The Influence of the Atmospheric Stability Conditions on the Available Wind Energy for Three Libyan Coastal Cities

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Abstract: The lowest portion of the atmosphere is vital to lives, infrastructure, and activities. It means air quality, air motion and momentum, solar and wind energy, and weather safety measures. Wind speed observations at three different heights for three Libyan coastal sites; Magron, Musrata and Darnah, were documented and analysed. Wind speed profiles were estimated employing the two common methods: logarithmic wind and power law profiles. The seasonal and annual patterns, and atmospheric stability classifications were obtained. The daily wind shear variation and wind velocity profiles were determined at different atmospheric stability conditions, neutral, stable and unstable.

The results confirm that the highest wind shear occurs during stable conditions at night and for longer in winter days, and the lowest during unstable and neutral atmospheric conditions near midday specially in summer days. Non-dimensional wind speed profiles were obtained and their behaviour was identified and compared. The available wind energy history was evaluated considering the effect of atmospheric stability conditions on the estimated extracted energy for each site

تأثير استقرارية الغلاف الجوي على الطاقة المتاحة من الرياح لثلاث مدن على الساحل الليبي

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ملخص: تعتبر الطبقة الدنيا من الغلاف الجوي أمراً حيوياً للحياة، وللبنية التحتية وللأنشطة. فهي تعنى بجودة الهواء وحركته وزخمه، الطاقة الشمسية وطاقة الرياح، وتدابير السلامة الجوية. تم توثيق وتحليل قياسات سرعة الرياح عند ثلاثة ارتفاعات مختلفة لثلاثة مواقع ساحلية ليبية؛ وهي المقرون ومصراته ودرنه تم تقدير منحنيات سرعة الرياح باستخدام الأسلوبين الشائعين؛ منحنى

الرياح اللوغاريتمي ومنحنى القانون المرفوع بالأس. تم الحصول على الأنماط الموسمية والسنوية، وتصنيفات استقرار الغلاف الجوي. وقد تم تحديد التغير في القص الريحي اليومي وأيضا تحديد منحنيات سرعة الرياح في ظروف استقرارية الغلاف الجوي المختلفة؛ محايدة ومستقرة وغير مستقرة.

وتؤكد النتائج أن أقصى قص ريحي يحدث أثناء الحالة المستقرة في الليل، وهو بزمن أطول في أيام الشتاء، وأن الأدنى يحدث خلال حالة الغلاف الجوي غير المستقرة والمحايدة قرب منتصف النهار خاصة في أيام الصيف. تم الحصول على منحنيات سرعة الرياح اللابعدية والتعرف على سلوكها ومقارنتها. وتم تقييم صورة الطاقة الريحية المتاحة باعتبار تأثير ظروف استقرار الغلاف الجوي على الطاقة المستخلصة المقدرة لكل موقع.

Keywords: *atmospheric boundary layer, thermal and static stratifications, turbulence, mixing, diffusion, convection, wind speed profiles, atmospheric stability parameters, available wind energy.*

1. INTRODUCTION

Referring to the physics of the lowest portion of the atmosphere, the surface-air interaction occurs in two primary forms: mechanical and thermal. The mechanical contact arises from the friction exerted by the wind against the ground surface and the thermal contact between the lower atmosphere and the ground surface due to the incident solar radiation [1].

The atmosphere near the surface of the earth can be divided into different layers. The lowest portion of the atmosphere is vital to life, infrastructure, and activities; air quality, air motion and momentum, solar and wind energy, and weather safety measures. Surface roughness is composed of elements such as buildings, forests, hills and mountains. The turbulent exchange occurs over a wide range of scales from millimetres to kilometres in size. These differently sized turbulent elements can be thought of as air parcels. These air parcels are called eddies and they have similar thermodynamic properties. Eddies transport energy and gases by their random motion in the atmosphere [2].

At sunrise, the sun starts to heat up the ground. The ground surface is heated up faster than the air. An air parcels above the ground surface is therefore warmer than the air above it. This warm air has higher buoyancy and it starts to rise. When it rises, it comes across colder air and hereby continues to rise. The air flow in the surface layer becomes turbulent. The turbulence increases and is generally higher at daytime. These conditions are called unstable conditions, which mean that the potential air temperature decreases with height in the surface layer. The effect of the shear stresses due to friction of the ground is reduced with height, whereas the effect of buoyancy increases with height. The height of the atmospheric surface layer is therefore increased in daytime in comparison to night time [1].

At night, the ground is usually colder than the air. An air parcel that is rising from the ground soon encounters warmer air, and therefore stops rising. The turbulence is hereby dampened and the turbulence is therefore generally lower at night than during the day. These conditions are called stable conditions, i.e. the air temperature increases with height in the surface layer [1].

It is very important to consider the effect of atmospheric stability specially at sites of low average wind speed (less than 5-6 m/s) since thermal effect will be significant. So in order to improve the assessment of wind power production and enhance forecasting it is important to consider the effect of atmospheric stability. Changes in atmospheric stability conditions affect the wind speed profile and the estimation of the annual energy production of wind turbine or a wind farm. So in assessment of wind potential, it is important to account for atmospheric stability conditions [3]. It also plays an important role in the transport and dispersion of air pollution [4].

As is well-known and mentioned above, the vertical temperature gradient in the atmosphere envelope influences vertical motion. A large negative atmospheric temperature gradient indicates an unstable condition which promotes vertical currents.

A small negative atmospheric temperature gradient indicates a stable condition which inhibits vertical motion. For a positive atmospheric temperature gradient, the atmosphere is extremely stable. Between stable and unstable atmospheric lapse rates we may have a conditionally unstable situation depending on whether or not the air is saturated. Atmospheric stability varies with local heating, with wind speed, surface characteristics, warm and cold air advection, and many other factors [1].

To estimate the annual energy production of a wind farm, it is necessary to predict the wind speed at hub height and the wind speed profile. Since wind speed is measured according to WMO standards at 10 m a.g.l., it is necessary to extrapolate the measured wind speed to hub height. The main factors affecting wind energy production are roughness and its change, orography and obstacles of the site. All these factors should be considered as well as the atmospheric stability which represents thermal effects on the wind speed profile. The effect of atmospheric stability is not taken into consideration in most calculations of wind energy assessment and forecast since it is considered neutral condition [5].

The main objective of this paper is to determine the atmospheric stability conditions for three sites: Magron, Musrata and Darnah using the wind data of the three cities in order to derive the climatology at these three coastal sites in terms of daily, seasonal and overall stability distribution. Also, to estimate the wind profiles using Monin-Obukhov similarity theory for surface-layer wind profiles [6].

2. THEORETICAL BACKGROUND

The growth of the boundary layer height during daytime conditions is strongly determined by the temperature lapse rate in this inversion layer. Profiles of wind, temperature and turbulence and the height of the boundary layer are not measured on a routine basis. Therefore, indirect methods are introduced to calculate these parameters. Such methods are generally based on concepts in which the heat, momentum and moisture fluxes at the surface play a central role. The profiles of temperature, wind and turbulence are all interrelated and dependent on atmospheric stability. There are several methods to determine atmospheric stability. Mathematical models that describe wind speed profile with atmospheric stability conditions should be taken into consideration, according to available measurements of wind speed and other parameters [7].

The standard method of acquiring wind data is by measuring the wind speeds with cup anemometers mounted on meteorological towers. Since cup anemometer towers typically do not exceed 60 m in height and the standard hub height of modern wind turbines is 80 m and higher, the wind speeds have to be estimated up to hub height. The two most common methods to estimate the wind speed at any height according to IEC standard [1] are the use of the logarithmic profile without adiabatic correction term or the empirical power law with the power exponent depending on wind speed only, although there are several correlations that consider the effect of surface roughness length and height above ground level. The study of the diabatic wind profile started from the work on a similarity theory by Monin and Obukhov [8] (Monin-Obukhov similarity theory - MOST), where the non-dimensional wind shear depends on atmospheric stability. Atmospheric stability is characterized in the form of a length scale, Ls, the Obukhov length, which describes the buoyancy effect on turbulence. It is derived by Obukhov in 1946. During the day it corresponds to the height where the production of the heat flux and momentum flux are equal.

2.1 Power Law Profile

The wind profile power law is a relationship between the wind speeds at two heights. The power law is often used in wind power assessments, where wind speed data at various heights must be adjusted to a standard height (z_r). The wind profile power law is often used as a substitute for the logarithmic wind profile when surface roughness or stability information is not available. The basic form of the power law profile is [9];

$$u = u_r \left(\frac{z}{z_r} \right)^{\alpha} \quad \text{....................................... (1)}$$

Where:

u_r: A reference wind speed at reference height z_r (m/s).

z_r: A reference height (m).

α: An empirical wind shear exponent.

The early work of Von Karman showed that under certain conditions α is equal to 1/7 [5]. Sisterson and Frenzen [9] measured wind profile exponents α which changed from 1/7 during the day to 1/2 at night, over the same terrain. Golding [10] described the wind shear α as an exponent which varies with height, time of day, season of the year, the nature of the terrain, wind speed and temperature [9].

A number of models have been proposed by many researchers for the variation of α with these variables. There are different empirical equations for determining power law exponents, which are described in the following sections.

2.1.1 Correlation as a Function of Velocity and Height

Justus [11] proposed his form for determining the variation of wind shear exponent with a reference height and the corresponding wind speed at the same height. It is as follows:

$$\alpha = \frac{0.37 - 0.088 \ln(u_r)}{1 - 0.088 \ln\left(\frac{z_r}{10}\right)} \quad \text{................................ (2)}$$

2.1.2 Correlation as a Function of Surface Roughness

Counihan [12] found an empirical equation for wind shear exponent based on the surface roughness height. This has the following form:

$$\alpha = 0.096 \ln(z_o) + 0.016 \left(\ln(z_o)\right)^2 + 0.24 \quad \text{... (3)}$$

Where z_0 is the empirical surface roughness height in m.

2.1.3 Correlation as a Function of Surface Roughness and Velocity

Spera and Richards [9] proposed an empirical equation for the wind shear exponent based on surface roughness height and wind speed at reference height:

$$\alpha = \alpha_o \left[1 - 0.55 \, \text{Log}(u_r)\right] \quad \text{.............................. (4)}$$

Where

$$\alpha_o = \left(\frac{z_o}{10}\right)^{0.2} \quad \text{.................................... (5)}$$

This equation was used extensively by researchers at the NASA Lewis Research Center[9].

3. LOGARITHMIC LAW PROFILE

The logarithmic wind profile can be derived theoretically from the basic principle of fluid mechanics. It is used to describe the vertical distribution of wind speeds above the ground within the atmospheric surface layer. The logarithmic wind profile is generally considered to be a more reliable estimator than the wind profile power law, which is commonly used when neutral conditions are assumed and roughness information is not available. The basic equation to estimate the wind speed (u) at a height (z) above the ground is [9]:

$$u = \frac{u_*}{k} \left[h\left(\frac{z}{z_o}\right) + \psi\left(\frac{z}{L_s}\right) \right] \quad \text{............................ (6)}$$

Where
u_*: the friction velocity (m/s).
k : Von Karman constant, approximately equal to 0.4.
z : the elevation above ground level (m).
z_0: the empirical surface roughness length (m).
ψ : the atmospheric stability function.
L_s : Monin-Obukhov stability length (m).

The term ψ is a function of the ratio of the elevation to the Monin-Obukhov stability length (z/L_s). There are different empirical equations for determining the atmospheric stability function. These are considered below.

3.1 Businger – Dyer Form

Businger and Dyer proposed an equation for the atmospheric stability function according to the

three conditions indicated below [13]:

For stable condition:

$$\psi = 4.7 \frac{z}{L} \quad .... \quad (7)$$

And for unstable condition:

$$\psi = \ln\left(\frac{(1 + x^2)}{2\left(\frac{1 + x}{2}\right)^2} \right) - 2\arctan(x) + \frac{\pi}{2} \quad .... \quad (8)$$

Where:

$$x = \left(1 - 15 \frac{z}{L}\right)^{1/4} \quad .... \quad (9)$$

3.2 Jensen form

The Jensen form of atmospheric stability functions is taken as [14]:

For stable condition:

$$\psi = 4.7 \frac{z}{L} \quad .... \quad (10)$$

And for unstable condition:

$$\psi = \left(1 - 16 \frac{z}{L}\right)^{1/4} - 1 \quad .... \quad (11)$$

3.3 Lange and Focken

Lange and Focken used the following stability functions for stable and unstable cases [15]:

For stable condition:

$$\psi = 5 \frac{z}{L} \quad .... \quad (12)$$

And for unstable condition:

$$\psi = 2\ln\left(\frac{1 + x}{2}\right) + \ln\left(\frac{1 + x^2}{2}\right) - 2\arctan(x) + \frac{\pi}{2} \quad .. (13)$$

Where:

$$x = \left[1 - 16\left(\frac{z}{L}\right)\right]^{1/4} \quad .... \quad (14)$$

The different functions reported in the literature for atmospheric stability function can be simplified for engineering purposes to the following [9]:

For neutral atmosphere:

$$\psi_s = 0 \quad .... \quad (15)$$

For stable atmosphere:

$$\psi_s = 4.5 \frac{z}{L_s} \quad \quad \text{for } z \le L_s \quad .... \quad (16)$$

$$\psi_s = 4.5\left[1 + \ln\left(\frac{z}{L_s}\right)\right] \quad \quad \text{for } z > L_s \quad .... (17)$$

For unstable atmosphere:

$$\psi_s = -0.5 \frac{z}{L_s} \quad \quad \text{for } z \le L_s \quad .... \quad (18)$$

$$\psi_s = -0.5\left[1 + \ln\left(\frac{z}{L_s}\right)\right] \quad \quad \text{for } z > L_s \quad .... \quad (19)$$

4. ATMOSPHERIC STABILITY CLASSIFICATION

The classification of the atmospheric stability conditions is based on parameters such as heat flux and temperature. In order to know if the conditions of the atmosphere are neutral, unstable or stable, we must know the effect of buoyancy on the turbulence of the atmosphere. There are many different parameters that describe the atmospheric stability. However, the one that is mostly used is called the Richardson's number. It is derived by comparing the contributions of buoyancy forces with the shear stress forces on the production of the turbulent kinetic energy [16].

4.1 Richardson Number

We have three fluid properties; pressure p, density ρ and absolute temperature T, linked by the hydrostatic balance, the equation of state and conservation of energy. In order to determine the variation of temperature with height, employ the indicated equations and eliminate p and ρ to obtain a single equation for T. Therefore, the vertical temperature gradient or lapse rate is found to be:

$$\frac{dT}{dz} = -\frac{g}{C_p} = \frac{9.81}{1005} = 0.00976 \frac{K}{m} \quad .... \quad (20)$$

This is about 1°C for every 100 m of altitude. This is the temperature gradient at which temperature decreases with elevation in a well-mixed atmosphere and is called the dry adiabatic lapse rate, where its value actually varies with moisture. The general definition of the thermal expansion coefficient α is the negative of the relative rate at which density changes with temperature when pressure is held constant [17]:

$$\alpha = -\frac{1}{\rho} \frac{d\rho}{dT}\Big|_p \quad \text{and for air, } \alpha = \frac{1}{T} \quad .... (21)$$

The potential temperature of an air parcel

is the absolute temperature that it would have if it were brought adiabatically to a reference pressure. Referring to thermodynamic relations, a temperature–pressure relation can be written as follows:

$$C_p \ln \frac{T}{T_o} = R \ln \frac{P}{P_o} \quad \text{.. (22)}$$

Where T and p are the actual temperature and pressure of the air parcel, and T_0 is the temperature it would take if its pressure was changed to p_0. If p_0 is the reference pressure used to compare the various air parcels, then T_0 is the potential temperature. Solving for T_0, the potential temperature is [18]:

$$\theta \equiv T_o = T\left(\frac{P_o}{P}\right)^{\frac{R}{C_p}} \quad \text{....................................... (23)}$$

Where, it is the tradition to denote the potential temperature by θ. For convenience, p_0 is usually taken as p_{atm}= 101,325 N/m². In order to know if the conditions of the atmosphere are neutral, unstable or stable, we must know the effect of buoyancy on the turbulence of the atmosphere. There are many different parameters that describe the atmospheric stability. However, the one that is mostly used is called the Richardson's number. It is derived by comparing the contributions of buoyancy forces with the shear stress forces on the production of turbulent kinetic energy. Richardson number is used to classify the atmospheric stability conditions by the following equation [16]:

$$R_i = \frac{\frac{g}{T_o} \cdot \frac{\partial \theta}{\partial z}}{\left(\frac{\partial U}{\partial z}\right)^2} \quad \text{..................................... (24)}$$

Where

g : the acceleration of gravity (m/s²).

T_0 : a reference temperature at the surface (K).

θ : the mean potential temperature (K).

z : the height above ground (m).

U : the mean wind speed (m/s).

Depending on the variation of temperature with height, Richardson states that a number will classify the atmospheric stability conditions as:

Ri > 0;   unstable condition.

Ri = 0;   neutral condition.

Ri < 0;   stable condition.

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4.2 Stability Ratio

Munn [19] states that the stability ratio is a simplified form of the Richardson number. The stability ratio can be used as an indicator of atmospheric stability conditions [19]:

$$SR = \frac{T_{z2} - T_{z1}}{u^2} \times 10^5 \quad \text{...................................... (25)}$$

T_{z1} and T_{z2} are the temperatures (°C) at heights z_1 and z_2 and u is the wind speed (cm/s) measured at a height equidistant from z_1 and z_2 on a log scale. Yates et al [19] used heights of 2.4 and 9.8 m for z_1 and z_2, respectively, and a wind speed measurement height of 4.9 m. The American Society of Agricultural Engineers (ASAE) standard [19] recommends z_1 and z_2 heights of 2.5 and 10 m, with wind speed measurement height set at 5 m. Yates et al [19] denoted four separate classes of atmospheric stability with corresponding ranges for the Stability Ratio (SR), as shown in Table 1.

Table (1). **Atmospheric stability conditions as a function of stability ratio ranges.**

Atmospheric stability condition	Stability Ratio Range
Unstable	-1.7 to -0.1
Neutral	- 0.1 to 0.1
Stable	0.1 to 1.2
Very Stable	1.2 to 4.9

5. AVAILABLE WIND ENERGY

Wind turbines are employed to extract energy from the available energy of the moving air. The captured energy is affected by a number of factors such as air density, turbine swept area and air velocity. Referring to the control volume momentum integral equation, the available power per a unit swept area of the wind rotor or the power density, can be evaluated by the following expression [5];

$$E_D = \frac{3}{\pi}\left(\rho_a\, V_m^3\right) \quad \text{.. (26)}$$

Where E_D is the power density in kW/m², ρ_a is the air density in kg/m³, and V_m is the mean wind speed in m/s. Therefore the energy intensity or the energy available from the wind over a period of time, can be expressed as [5]:

$$E_I = t\, E_D \quad .... \quad (27)$$

Where E_I is the available wind energy upstream of the wind turbine in kWh/m², and t is the number of wind working hours over the desired study period of time. The extracted energy comes from the turbine based on its power coefficient, where the maximum power coefficient is 16/27 due to Betz cited in [5].

6. METHODOLOGY

The wind speed data at three levels (10, 20 and 40 m a.g.l.) were documented for three Libyan coastal cities where they could be used to identify, classify, and study the atmospheric stability conditions for the four annual seasons as well as diurnal pattern. Wind data were measured every ten minutes and averaged on hourly bases. The sites were chosen to represent three Libyan coastal regimes; Eastern coast, Darnah; middle region, Magron; and Western coast, Musrata. At noon time, the atmosphere is well mixed and neutral condition applies, so $\psi_s = 0$.

The wind velocity profiles were determined using the logarithmic and power law. The effect of the atmospheric stability on the vertical wind velocity profiles as well as on the wind energy intensity was studied. The methodology for calculating each model is represented in details elsewhere [20].

The daily wind shear variation with time of the day is evaluated by using the daily average wind speeds for every season, and accordingly the atmospheric stability condition was determined. The surface roughness height z_o, the stability length Ls, for stable and unstable conditions and the wind speed profiles under different stability conditions were estimated.

For the power law calculations, the wind shear exponent α was determined and the variation of wind speed profiles were estimated. The available power and the energy intensity of the wind at different heights for stable, unstable and neutral conditions were determined. The variation of energy with height under different stability conditions was evaluated.

7. RESULTS AND DISCUSSION

Atmospheric stability analysis was performed using measured wind data for three heights at the three different coastal sites. Employing the mathematical models presented above with the use of the Microsoft Excel Spread Sheet Program, the wind shear, wind speed profile, stability parameter, and available wind energy were determined and presented. Here, the characteristics of each city's atmosphere were studied.

7.1 Wind Shear Ratio

The average daily wind shear ratio variation for the four seasons of the year at Magron city, Libya is illustrated in Figure 1. The atmospheric stability states can be identified clearly from this figure. During the period from sunset to sunrise, the heat flux is negative and the air temperature gradient is positive with elevation, i.e. there is no mixing process, the wind shear is high. Referring to the parcel rule, this period is described as stable atmosphere. The lengths of this period depend on the seasonal variation during the year, where in winter this condition tends to be longer than in summer as indicated clearly in the Figure.

The period from sunrise to approximately noon time, where a positive heat flux occurs due to the solar thermal radiation, the air temperature gradient with the vertical near the ground is negative. Hence, the temperature of air parcel, that is displaced upward, is higher than its surrounding air temperature and the parcel moves further upward due to the buoyancy effect. This period is classified as unstable state. Along this period, the surface heat flux increases steadily and the wind shear decreases because of the large amount of mixing that often occurs.

In summer, the wind shear ratio decreases

sharply from 0.5 to 0.1 during the two hours of the early morning, because of the rapidly increasing surface heat flux and large amount of mixing. Because of the gradually increase in surface heat flux, the decreasing amount of wind shear in winter is less than that during summer. The neutral atmospheric condition can be found along the hours after noon to approximately one hour prior to sunset, where the solar heat flux reaches its maximum value.
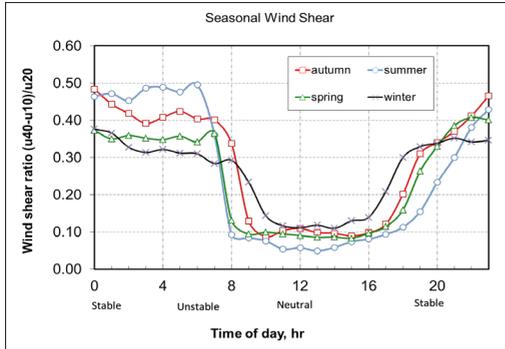

Figure (1). Seasonal cycle of wind shear at Magron city.
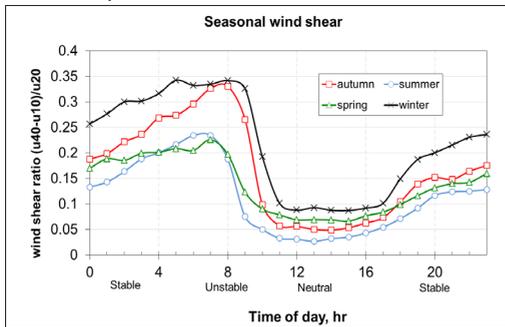
Figure (2). Seasonal cycle of wind shear at Musrata city.

Figure 2 presents the average daily wind shear ratio variation for the four seasons of the year at Musrata city, and identifies the atmospheric stability conditions. It can be noticed that atmospheric conditions for Musrata city have almost the same trend as Magron city conditions while the values and periods are different. The cases can be discussed with same words as it was made with Magron city atmospheric conditions.

Figure 3 is related to the average daily wind

shear ratio variation for the four seasons of the year at Darnah city. The atmospheric conditions of this city have a different trend as well as different values and periods compared to the other two cities since the topography of this city is different. It is a coastal city but it is located between the Mediterranean sea and a mountain (Green mountain). The height of meteorological station is about 26 m above sea level
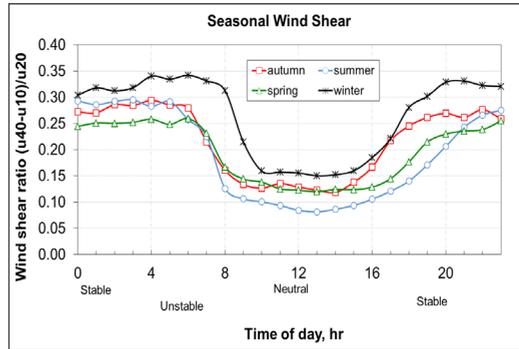
Figure (3). Seasonal cycle of wind shear at Darnah

7.2 Seasonal distribution of atmospheric stability

Referring to the seasonal variation of wind speed profiles for Darnah city, Figures 4-7 below, illustrate such profiles associated with seasonal variation of wind speed profiles according to stability conditions: stable, unstable and neutral conditions using diabatic wind speed profiles or using the logarithmic law that accounts for stability conditions and the power law.

According to these figures, it could be noticed that in all seasons the neutral and power law velocity profile curves are almost identical, and in the stable condition, the wind speed gradient is increased obviously, because of the reduced mixing process. At high levels over 80 m a.g.l. stable condition curve will be overestimated using neutral and power law modelling while unstable curves will be underestimated. Same patterns are seen for summer and spring seasons with different and lower values of wind speeds. In all seasons we notice that high speeds appear in the stable period at a height higher than 80 m a.g.l.

According to Figure 4, the unstable condition indicates that the wind speed gradient is diminished; the vertical mixing creates a generally homogeneous wind profile with higher magnitude. The wind speeds are 8.15 and 8.5 m/s at 60 m and 80 m, respectively. This condition starts at morning by 8 am and extended to noon time. However, in the stable condition at night, obviously the wind speed gradient is increased, because of the reduced mixing process, where the wind speeds are relatively higher of around 10 m/s. In neutral condition the homogeneous wind speed profile with elevation still exists, because the convective mixing layer reaches its maximum value. This period extends from noon to almost sunset.
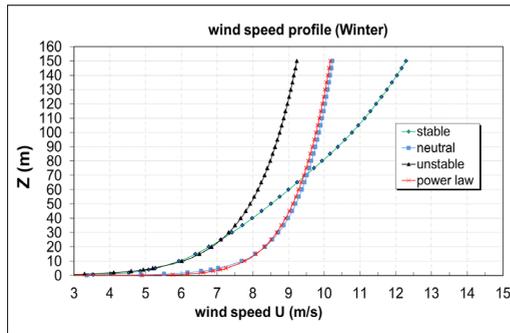
Figure (4). Wind speed profiles for different conditions in winter.

Note that the wind speed profile generated by the power law, behaves as the neutral condition, since the power law does not consider the atmospheric stability effect. Here, using neutral stability condition while ignoring atmospheric stability conditions for all seasons will result in overestimating wind speed for unstable condition and underestimation of wind speed for stable condition at the high elevations. Figures 5-7 represent the scenarios for spring, summer and autumn seasons. The values and periods are different, however, they have the same trend as winter and can be interpreted as done above. In summer season, it illustrates that the wind speed gradient in neutral, unstable and power law is not increased obviously compared with cold seasons, due to the large amount of heat flux during the daytime.
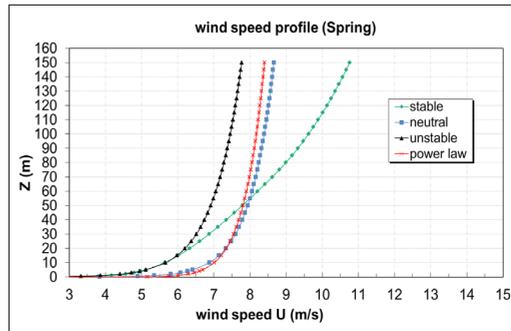
Figure (5). Wind speed profiles for different conditions in spring.
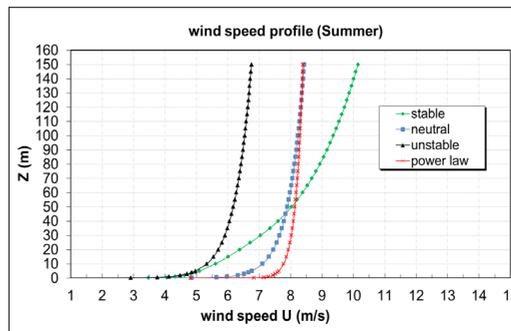
Figure (6). Wind speed profiles for different conditions in summer.

The results obtained from this study could be looked to have the same trend as those ones published in the literature. These results obviously should affect the technical and economic feasibility studies performed for any proposed wind energy project at such sites.

7.3 Overall distribution of atmospheric stability

As Figure 8 illustrates the overall distribution of atmospheric stability at the three sites is of stable condition followed by unstable condition. The overall contribution of stable condition is 50% in Magron, 46% in Musrata and 42% in Darnah. The share of unstable condition is 33% in both Darnah and Musrata while its share in Magron is 29%. Neutral condition represents 21% in both Magron and Musrata and 25% in Darnah.
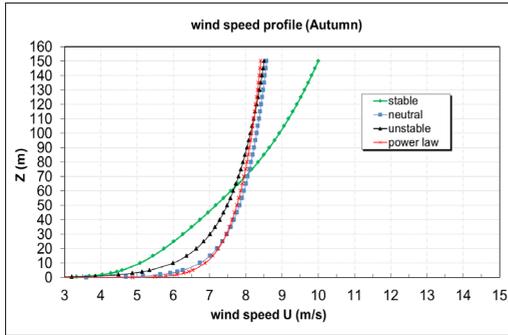
Figure (7). Wind speed profiles for different conditions in autumn.

This result confirms the importance of stability analysis, where for example, ignoring the effect of atmospheric stability will lead to under estimating or over estimating wind speeds, expected available wind energy and energy produced by wind turbines. This could lead to margin errors in wind resource assessment and feasibility studies of wind projects.

It could be noticed that using diabatic wind speed profile (equation (6)) over predicts stable wind profile. Stable condition is dominating the three sites in this study with different percentages. It represents 50% in Magron, 46% in Musrata and 42% in Darnahh. This implies that using diabatic wind profile should be considered when extrapolating wind speeds to heights above measured values at meteorological stations/towers.

7.4 Non-dimensional Wind Profiles

Figures 9 and 10 illustrate the non-dimensional velocity profiles in the winter and summer at Darnah city. It is clear that the stable condition behaves as laminar flow, while the neutral and unstable conditions behave as turbulent flow. The shear near the surface of the earth is greater for turbulent speed profiles than in the laminar profile, because of the turbulent mixing process that occurs at daytime due to the heating of the earth's surface by the incident solar radiation. In summer, the shear near the surface is greater for turbulent and laminar profiles than in the winter, due to the large amount of heat flux during the summer season.
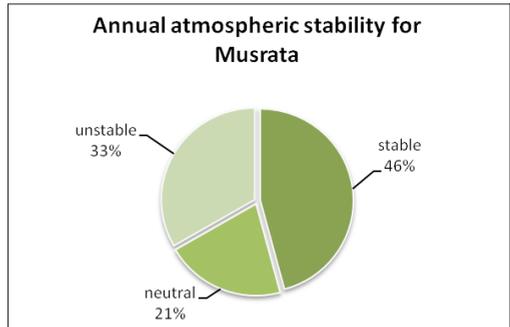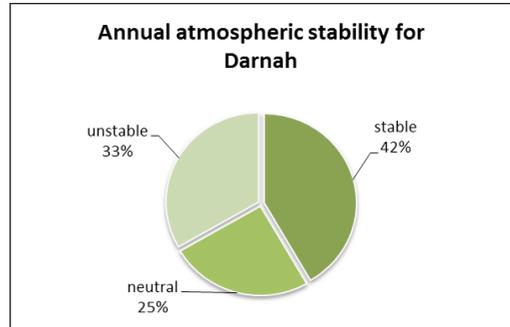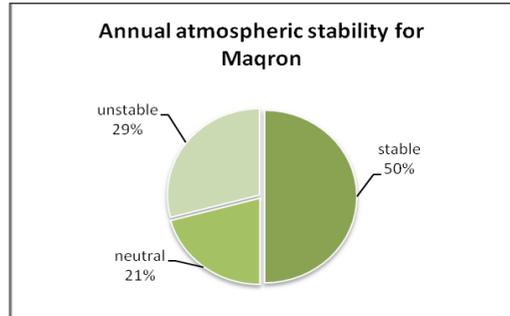
Figure (8). Seasonal distribution of atmospheric stability conditions for the three sites.
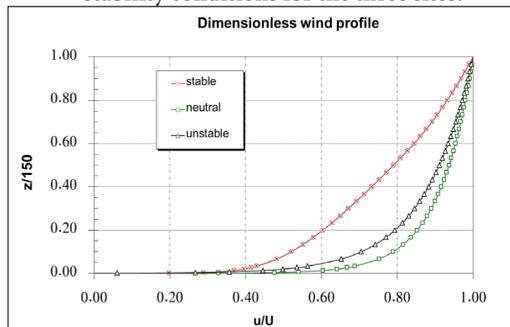
**Figure (9). Non-dimensional velocity profiles at Darnah city in winter**

25
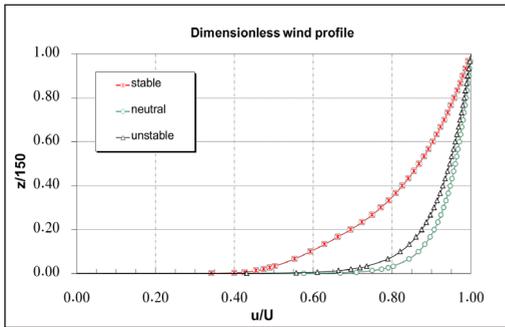
Figure (10). Non-dimensional velocity profiles at Darnah

7.5 The Available Wind Energy

Figure 11 illustrates the variation of available wind energy with height at Magron. In winter, the maximum available energy from the wind obtained at stable condition increases obviously with height, it is 5.85 kWh/m^2 at 60 m, while at 80 m it is 7.24 kWh/m^2. For the unstable and neutral conditions the increase with height is not large, it is estimated to be 1.69 kWh/m^2 at 60 m and 1.8 kWh/m^2 at 80 m for the neutral condition.

It is clear that for stable condition the available energy is higher than that in neutral condition and it is increasing with height. At 60 m a.g.l. the increase is 246% while at 80 m a.g.l. it reaches 300% the neutral condition. This illustrates the importance of considering the effect of atmospheric stability in estimating the velocity profile when considering wind resource assessment as well as when studying loads and stresses affecting the blades of the wind turbine rotors. Figure 12 is for spring with the same trends but with lower available energy values.

Figure 13 illustrates the seasonal available wind energy at height of 80 m. In winter the maximum available energy can be attained in stable condition, where it is about 7.24 kWh/m^2, while the minimum available energy in stable condition occurs in summer with an estimated value of 0.641 kWh/m^2. It could be noticed that the maximum energy occurs in stable conditions, while the minimum energy occurs in unstable conditions
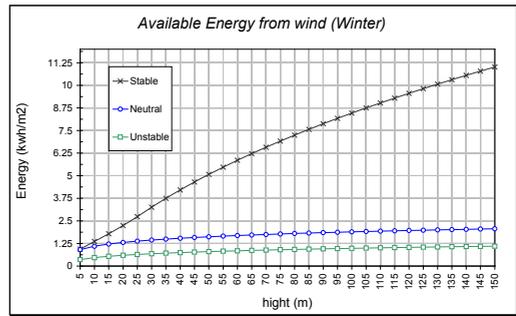

Figure (11). Available wind energy at Magron city in winter.
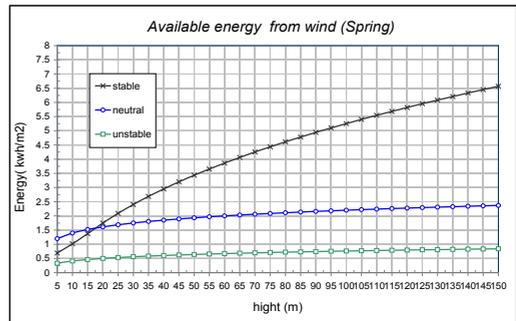

Figure (12). Available wind energy at Magron city in spring.

Figures 14 and 15 are related to the available wind energy at Musrata. The maximum available wind energy obtained at stable condition is 4.24 kWh/m^2 at 60 m, while at 80 m it is 5.08 kWh/m^2, which are lower than the values of Magron city. In unstable and neutral conditions, the available wind energy is estimated to be lower than 2.0 kWh/m^2 for both considered heights.
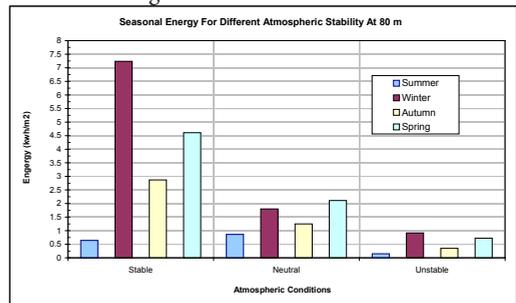

**Figure (13). Seasonal available wind energy at 80 m for Magron city.**
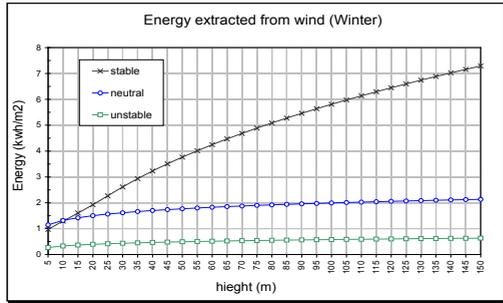
Figure (14). Available wind energy at Musrata city in winter.

Figure 16 presents the available wind energy at Darnah in winter with the estimated maximum achieved at stable condition. It is 6.708 kWh/m^2 at 60 m, while at 80 m it is 9.027 kWh/m^2, which is higher than that at Magron city. In unstable and neutral conditions, the values are below one third of that for the stable condition. Figure 17 is for the summer season. The estimated maximum energy is almost one half of that obtained in winter. Here, it could be deduced that the highest deviation from neutral conditions occurs in winter season, where the underestimation of available energy for stable condition is about 170 % of that at neutral conditions at 60 m a.g.l. and by 229 % at 80 m a.g.l.

The seasonal available wind energy at 80 m is given in Figure 18 with the maximum attained in the stable atmospheric condition for all seasons, while the minimum available energy is obtained in the unstable condition for all seasons.
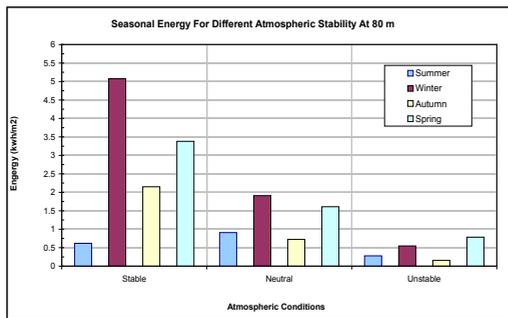

**Figure 15. Seasonal available wind energy at 80 m for Musrata city.**
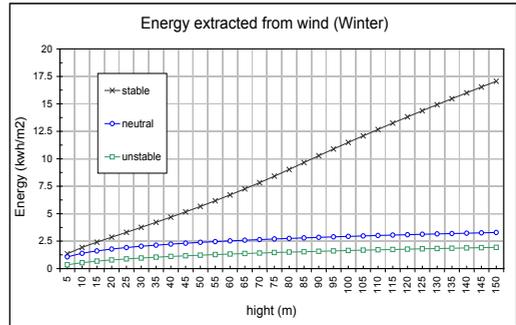
**Figure (16). Available wind energy at Darnah city in winter.**
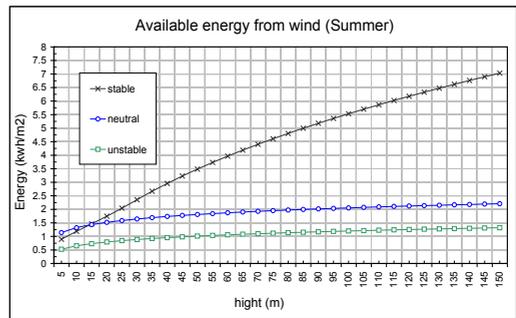
Figure (17). Available wind energy at Darnah city in summer.
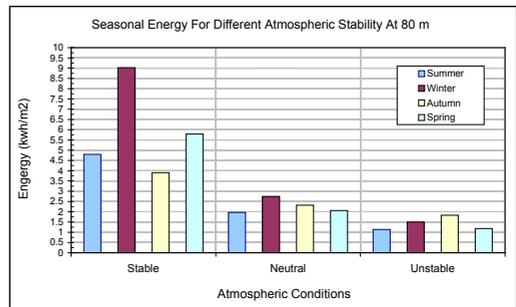

Figure (18). Seasonal available wind energy at 80 m for Darnah city.

8. CONCLUSIONS

The characteristics of the atmosphere of three Libyan cities; Magron, Musrata, Darnah, were determined. The wind shear ratio, velocity profiles, stability criteria, stability conditions, and the

annual and seasonal available wind energy were documented. This study confirms the importance of the atmospheric stability on the wind resource assessment and ignoring these facts results in error-based decisions.

Referring to the present study, one may conclude that the overall contribution of stable condition is 50% in Magron, 46% in Musrata and 42% in Darnah. The share of unstable condition is 33% in both Darnah and Musrata while its share in Magron is 29%. Neutral condition represents 21% in both Magron and Musrata and 25% in Darnah.

It could be noticed that in stable condition, the wind speed gradient is increased significantly in winter season, while it is increased slightly in summer. For Magron city the wind shear of stable conditions varies from 58% in winter season to 42% in summer. Also, there is no significant variation on daily variation of atmospheric conditions at Magron and Musrata, while there is a slight difference in Darnah.

Considering seasonal variation of atmospheric condition at the three sites, it could be noticed that at Magron and Musrata stable condition is dominant in all seasons except summer, where neutral condition is domination the atmospheric. In Darnah stable condition is dominant at all seasons.

The non-dimensional wind profiles presented where the stable wind speed profiles are over predicted when using diabatic wind profiles (when using neutral condition and ignoring effect of atmospheric stability), while the unstable and neutral profiles are close to each other.

The results confirm the importance of stability analysis, where for example, ignoring the effect of atmospheric stability will lead to under estimating or over estimating wind speeds, expected available wind energy and energy produced by wind turbines. This could lead to margin errors in wind resource assessment and feasibility studies of wind projects.

The maximum available wind energy at Darnah is in winter with the estimated maximum achieved at stable condition. In unstable and neutral conditions, the values are below one third of that for the stable condition. In the summer season the estimated maximum energy is almost one half of that obtained in winter.

The highest deviation from neutral conditions at Darnah occurs in winter season. Similar results are obtained for the other sites. This illustrates the importance of considering the effect of atmospheric stability in estimating the velocity profile when considering wind resource assessment as well as when studying loads and stresses affecting the blades of the wind turbine rotors

9. ACKNOWLEDGEMENT

10. NOMENCLUTURE

E_D	the power density	kW/m².
E_I	the available wind energy	kWh/m².
g	the acceleration of gravity	m/s².
k	Von Karman constant, proximately equal to 0.4.	
L_s	Monin-Obukhov stability length	m.
p	pressure	Pa.
u_r	A reference wind speed at reference height z_r	m/s.
u_*	the friction velocity	m/s.
uU	A reference wind speed	m/s.
V_m	the mean wind speed	m/s.
T	temperature	K.
t	the number of hours	h.
T_0	a reference temperature	K.
z	the height above ground	m.
z_r	A reference height	m.

z_0	the empirical surface roughness	m
ψ	the atmospheric stability function.	
ρ_a	the air density	kg/m³
α	An empirical wind shear exponent.	
θ	the potential temperature	K

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