.

Table (5–4): Annual corrected air density, corrected and uncorrected specific wind power and bias for all stations beside annual values of air temperature and pressure.

Name of Station	T (K)	P x10^2 (N/m^2)	P_{Wind} (W/m^2)	P_{10} (W/m^2)	$\bar{\rho}$ (kg/m^3)	Bias ($\bar{\rho}$, ρ)	Bias (P_{10}, P_{Wind})
Ismailia	294.8	1013.0	17.54	17.20	1.198	-0.022	-0.019
Suez	295.4	1013.5	54.83	53.28	1.196	-0.024	-0.028
Abu Darag	295.7	1013.0	239.6	232.88	1.194	-0.025	-0.028
Zafarana	296.2	1013.0	240.91	233.72	1.192	-0.027	-0.030
Hurghada	296.2	1011.2	159.82	155.25	1.190	-0.029	-0.029
Quseir	297.3	1011.3	59.42	57.90	1.186	-0.032	-0.026
Ras Benas	298.8	1009.5	106.07	101.80	1.178	-0.039	-0.040

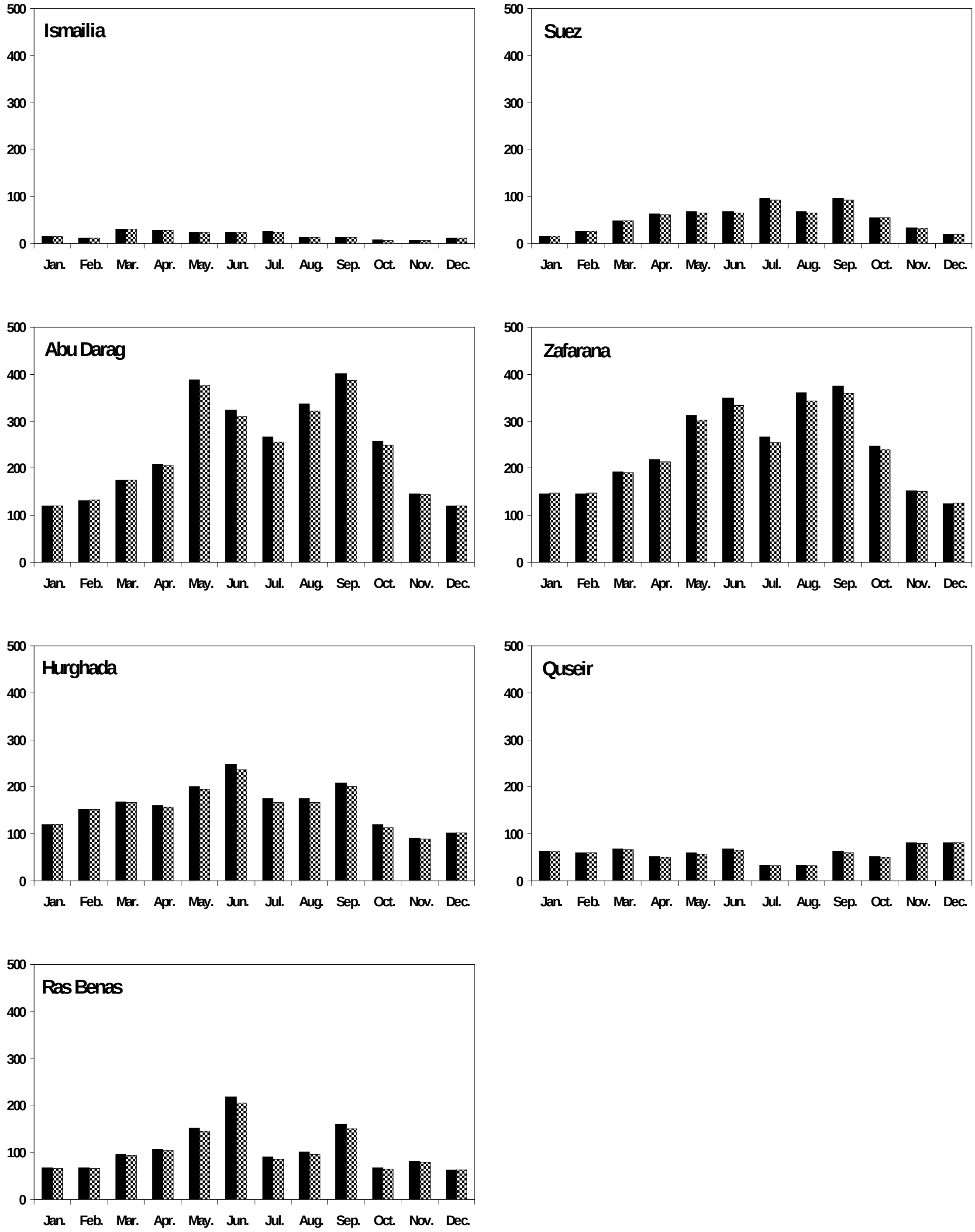


Fig. (5–7). Monthly corrected and uncorrected wind power P_{10} ▒, P_{wind} █ (W/m^2) respectively, throughout the year at a height 10 m for all stations.

For simplicity, when considering the calculation of monthly corrected wind power, $\mathbf{P_{10}}$, from the monthly uncorrected values, $\mathbf{P_{wind}}$, a correlation between $\mathbf{P_{10}}$ and $\mathbf{P_{wind}}$ has been investigated and illustrated by Fig. (5–8). A strong linear fit has been found between $\mathbf{P_{10}}$ and $\mathbf{P_{wind}}$, where we obtain a correlation coefficient CC = 0.99.

The recommended correlation equation is:

$$\mathbf{P_{10}} = 0.96\, \mathbf{P_{wind}} + 1.4226 \qquad (5\text{–}1)$$

Eqn. (5–1) is quite practical to calculate $\mathbf{P_{10}}$, along the coast of Red Sea in Egypt.

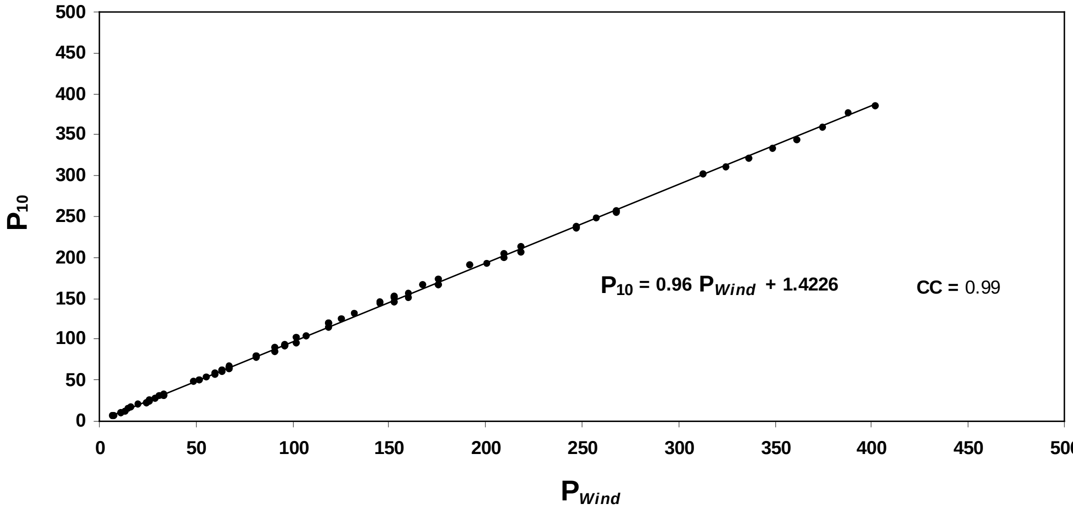


Fig. (5–8). Correlation between monthly values of corrected P_{10} and uncorrected P_{wind} wind power (W/m^2) of the selected stations.

5.3.2 Extrapolation of wind power with height

From our results in Table (5–4), we concluded that, it was evident from the values of corrected air density that they are almost stable and the shift from the standard air density (ρ = 1.225 kg/m^3), is very small. This confirms the stability of the atmosphere along the coast of Red Sea in Egypt. Also due to the common heights of medium and large wind turbines from 50–70 m above the ground level, the vertically extrapolated wind power values from 50 to 70 m for all stations are calculated based on the results of $\mathbf{P_{10}}$ in Table (5–4), and from Eqn. (2–14). The results are presented in Fig. (5–9).

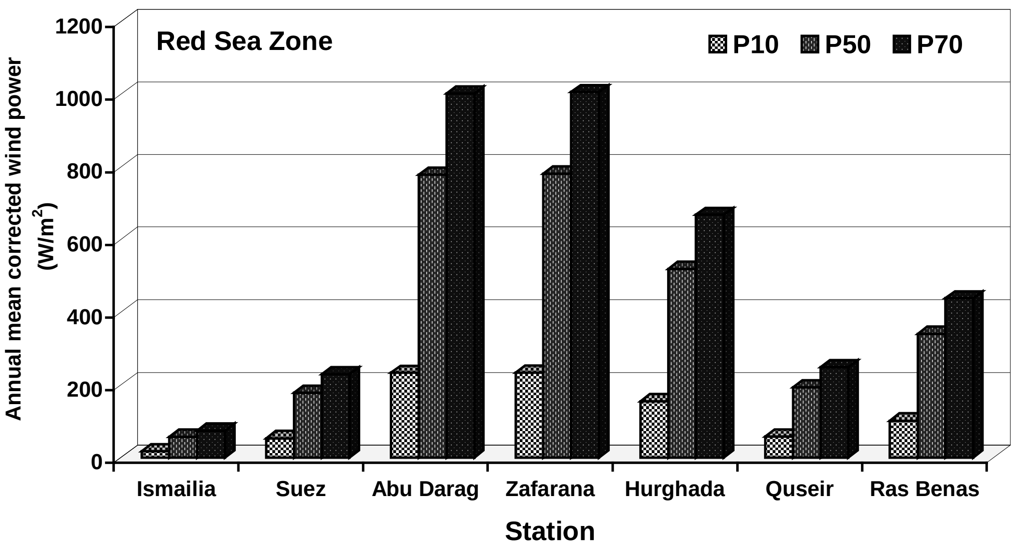


Fig. (5–9). Annual mean wind power throughout the year for all stations at the heights 10, 50, 70 m, respectively.

After having done the extrapolation of wind power with height, a classification into two different regions can be done:

Region A, which contains (***Abu Darag, Zafarana, Hurghada and Ras Benas***), has specific wind power in the range from 340 to 780 W/m^2 at a height 50 m above ground level. While this region has annual mean wind power in the range from 430 to 1000 W/m^2 at a height 70 m. This Region A, is ideal for electricity generation because it has already annual mean wind speeds between 5.5 and 7.3 m/s (at a height 10 m, see Table (5–2)) and has the highest mean power density at the height of 50 and 70 m. Region A is suitable for large wind turbines with a capacity of 1000 kW or more.

Region B, which contains the stations (***Suez and Quseir***), has an annual mean specific wind power between 175–190 W/m^2 and 230–250 W/m^2 at the heights of 50 and 70 m, respectively. Region B is suitable for installations of medium size **WEC** systems with the power range of 150–600 kW.

5.4 Electricity generation and cost analysis

5.4.1 Turbines wind power

In this section, we focus on six stations divided into two Regions A and B. The choice of these sites is based on the data presented in previous sections (see Tables (5–2) and (5–4)). These selected sites are suited for electricity generation. In order to calculate the energy two different turbines were selected: Turbine (5) has rated power P_r = 1000 kW, (with hub height 70 m), for Region A, Turbine (6) has rated power P_r = 600 kW, (with hub height 50 m) for Region B. Table (5–5), lists the characteristic properties of the selected wind turbines. With respect to the wind characteristics the two machines are similar in the values of cut–in speed (V_{ci}), and cut–out speed (V_{co}).

Fig. (5–10) shows the power curve (maximum power from optimum system) for the two selected wind turbines. Whereas at wind speed below 3 m/s, the threshold value, there is no power produced, but for wind speed more than the threshold, the rated power produced increases continuously up to saturation values, between 600 kW to 1000 kW for Turbine (6) and Turbine (5), respectively. A saturation power of 600 kW and 1000 kW corresponds to a wind speed of 15 m/s for both turbines. Both turbines are pitch controlled.

Table (5–5): Main characteristics of both wind turbines.

Characteristics	***Turbine (5)***	***Turbine (6)***
Turbine model	***AN Bonus 1 MW/54***	***AN Bonus 600 kW/44-3***
Rated Power (P_r)	***1000 kW***	***600 kW***
Hub height	***70 m***	***50 m***
Rotor diameter	***54.2 m***	***44 m***
Swept area	***2300 m^2***	***1520 m^2***
Number of blades	***3.0***	***3.0***
Cut-in wind speed (V_{ci})	***3 m/s***	***3 m/s***
Rated wind speed (V_r)	***15 m/s***	***13 m/s***
Cut-off wind speed (V_{co})	***25 m/s***	***25 m/s***
Price / Euro	***899,000***	***490,000***

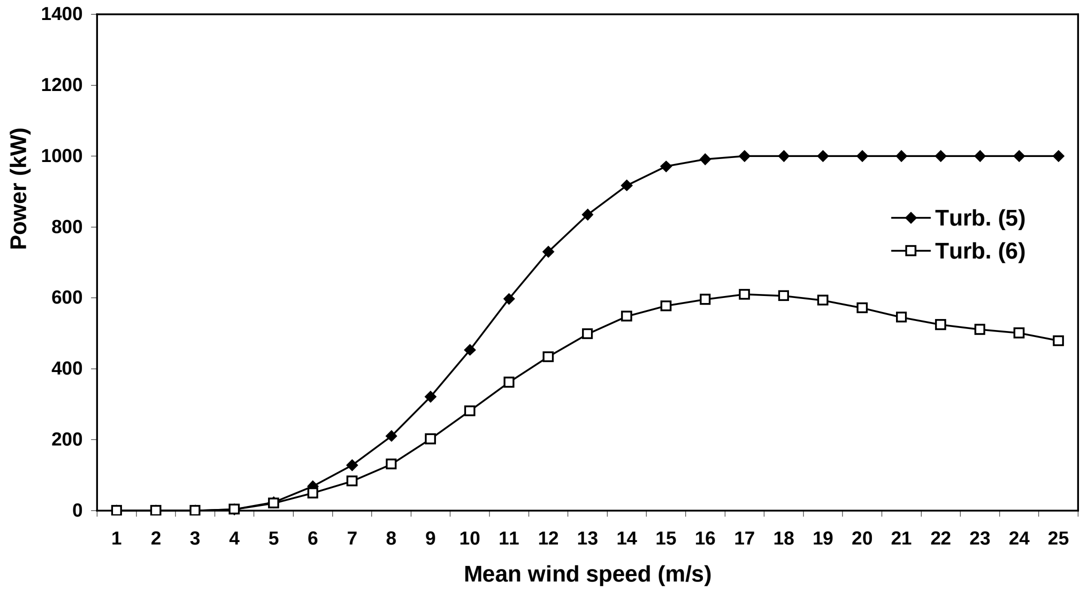


Fig. (5–10). The power curve for the two chosen wind turbine [16].

http://www.anwind.de/1MWe.htm

http://www.anwind.de/600kwce.htm

5.4.2 Extrapolation wind speed at WECS hub height

The wind speed increases with increasing height. The rate of increasing wind speed with height strongly depends upon the roughness of the terrain and the changes in this roughness [20]. As mentioned in the beginning of the study, from the wind atlas analysis the roughness factor is kept constant. Wind data measurements used in this study are based on the standard height of 10 m. In addition, we must find the wind speed at the hub height of the turbine. This is done using Eqn. (2–13). So in Region A, the annual mean wind speed for (Abu Darag, Zafarana, Hurghada and Ras Benas) will be: (11.70, 11.83, 10.33 and 8.90) m/s at 70 m height, respectively.

For Suez and Quseir stations of Region B, the annual mean wind speed is calculated to be 6.52 and 6.85 m/s at 50 m height, respectively.

5.4.3 Wind turbine generation

WASP is based on the physical principles of flow in the atmospheric boundary layer and takes into account the effects of different surface roughness conditions, sheltering effects due to buildings and other obstacles, and modification of the wind imposed by the specific terrain height around the met station [60].

Given the power curve of the Turbines (5) and (6), the WASP program was used to estimate the actual yearly energy production. The yearly energy output, E_{out} (kWh/year), for selected stations is summarized in Table (5–6). Fig. (5–11) shows the relation between the yearly energy output as a function of mean wind speed for the two wind turbines of capacity 1000 and 600 kW for the selected stations.

Table (5–6): Yearly energy gain of Turbines (5) and (6), capacity factor and cost of kilowatt-hour.

Name of Station	WECS and Height	Rated Power (kW)	E_{out} (kWh/year)	C_f	Cost (cent/kWh) (100 cent = 1 Euro)*
Zafarana	Turb. (5) / H= 70m	1000	4704620	0.537	1.26
Abu Darag	Turb. (5) / H= 70m	1000	4654557	0.531	1.27
Hurghada	Turb. (5) / H= 70m	1000	4034500	0.460	1.47
Ras Benas	Turb. (5) / H= 70m	1000	3227969	0.368	1.83
Quseir	Turb. (6) / H=50m	600	1185705	0.225	2.72
Suez	Turb. (6) / H=50m	600	1058528	0.201	3.05

**** 1 Euro ≈ 7.5 Egyptian pounds; 1 Pound = 100 Piaster.***

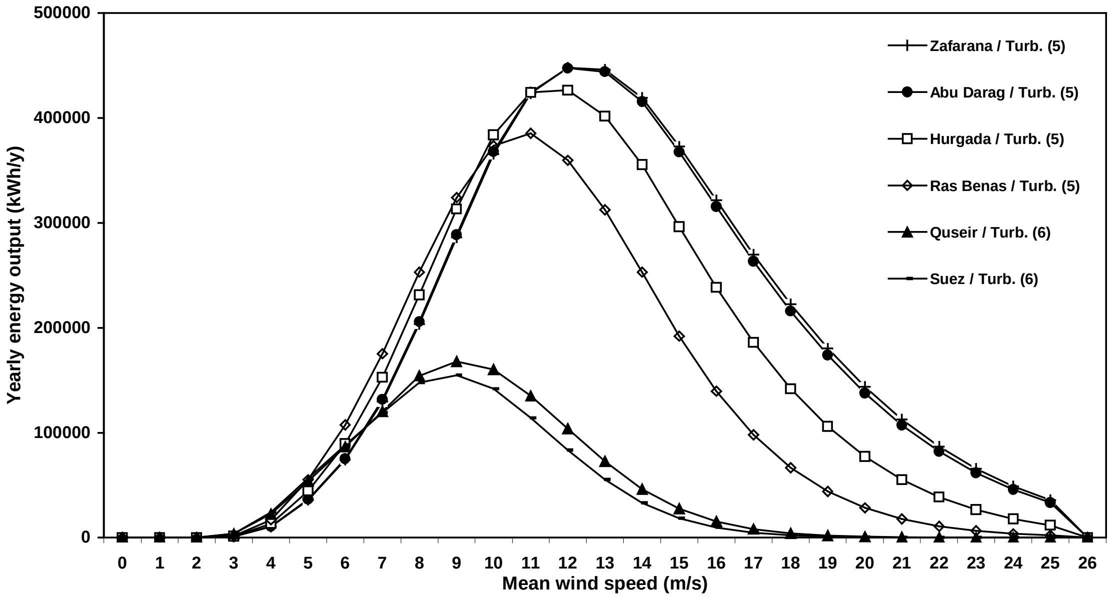


Fig. (5–11). Yearly energy output by Turbine (5) and (6) as function of mean wind speed for selected stations.

From Fig. (5–11) we can derive:

(1) The maximum yearly energy is derived from a wind speed of 12 m/s (Turbine 5) and 9 m/s (Turbine 6).

(2) In case of Turbine (5), the accumulated annual wind energy in the considered stations ranges from 385 MWh (in Ras Benas station) to a maximum of 448 MWh (in Zafarana station) per year.

(3) In case of Turbine (6), the range is from 154 MWh/y to 167 MWh/y for the stations Suez and Quseir, respectively.

(4) The bulk of the annual energy (in all stations) is obtained for wind speeds between 4 to 24 m/s for Turbine (5), and from 4 to 17 m/s for Turbine (6).

(5) Very little wind energy exists below a wind speed of 3 m/s (typical cut-in wind speed for the Turbines (5) and (6)).

Finally, it is noted from Table (5–6) that, the maximum yearly energy gain from the wind Turbine (5) is 4704 MWh/y and 4654 MWh/y, at Zafarana and Abu Darag stations, respectively.

5.4.4 Economic analysis: (capacity factor and cost analysis)

The capacity factor C_f, is one of the performance parameters of wind turbines which both the user and manufacturer need to know. The annual capacity factor for considered turbines in our study is estimated using Eqn. (2–16) and is introduced in Table (5–6). We note from the table that, the capacity factor is high ***0.53*** for two stations (***Zafarana and Abu Darag***) which have the higher (E_{out}).

On the other hand, there are many methods which have been used to evaluate the cost of energy production. In this study the value of money method has been used, which is the best method to determine the present value of costs (**PVC**) of electricity produced per year under the mentioned assumptions with Eqn. (2–17) [50].

For ***Region A*** we study the 1000 kW wind energy conversion system and for ***Region B*** we look at the 600 kW system. The technical data of the chosen wind energy system are given in Table (5–5). By substituting these values in Eqn. (2–17) with all the mentioned assumptions we obtain the **PVC** for each location. The cost of electricity per kWh at each location is obtained by dividing the **PVC** by the total energy production of the wind turbine over its life time (20 years), see Table (5–6).

In Region A, the cost of each kWh electricity produced varies between 1.26 and 1.83 € cent/kWh (1EURO≈7.5 Egyptian pounds). It is pointed out that the costs of wind power utilization at Zafarana, Abu Darag, Hurghada and Ras Benas is approximately a ***third*** of the average cost given in Table (5–7) [49,61].

In Region B, the cost of electricity produced from wind turbine of capacity 600 kW was found to between 2.72 and 3.05 € cent/kWh.

These results agree with El-Kordy et al. [14], who concluded that from the results of an economic evaluation, **WECS** have the lowest cost in Egypt with 1.8 US cent/kWh.

Table (5–7): Average cost of new electricity generation [61].

System	***Cost (cent/kWh)***
Solar thermal hybrid	*6.9*
Nuclear	*7.3*
Natural gas (intermediate)	*6.4*
Hydro	*12.1*
Wind	*6.0*
Coal boiler	*5.8*
Natural gas (combined)	*4.7*
Geothermal	*5.6*
Biomass	*6.1*

5.5 Conclusions

The findings in this chapter can be summarized as:

(1) Wind energy potential along the east coast of Red Sea in Egypt is more abundant, where the chances of having wind speeds less than 3.1 m/s are very small.

(2) The very small shift of the values of air density from the standard air density (ρ = 1.225 kg/m^3) along the east coast of Red Sea may cause an improvement in the power output of wind turbines (Table (5–4)).

(3) There are two regions in which wind power can be used economically on a significant scale. ***Region A***: ***Zafarana, Abu Darag, Hurghada and Ras Benas***. They have annual mean wind speeds 7.3, 7.2, 6.4 and 5.5 m/s, respectively at 10 m height (Table (5–2)). The region is suitable for large–wind turbines each having a capacity of at least 1000 kW. ***Region B***: ***Quseir and Suez*** which have moderate wind speeds at 10 m height (4.6 and 4.4) m/s, respectively. This region is suitable for installations of wind turbines of medium size (150–600) kW capacity, used in conjunctions with other resources to meet the present electricity demands.

(4) The power density obtained from the wind in ***Region A***, is ranging from 340 to 780 W/m^2 and 430 to 1000 W/m^2 at the heights of 50–70 m, respectively, which is higher than the power density in European countries. At Abu Darag and Zafarana sites the power density is ***twice*** as high as the inland potential close to Vindeby (Denmark). Therefore wind farms can be installed in these four sites of Region A, using a large number of wind turbines, like Turbine (5) with 1 MW, for electricity generation.

(5) In Quseir and Suez (***Region B***), the sites have wind speeds estimated at 50 m height: 6.85 and 6.52 m/s, respectively. They have wind power density ranging from 175 to 190 W/m^2 at the same height. So the two foreseen applications in this Region B should use wind turbines with a capacity of 600 kW, like Turbine (6).

(6) ***In Region A***, the expected cost of each kWh produced using the chosen wind turbine of 1 MW varies between 1.26 and 1.83 € cent/kWh.

(7) ***In Region B***, the cost of electricity produced from wind turbine of capacity 600 kW was found to vary between 2.72 and 3.05 € cent/ kWh.

Finally, we can reach the conclusion that the expected electricity generation costs of 1 kWh in four locations of ***Region A*** along the Red Sea in Egypt is ***less than 2*** € cent/kWh, which is very competitive compared to the actual tariff system as shown in Table (5–7) [16].

New information about recent developments in Egypt are introduced on *http://www.iset.uni-kassel.de*. Where the wind park Zafarana on the Red Sea coast is being developed over a number of years as a German-Danish-Egyptian joint-venture: its installed capacity will reach 430 MW by the end of year **2007**.

Chapter 6

Electricity generation and wind potential assessment at Hurghada, Egypt

6.1 Introduction

Hurghada city is growing very fast due to the development of Tourism. This development has been going on for some time and is expected to continue. How long this will continue and what the level of the tourist activities is going to rise? These are not known update. Sitting is defined as the estimation of the mean power produced by a specific wind turbine at on or more specific locations [17]. In the last chapter 5, we made a technical assessment of the potential of electricity generation along the Red Sea in Egypt. The assessment entailed studies of seven different sites from north to south along the east coast of Red Sea. Hurghada station was one of the most promising sites and will be in the focus of this study because it is the most populated and industrial region at the Red Sea. At the meteorological station in Hurghada wind data have been recorded over 23 years. Therefore the seasonal variation of the measured and calculated frequency distribution of the wind speed at this site could be analyzed.

The main aim of this chapter is to present a new analytical method to choose suitable large wind turbines with low rated wind speed and high capacity factor at this site. An estimation of the expected cost in € cent/kWh for the power level of 2000 kW is done.

6.2 Seasonal wind speed frequency distribution

Engineers should know the real distributions of the wind speed, solar energy and other alternative sources of energy, that could be obtained from real recordings of random series in order to explore these sources efficiently [62,63].

Fig. (6–1) shows the location of Hurghada city at Red Sea zone in Egypt. The measurements of monthly wind speed and percentage frequency of winds were taken at a height of 10 m above ground level in an open area. Data were obtained from the Egyptian Meteorological Authority, for a period of more than 23 years as shown in Table (6–1). The wind potential analysis of this region is reported at chapter 5.

Table (6–1): Percentage frequency of wind speeds within the following speed ranges and mean wind speed in (m/s) at a height of 10 m.

Month	0.5 – 1.5	2 – 3.1	3.6 – 5.2	5.7 – 8.2	8.7 – 10.8	11.3 – 13.9	14.4 – 17	≥ 17.5	Mean wind speed
Jan.	8.0	12.0	22.3	35.7	13.8	5.9	1.1	0.1	5.8
Feb.	7.3	11.0	21.3	30.8	15.9	9.6	1.8	0.2	6.3
Mar.	8.2	11.3	20.0	27.5	15.8	11.9	3.0	0.3	6.5
Apr.	11.3	12.0	18.2	25.4	15.4	11.6	3.3	0.3	6.4
May.	7.8	9.8	17.3	29.3	17.9	13.5	2.9	0.4	6.9
Jun.	6.0	7.5	15.0	30.6	21.9	16.0	2.2	0.1	7.4
Jul.	8.8	10.4	16.7	30.1	18.8	12.0	1.5	0.0	6.6
Aug.	7.8	9.8	17.3	31.5	19.9	10.4	1.3	0.0	6.6
Sep.	4.5	7.1	15.4	33.2	23.6	13.7	1.6	0.0	7.0
Oct.	10.4	11.6	20.1	31.4	16.0	7.2	0.7	0.0	5.8
Nov.	11.6	13.5	21.9	35.2	12.1	4.0	0.3	0.1	5.3
Dec.	9.4	13.6	22.1	35.2	12.7	4.9	0.4	0.0	5.5
Annual mean	8.4	10.8	19.0	31.3	17.0	10.1	1.7	0.1	6.4

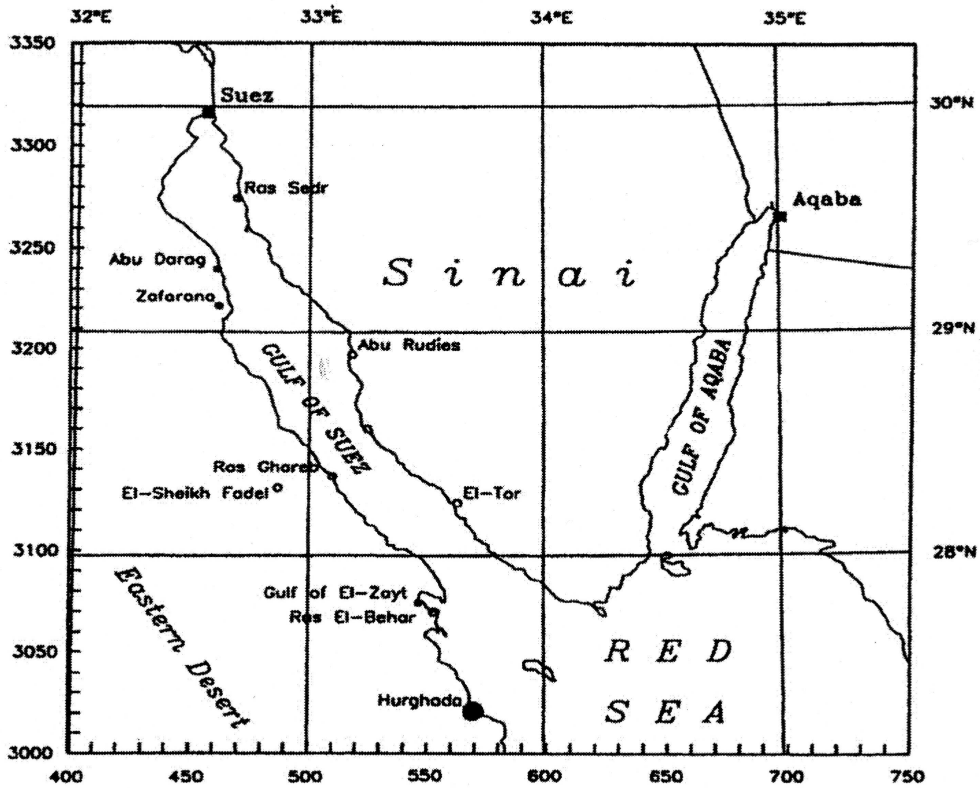


Fig. (6–1). Distribution of meteorological stations over Gulf of Suez and northern Red Sea; (●) indicates the location of Hurghada station [12].

Table (6–2): Percentage frequency of seasonally wind speeds within the following speed ranges and mean wind speed of all seasons (m/s) and its direction (at a height 10 m).

Season	0.5 – 1.5	2 – 3.1	3.6 – 5.2	5.7 – 8.2	8.7 – 10.8	11.3 – 13.9	14.4 – 17	≥ 17.5	Mean wind speed	Wind direction
Winter	8.2	12.2	21.9	33.9	14.1	6.8	1.1	0.1	5.9	330 NW
Spring	9.1	11.0	18.5	27.4	16.4	12.3	3.1	0.3	6.6	330 NW
Summer	7.5	9.2	16.3	30.7	20.2	12.8	1.7	0.0	6.9	330 NW
Autumn	8.8	10.7	19.1	33.3	17.2	8.3	0.9	0.0	6.0	330 NW
Annual mean	8.4	10.8	19.0	31.3	17.0	10.1	1.7	0.1	6.4	330 NW

The topography of Hurghada station is responsible for the generally high mean wind speeds measured. As the wind flow enters the Red Sea the terrain opens up, the wind looses momentum, and the mean wind speed immediately decreases by about 20 per cent [12], see Fig. (3–1).

Table (6–2) gives the measured percentage frequency (*f* %) of wind speeds for all seasons at Hurghada and its direction. The results lead to Fig. (6–2a). The statistical analysis of wind speeds has been made using WASP program [64]. The estimated wind speeds frequencies obtained for all seasons are plotted in Fig. (6–2b).

Fig. (6–2) gives the following findings:

(1) The curves of measured and estimated frequency distributions of wind speeds at Hurghada for all seasons of the year are very similar in the considered interval which varies from 0 to 18 m/s and there are no frequencies for mean wind speed of zero speed (calm winds).

(2) The bulk of (*f* %) ranges between 15% and 35% of the measured data at winds between 3.6 and 10.8 m/s.

(3) All the measured frequencies have the same trend and have pronounced peaks in all seasons, which confirms the stability of weather condition at Hurghada throughout the year.

(4) All seasons have peak frequencies in the range between 27% and 34% with wind speeds between 5.7 and 8.2 m/s.

(5) Hurghada has measured frequencies in the order of 10% for speeds greater than or equal to 11 m/s (at a height 10 m) throughout the year.

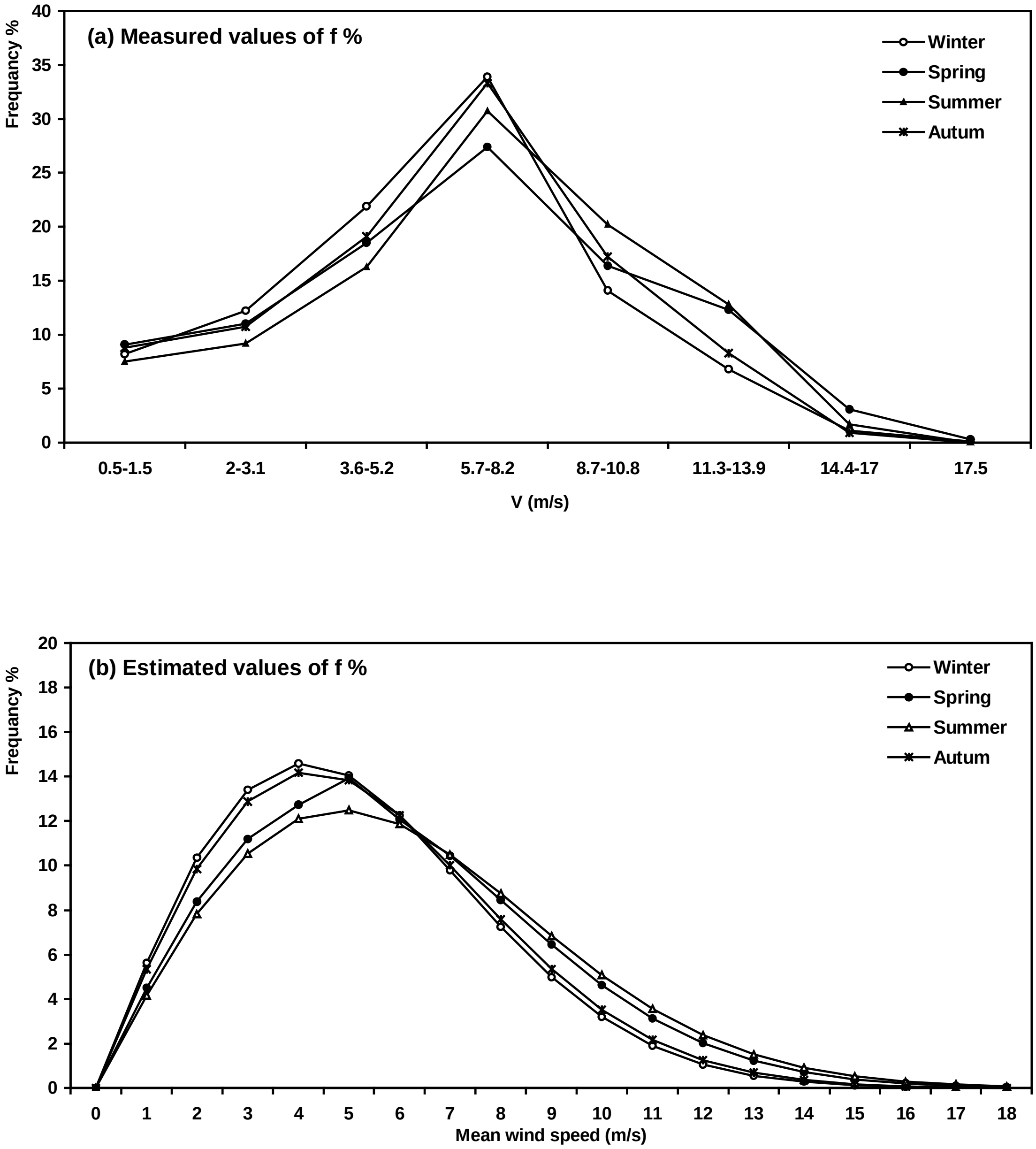


Fig. (6–2). Measured and estimated percentage frequency of wind speeds of all seasons at Hurghada.

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6.3 Seasonal Weibull parameters at different heights and power law coefficient

The calculation of the output of a wind turbine at a particular site requires knowledge of the distribution of the wind speed. Most attention has been focused on the Weibull function and the adaptation to the experimental data [65]. Table (6–3) gives the Weibull parameters: seasonal shape parameter *k,* and scale parameter *c*, at different heights (10–70) m. They are calculated by using Eqns. (2–6) and (2–7) as mentioned in chapter 2, and by using the data from Ref.[12]. Also the power law coefficient of all seasons is calculated using Eqn. (2–8) and the results are given in Table (6–3). From this table we can derive the following Table (6–4).

From Tables (6–3) and (6–4)we can derive:

(1) The values obtained of *n* have low values for high speeds (c_{10} *or* v_{10}). These agree with Justus and Amir Mikhail [24], who concluded that for high wind speeds (v_{10}≥10 m/s), the exponent *n* would equal about 0.15, closely corresponding to 1/6 (0.17) or 1/7 (0.14) power law coefficient often assumed for neutral stability (high wind) cases. This argument breaks down above 100 m (300 ft).

(2) From Table (6–4), small values of *k* are obtained at ***autumn*** and ***spring*** seasons. This indicates widely dispersed data, i.e. the data tend to be distributed uniformly over a relatively wide range wind of speeds. This has a positive implication on wind power generation because this means that Hurghada station experiences enough wind speed to operate a wind turbine for at least a short period [19].

(3) For large values of *k* at ***winter*** and ***summer*** seasons, the majority of the wind speed data tend to fall around the mean wind speed, and if the mean wind speed is high, then the wind would be useful for power generation for a large part of time.

(4) Hurghada station at ***summer*** season has a large value of the mean wind speed (c_{10}= *6.55 m/s*) and (v_{10}= *6.9 m/s*) and the value of *k* is high (see Tables (6–2) and (6–4)). Hence, the wind speed is sufficient during this season for high power generation.

Table (6–3): Calculated values of c and k at different heights for all seasons and the power law coefficient for each season at Hurghada.

Season	***Height*** (m)	***c*** (m/s)	***k***	**Power Law Coefficient** *n*
Winter	10	6.23	2.21	0.2088
	30	7.84	2.45	
	50	8.72	2.58	
	70	9.35	2.67	
Spring	10	6.15	1.63	0.2099
	30	7.75	1.8	
	50	8.62	1.9	
	70	9.25	1.97	
Summer	10	6.55	2.05	0.2044
	30	8.20	2.27	
	50	9.1	2.39	
	70	9.75	2.47	
Autumn	10	5.83	1.82	0.2146
	30	7.38	2.02	
	50	8.24	2.12	
	70	8.85	2.20	

Table (6–4): Seasonal power law coefficient and Weibull parameters at 10 m height.

Season	***autumn***	***spring***	***winter***	***summer***
n x10^{-4}	2146	2099	2088	2044
c_{10} (m/s)	5.83	6.15	6.23	6.55
k_{10}	1.82	1.63	2.21	2.05

6.4 Monthly wind power and plant load factor estimations

Egypt does not possess very high conventional fossil fuel reserves, but possesses rich renewable energy resources such as hydro, solar, geothermal and wind. Of these, wind seems to be the most suitable renewable energy resource for electricity production [19]. The wind power estimation is based on a simple model. Where the total theoretical mechanical power available in a given air stream is equal to the volumetric rate times the kinetic energy per unit volume of air stream. This is expressed in Eqn. (2–12). However, not all of the power $\mathbf{P_{10}}$ can be converted into useful work.

Based on simple momentum theory, it has been shown that the maximum power any wind turbine can convert into useful energy is equal to **0.593** from available power in wind. The factor **0.593** is commonly known as the Betz limit. It represents the maximum theoretical value of the power coefficient. This limit cannot be surpassed by any improvements of wind energy conversion systems (**WECSs**). The real wind energies that could be produced by modern aero-generators are much less and vary between 25% and 48% [66–68].

On the other hand, the plant load factor (**PLF**) is defined, as mentioned in Eqn. (2–15) in chapter 2, as the ratio between the actual power available in the wind and the rated power of the **WECSs**. This factor is used in determining the monthly and annual output of the wind energy conversion system. Then by using the corrected monthly values of available wind power $\mathbf{P_{10}}$ of Hurghada at a height of 10 m from Table (5–4) and then by substituting these values in Eqns. (2–12) and (2–14). Also we obtain the monthly wind power and monthly **PLF** at hub height 70 m for turbine 1000 kW, using Eqn. (2–15), see Table (6–5) and Fig. (6–3).

From these table and figure, we found that:

(1) The values of monthly **PLF** are greater than **0.60** for 3 months, May, June and September.

(2) The average annual **PLF** was found to be 48% for the considered wind turbine with a capacity of 1 MW.

(3) Hence, we recommended that the envisaged **WECSs** at Hurghada should have a rated power greater than 1000 kW at 70 m.

Table (6–5): Specific wind power at the heights of 10 m and 70 m and plant load factor of turbine 1000 kW considered at Hurghada for each month.

Month	P_{10} (W/m^2)	$P_{m\,70}$ (kW/m^2.month)	*PLF* at P_{rated}=1000 kW
Jan.	119.72	370.9	0.37
Feb.	152.77	473.4	0.47
Mar.	166.05	514.5	0.52
Apr.	156.24	484.1	0.48
May.	193.38	599.2	0.60
Jun.	235.61	730.0	0.73
Jul.	166.28	515.2	0.52
Aug.	166.10	514.7	0.52
Sep.	200.20	620.3	0.62
Oct.	115.43	357.70	0.36
Nov.	89.57	277.5	0.28
Dec.	101.63	314.9	0.31
Annual mean	155.25	481.0	0.48

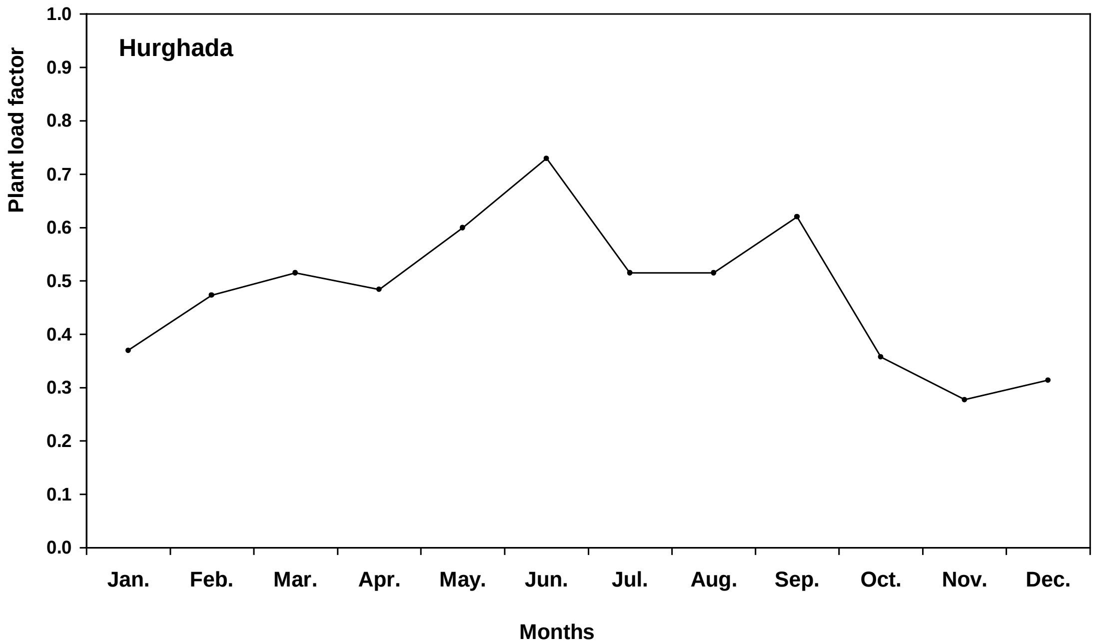

Fig. (6–3). Monthly plant load factor for considered wind turbine of 1000 kW at height 70 m.

6.5 Rated wind speed and capacity factor of WECS

The following analysis is to help designers and users to choose the most suitable wind turbines. The annual energy products of 10 different commercial wind turbines (each two of them have the same hub height and the same rated power but are different in their rated wind speed (V_r)) were calculated by WASP program using measured data [54]. The result are presented in Fig. (6–4).

The capacity factor is an important index in measuring the energy yield of a wind machine [69]. The rated powers of these turbines are 150, 250, 600, 750 and 1000 kW. Table (6–6) shows their annual energy productions, E_{out}, and capacity factors. Where capacity factor is the ratio between the actual yearly energy output, E_{out}, and the rated yearly energy, which was calculated by using Eqn. (2–16).

From Table (6–6) we can conclude:

(1) It is obvious that the use of wind turbines with lower rated speeds will produce more energy in a year than wind turbines with higher rated speeds, see Fig. (6–4), where the peak energy output is shifted towards wind turbines which have lower values of rated wind speeds.

(2) From the results in the table, which are presented in Fig. (6–5), we can conclude that the capacity factor is greater for wind turbines with lower rated wind speeds.

(3) Designers and users can optimize the selection of wind turbines by relating the mean wind speed of the location to optimum rated wind speed (the speed at which annual output of used turbine is maximum).

Table (6–6): Annual energy output and capacity factor of 10 different commercial wind turbines (each two of them have the same hub height and rated power but they are different in their rated wind speed).

Turbine model	***Hub height*** (m)	***Rated power*** P_r (kW)	V_{ci} (m/s)	V_r (m/s)	V_{co} (m/s)	E_{out} (kWh/year)	C_f (per cent)
An Bouns 150/23	30	150	4	**13**	25	489,995.2	**37%**
Nordex N 27/150	30	150	4	**11**	25	628,685.9	**48%**
Lagerwey LW 30/250	40	250	4	**14**	25	843,658.1	**39%**
Nordex N 29/250	40	250	3	**13.5**	25	872,512.2	**40%**
Nordex N 43/600	40	600	3	**14**	25	2,024,773.4	**39%**
Dewind 46/600	40	600	3	**12**	25	2,262,145.7	**43%**
Repower 48/750	50	750	4	**15**	25	2,692,360.5	**41%**
Lagerwey LW 50/750	50	750	3	**14**	25	2,914,805.3	**44%**
An Bouns 1MW/54	70	1000	3	**15**	25	4,034,499.5	**46%**
HSW 1000/57	70	1000	4	**13**	25	4,217,892.7	**48%**

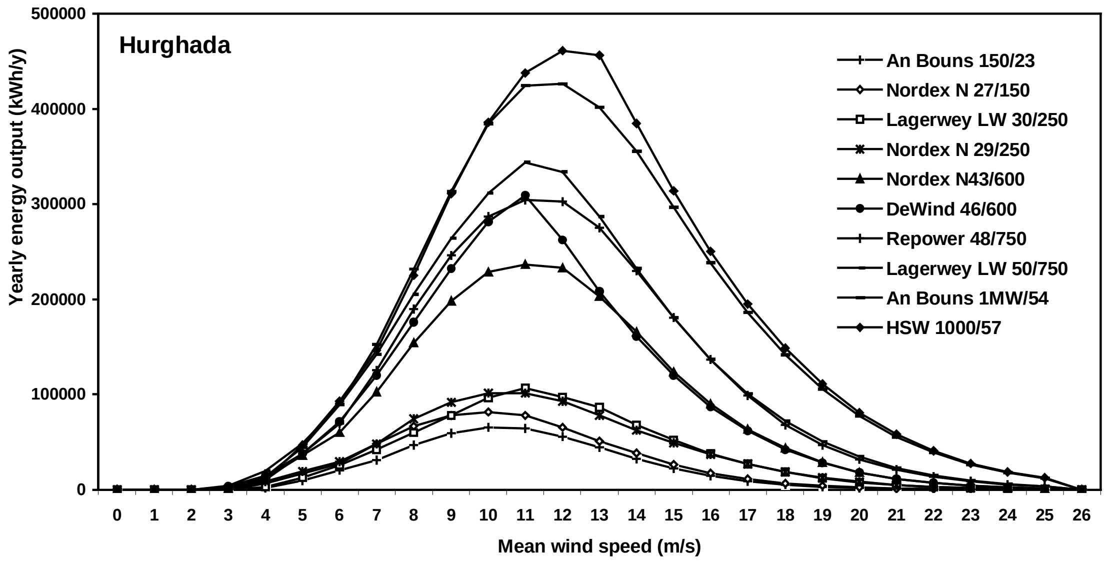

Fig. (6–4). Yearly energy output from 10 wind turbines, they have rated powers 150, 250, 600, 750 and 1000 kW.

6.6 Economic analysis

6.6.1 Selecting best fit turbines and energy output

In this section, the choice of the best suitable wind turbine for Hurghada station is discussed. Whereas a technical and economic assessment of elect-ricity generation from two turbines machines having capacities of 600 and 1000 kW considered in seven different sites along Red Sea in Egypt (Hurghada station was one of them) was made in chapter 5, and from the data presented and results in previous sections in this chapter. From the results (Table (6–5) and Fig. (6–3)) where the values of monthly plant load factor are greater than **0.6** in some months throughout the year for considered wind turbine with capacity of 1 MW, the use of a wind turbine which has a rated power greater than 1000 kW at Hurghada station is recommended. Then, based on results (see Table (6–6) and Fig. (6–4)) it is concluded that the use of a wind turbine with lower rated speed will produce more energy over a year than a wind turbine with higher rated speed. And the results from Table (6–6) lead to Fig. (6–5), we know that the capacity factor is greater for wind turbine with lower rated wind speeds. Hence, for this study the commercial wind turbine "***Repower MM82***" with a capacity of 2 MW was chosen, which has lower rated speed of 13 m/s competitive with another commercial wind turbines of capacity 2000 kW.

The technical data of the wind turbine used are summarized in Table (6–7). It is necessary to know the wind speed at wind turbine hub height. The wind power law has been recognized as a useful tool to transfer the anemometer data recorded at certain levels to the desired hub center [59]. Thus the estimated annual mean wind speed at 100 m (hub height of this wind machine) will be 11.29 m/s at Hurghada station.

The annual energy that can be generated at the considered site by a *Repower MM82* wind machine was obtained using wind power curve of the machine and 23 years wind duration data recorded at this site [70]. Yearly energy gain, $\boldsymbol{E_{out}}$ (kWh/y), is estimated by using WASP program. The result is about 9663 MWh and the obtained capacity factor **55%** is high, see Table (6–7).

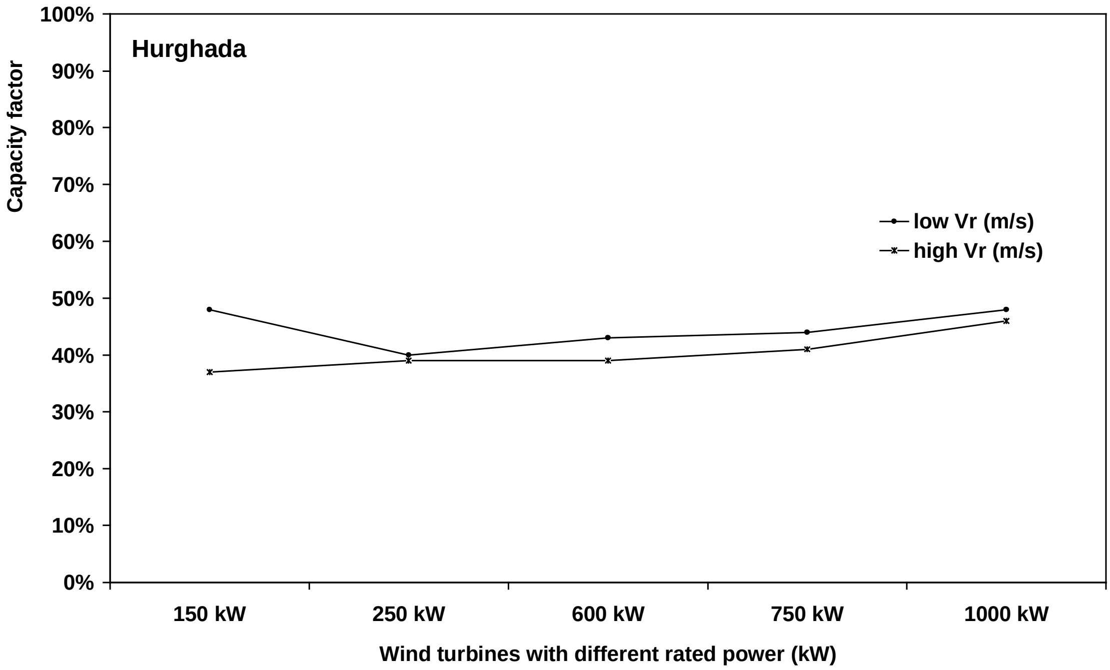

Fig. (6–5). Annual capacity factor for 10 different wind turbines with rated speed as parameter.

Table (6–7): Yearly energy gain, capacity factor and technical data of wind turbine Repower MM82.

Turbine model	***Repower MM82***
E_{out} (kW/h/year)	***9,663,578.2***
C_f (per cent)	***55%***
Rated Power (P_r)	***2000 kW***
Hub height	***100 m***
Rotor diameter	***82 m***
Swept area	***5281 m^2***
Number of blades	***3***
Cut-in wind speed (V_{ci})	***4 m/s***
Rated wind speed (V_r)	***13 m/s***
Cut-off wind speed (V_{co})	***25 m/s***
Price / Euro	***1,850,000***

Further technical details can be found in *http:// www.repower.de*. The type of control is pitch control.

6.6.2 Cost analysis

The estimation of the cost per kWh of energy produced by the wind turbine "*Repower MM82*", which has a capacity of 2000 kW, to operate at Hurghada station has been done under the mentioned assumptions with Eqn. (2–17).

From Table (6–7), the price of this turbine *Repower MM82* is taken to be € 1,850,000, and the cost of civil work (20% of the price) = € 370,000. Therefore investment **I** = € 2,220,000, $\mathbf{C}_{omr}$ = € (1,850,000/20) x 0.25 = € 23,125 and **S** = € (2,220,000 x 0.1) = € 222,000, where **r** = 0.15 and **i** = 0.12.

Using all these values in Eqn.(2–17), we get:

$$\mathbf{PVC} = 2{,}443{,}615.8$$

Also from Table (6–7), the annual output of turbine *Repower MM82* at Hurghada is 9,663,578.2 kWh. So the total output over 20 years = (20 x 9,663,578.2) kWh.

Hence, the specific cost per kWh = [(2,443,615.8)/ (20 x 9,663,578.2)) = ***1.26 € cent***.

These results are in line with the results in chapter 5 where we concluded that the expected cost of electricity generation on the east coast of Red Sea in Egypt was found to be ***1.47*** € cent/kWh at Hurghada station, where another wind turbine with 1000 kW capacity (AN Bonus 1MW/54) had been used. So the ***Repower MM82*** system is very competitive. And in this study the expected cost per kWh at Hurghada will be ***10 Piaster***, where 1 € ≈ 7.5 Egyptian pounds, (one Pound = 100 Piaster).

6.7 Conclusions

From this chapter, we can draw the following conclusions:

(1) All the measured percentage frequency of wind speeds of this site have the same trend and have pronounced peaks at all seasons, which confirms the stability of weather condition at Hurghada station throughout the year.

(2) During the ***summer season*** a high value of mean wind speed 6.9 m/s occurs (at a height of 10 m), so the wind is sufficient during this season for high expected power generation.

(3) The prevailing wind direction was north–west during the year in Hurghada, see Table (6–2).

(4) The use of wind turbines with lower rated speeds will produce more energy in a year than wind turbines with higher rated speeds, also the capacity factor is greater than with wind turbines characterized by lower rated wind speeds.

(5) The important result derived from this study encourages the construction of wind farms at Hurghada for electricity generation using large wind turbines each having a capacity of greater than 1000 kW and we recommend usage of the wind turbine model "***Repower MM82***" of capacity 2 MW at 100 m hub height. The expected electricity generation costs of 1 kWh using this machine was found to be ***1.26 € cent***, which is a very competitive price compared to the actual tariff system [19].

Chapter 7

Conclusions

From the last calculated results and measured data we can conclude that:

(1) The wind energy potential along the coast of Mediterranean Sea in north Egypt is quite promising. Because the required wind speed range for electricity generation is 5–6 m/s, the following sites are suitable for electric wind generators: ***Sidi Barrani, Mersa Matruh and El Dabaa.***

(2) The shift of the values of air density from the standard air density (ρ=1.225 kg/m^3) along the coast Mediterranean Sea is very small. This confirms the stability of the atmosphere along the coast of Mediterranean Sea in Egypt.

(3) The prevailing wind direction was north–west during the year at the three contiguous sites: ***Sidi Barrani, Mersa Matruh and El Dabaa***.

(4) At these contiguous stations along the western cost of Mediterranean Sea the power density obtained from the wind, is ranging from 340 to 425 W/m^2 and 450 to 555 W/m^2 at the heights of 70–100 m, respectively, at the three stations. This power density is ***equally*** as high as the inland potential close to Vindeby (Denmark) and is similar to the power density in European countries.

(5) The use of a single wind turbine with 2 MW capacity at the three sites will produce more energy per year than the wind farm of 2 MW total power. The maximum yearly energy gain from the wind turbines in the two cases are 5510 MWh/y and 7975 MWh/y at El Dabaa station.

(6) The single wind turbine 2 MW was found to be more effective than the wind farm. For all three envisaged stations the electricity production cost was found to be ***less than 2€*** cent/kWh which is about ***half*** the specific cost of the wind farm.

(7) The important result derived from this study encourages the construction of large wind turbines with a power level of 2000 kW at the three stations, where the expected cost of electricity generation by using a single 2 MW wind turbine was found to be very competitive with the cost of kilowatt–hour produced by the Egyptain Electricity Authority.

Then, the wind energy potential along the east coast of Red Sea in Egypt was analyzed:

(1) The wind energy potential along the east coast of Red Sea in Egypt is high. The very small shift of the values of air density from the standard air density (ρ = 1.225 kg/m^3) along the east coast of Red Sea may cause an improvement in the power output of wind turbines.

(2) There are two regions in which wind power can be used economically on a significant scale. ***Region A***: ***Zafarana, Abu Darag, Hurghada and Ras Benas***. These locations have annual mean wind speeds of 7.3, 7.2, 6.4 and 5.5 m/s, respectively at 10 m height. The region is suitable for large–wind turbines each having a capacity of at least 1000 kW. ***Region B***: ***Quseir and Suez***, these stations have moderate wind speeds at 10 m height 4.6 and 4.4 m/s, respectively. This speed level is suitable for installations of wind turbines of medium size (150–600) kW capacity. The systems can be used in conjunctions with other resources to meet the present electricity demands.

(3) The power density obtained from the wind in ***Region A***, is ranging from 340 to 780 W/m^2 and 430 to 1000 W/m^2 at the heights of 50–70 m, respectively, which is higher than the power density in European countries. At ***Abu Darag and Zafarana*** sites the power density is ***twice*** as high as the inland potential close to Vindeby (Denmark). Therefore wind farms can be installed in these four sites of Region A, using a large number of wind turbines, like wind turbines of 1 MW, for electricity generation.

(4) The expected electricity generation costs of 1 kWh in four promising locations: ***Zafarana, Abu Darag, Hurghada and Ras Benas*** along the coast of Red Sea using a wind turbine with 1 MW is ***less than*** 2 € cent/kWh, which is very competitive compared to the actual tariff system.

Finally, Hurghada station was one of the most promising sites along the east coast of Red Sea in Egypt. It is the most populated and industrial region at the Red Sea. From our investigation and results we conclude:

(5) The stability of weather condition at Hurghada station throughout the year is high and the prevailing wind direction was north–west during the year.

(6) The use of wind turbines with lower rated speeds will produce more energy in a year than wind turbines with higher rated speeds, also the capacity factor is greater compared with wind turbines characterized by lower rated wind speeds.

(7) The important result derived from this study encourages the construction of wind farms at Hurghada for electricity generation using large wind turbines each having a capacity of greater than 1 MW. We recommend usage of the wind turbine model "***Repower MM82***" with a capacity of 2 MW at 100 m hub height. The expected electricity generation costs of 1 kWh using this machine was found to be ***1.26 € cent***, which is very competitive price compared to the actual tariff system.

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Annex A

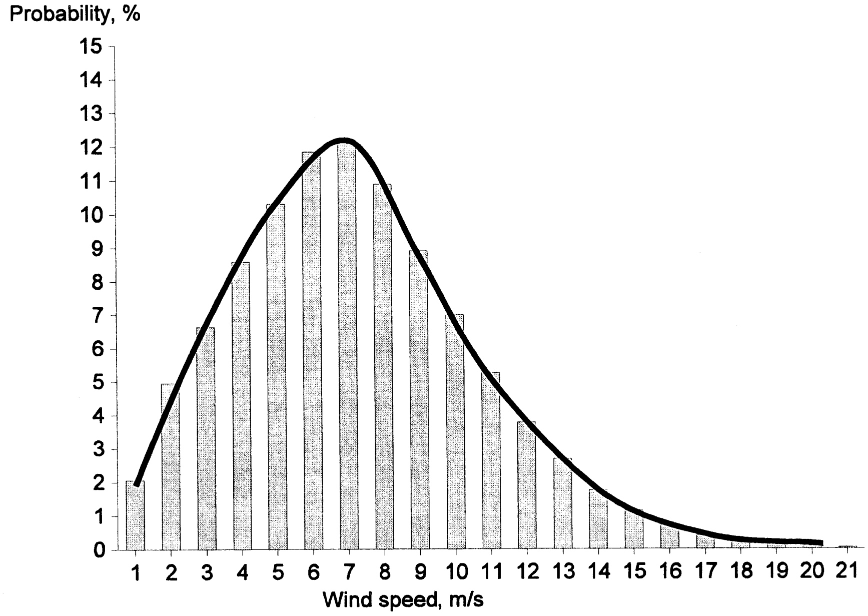

Figure A: Distribution of hourly mean wind speeds of a typical lowland site [71].

Annex B

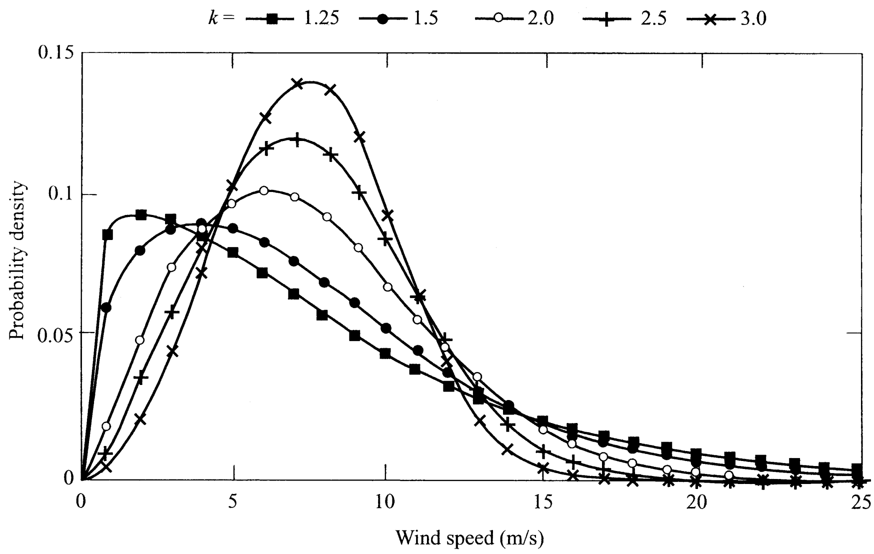

Figure B: Example Weibull Distributions [72].