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ESTIMATION OF ATMOSPHERIC STABILITY, WIND POWER AND ENERGY DENSITY AT AL MAGRUN TOWN IN LIBYA

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الملخص

تم في هذه الورقة البحثية تحليل ظواهر سرعة الرياح لعام 2003 لمدينة المقرون الليبية بهدف دراسة أثر استقرار الغلاف الجوي على المنحنيات الجانبية لسرعة الرياح، وتأثير ذلك على كثافة الطاقة المتاحة. كان تقدير المنحنيات الجانبية عند ثلاثة ارتفاعات هي مشابهة للتكنولوجيا الحديثة لارتفاعات محاور التوربينات، وذلك باستخدام قانون الأس والقانون اللوغاريتمي الكلاسيكي والقانون اللوغاريتمي التصحيحي لشروط الاستقرار. لقد تم تصنيف شروط استقرار الغلاف الجوي المتاحة في مدينة المقرون، وقد تم الحصول على التغير الكلي في استقرار الغلاف الجوي إلى جانب تحديد الأنماط اليومية والموسمية. قامت الورقة بتحديد المنحنيات الجانبية لسرعة الرياح تحت ظروف استقرار الغلاف الجوي المختلفة؛ محايدة، مستقرة وغير مستقرة، فضلا عن تعيين كثافة القدرة وكثافة الطاقة بهدف تقدير الانحراف أو الاختلاف عند استخدام القانون اللوغاريتمي الكلاسيكي أو تحت الظروف المحايدة.

وتبين النتائج أن تجاهل تأثير استقرار الغلاف الجوي على المنحنيات الجانبية للسرعة كان ملحوظًا. عند أخذ قراءات استقرائية لسرعة الرياح على ارتفاعات قريبة من ارتفاعات محور التوربينات الريحية، ستكون هناك مبالغة في تقدير سرعات الرياح للحالة غير المستقرة. وفي ظل تقدير سرعة الرياح لحالته المستقرة لجميع المواسم بنسب مختلفة باستثناء موسم الصيف حيث تجاهل تأثير استقرار الغلاف الجوي سيؤدي إلى المبالغة في تقدير الرياح بسرعة للظروف المستقرة وغير المستقرة على حد سواء. تهيمن الحالة المستقرة على جميع المواسم، حيث يكون نصيبها 58% في الشتاء، و50% لكل من فصلي الربيع والخريف و42% في الصيف. ويمثل شرط المحايدة 29% لكل من فصلي الخريف والربيع، بينما 33% في الصيف و25% في فصل الشتاء. مساهمة حالة الجو غير المستقرة هي 25% في فصل الصيف، و21% لكل من فصلي الربيع والخريف و17% لفصل الشتاء. حالة الغلاف الجوي لمدينة المقرون تتميز بوتيرة عالية تتمثل في 68 في المائة للحالة غير المستقرة مع سرعة رياح منخفضة من 3-3.5 م/ث، وشرط المحايدة يتمثل في 65% للسرعات المتوسطة 6-6.5 م/ث، وأن 38 % تمثل الظروف المستقرة لسرعات الرياح فيما بين 4.4-5 م/ث.

ABSTRACT

Atmospheric stability conditions have a pronounced effect on velocity profiles and therefore on power density at a site and energy produced by wind turbines at these sites. So, accessing this effect is a main issue to be tackled in wind energy resource assessment and feasibility studies of any wind energy projects. In this paper wind speed observations for the year 2003 for Magroon city in Libya were analyzed in order to study the effect of atmospheric stability on wind speed profiles, and therefore on the available energy intensity. Wind speed profiles were estimated at three heights similar to recent technology turbine hub heights, using power law, classic logarithmic law, and corrected logarithmic law for stability conditions. The available atmospheric stability conditions in Magrun town were classified. The overall atmospheric stability variation was obtained as well as daily and seasonal patterns. Wind velocity profiles were determined at different atmospheric stability conditions, neutral, stable and unstable, as well as the power density and energy intensity in order to estimate the deviation or the difference when using the classical logarithmic law or neutral condition.

The results showed that ignoring the atmospheric stability effect on velocity profiles is noticeable. When extrapolating wind speed to heights close to wind turbine hub heights will result in overestimation of wind speeds for unstable condition and under estimation of wind speeds for stable condition for all seasons with different percentages except for summer season where ignoring the atmospheric stability effect will result in overestimation of wind speeds for both stable and unstable conditions. Stable condition is dominating all seasons, where its share is 58% in Winter, 50% for both Spring and Autumn and 42% in Summer. Neutral condition represents 29% for both Autumn and Spring, 33% in Summer and 25% in Winter. The contribution of unstable condition is 25% in Summer, 21% for both Spring and Autumn and 17% for Winter. Magrun's atmospheric status is characterized with high frequency of 68% for unstable condition with low wind speeds of 3-3.5 m/s, 65% neutral condition for medium wind speeds of 6-6.5 m/s, and 38% stable condition for wind speeds of 4-5.5 m/s.

KEYWORDS: Atmospheric Stability Conditions; Convection Boundary Layer; Diabatic Wind Speed Profiles; Magrun Town -Libya, Monin-Obukhov Stability Length; Similarity Theory; Surface Boundary Layer; Wind Energy Intensity.

INTRODUCTION

The planetary boundary layer is the layer near the ground surface where the transport of heat, momentum and turbulence takes place. The boundary layer is defined as the layer between the surface and the free stream where the velocity is 99% of the free stream velocity. It is usually turbulent and well mixed. Its height is changing over time and space. The height of PBL might reach up to 3 km in lands and up to 1-2 km offshore or on wetlands or surfaces. It consists of a surface layer, a well-mixed layer and an entertainment layer [1]. It is important to study this layer since most of the kinetic energy is dissipated in it, but in the wind energy field, it is important to concentrate on the surface layer where wind turbines are installed.

In this layer the vertical gradient of temperature, humidity, wind and turbulence exist. At the surface layer or the constant flux layer, which extends up to 200 m above ground level, wind speed profiles over homogeneous lands could be described by Monin-Obukhov similarity theory “MOST” with the use of appropriate stability functions [2]. “MOST” is tested widely and applied to describe wind speed, temperature and turbulence profiles [3,4].

Atmospheric stability is defined as the parameter that defines the turbulent condition of the atmosphere and describes its dispersion capabilities [5]. It is also defined as suppressing or enhancing vertical air motion or existing turbulence [6] or the tendency to reduce or intensify vertical motion [7]. The distribution of temperature inside atmospheric boundary layer has a significant impact on atmospheric stability. The atmospheric boundary layer is directly influenced by the presence of the earth's surface. The solar heating causes thermal air plumes to rise, transporting moisture, heat and aerosols. The plumes rise and expand adiabatically due to the negative pressure gradient until they reach the top of the atmospheric boundary layer [2].

During the day cooling and heating of the ground surface takes place, causing different air stratification. Atmospheric stability conditions can be determined by the net heat flux to the ground, which is the sum of incoming solar radiation and outgoing thermal radiation and of latent and sensible heat exchanged with the air and subsoil. The main three atmospheric stability classifications are: Stable, neutral and unstable conditions [6-8].

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 are all interrelated and dependent on atmospheric stability. There are several methods performed to assess and determine the atmospheric stability using different methodologies depending on the measured parameters and available data [9-17].

Wind speed profiles can be predicted or estimated over lands by using “MOST” for surface layer. Thomas Foken introduced the Monin-Obukhov Similarity Theory as it is well known for over 50 years [3]. It is used to predict wind speeds in the surface layer over seas and oceans. It cannot be used above surface layer since other parameters such as boundary layer height could influence modeling wind speed profiles [3].

Referring to this present study, the main objective of this paper is to determine the atmospheric stability conditions in detail for Magrun town, based on the available wind data at three altitudes, 10, 20 and 40 m above the ground. Magrun’s wind characteristics would be analyzed in terms of daily, seasonal and overall stability distribution. This would be done in order to study the effect of the atmospheric conditions on wind speed profiles and therefore on the available energy intensity.

THEORETICAL BACKGROUND

The atmospheric boundary layer is influenced by the nature of the ground surface. The thickness of the boundary layer depends on the forces interacting on its surface, which depends on shear stress or wind shear, heat transfer or buoyant forces and evaporation. Turbulence in the boundary layer is produced by wind shear due to shear stress and buoyancy forces due to heating effects on the ground. According to turbulence sources, the boundary layer can be classified as: convective boundary layer, which is generated by heat effect or buoyancy forces during the day and it is characterized by unstable condition. Its thickness might reach 1-2 km. Stable Boundary Layer is generated from cooling of the earth's surface at night times and this tends to suppress turbulence. The typical height of this layer is 100-200 m above ground level. It is characterized by strong wind shear and small eddies. In the neutral condition, the flow is characterized by a combination of wind shear and convective or buoyant forces [1, 15].

Wind measurements are usually taken at heights proposed by meteorological authorities which are lower than modern wind turbine hub heights. Estimation of wind speeds at any height are usually performed, as suggested by IEC standards [18], by the use of either power law with the power exponent, which is an empirical law, or a logarithmic profile without the diabatic correction term. The diurnal variation of heating and cooling of ground surface can create different stratification and different stability conditions. These variations should be considered in predicting wind speed profiles. These variations were tackled at different research works [19-24].

The study of the diabatic wind profile over ground can be performed by the use of "MOST" for surface layer, where the non-dimensional wind shear depends on the atmospheric stability. It is described by a stability parameter z/L_s, where L_s is a length scale known as Obukhov length. "MOST" is valid only in the surface layer up to 100-200 m above the ground. According to this theory, wind speed profiles are corrected for the effect of atmospheric stability [8,25,26] as follows:

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right) + \psi\left(\frac{z}{L_s}\right)\right] \quad (1)$$

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 (z/L_s) = the atmospheric stability function.

L_s = Monin-Obukhov stability length (m).

(z/L_s) = stability index

The term $\psi(Z/L_s)$ is a function of the ratio of the elevation to the Monin-Obukhov stability length or index (z/L_s). It could be noticed that from above equation the change of wind speed with height depends on surface roughness of the site and the atmospheric stability prevailing at the site. There are different empirical equations for determining atmospheric stability function. In this study the following equations were adopted [25]:

Neutral atmospheric: $\psi_s = 0$ (2)

Stable atmospheric:

$$\psi_s = 4.5z/L_s \qquad , z \le L_s$$
$$\psi_s = 4.5[1 + \ln(z/L_s)] \qquad , z > L_s \quad (3)$$

Unstable atmospheric:

$$\psi_s = -0.5z/L_s \qquad , z \le L_s$$
$$\psi_s = -0.5[1 + \ln(z/L_s)] \qquad , z > L_s \quad (4)$$

Power law profile

The power law is commonly used in wind engineering models for defining vertical wind profile because it represents a simple model for the vertical wind speed profile; the basic equation is [25]:

$$u = u_r (z/z_r)^{\alpha} \quad (5)$$

Where:

u_r = the reference wind speed at a reference height z_r (m/s).

z_r = the reference height (m)

α = the empirical wind shear exponent.

The exponent α is a variable quantity, where it varies with elevation, time of the day, season of the year, nature of the terrain, wind speed, temperature, and various thermal and mechanical mixing parameters. Some empirical equations were proposed by researchers for the variation of α with these variables.

Spera proposed an empirical equation for α based on the surface roughness length z_0 and the wind speed at reference height u_r, as follows [25];

$$\alpha = \alpha_0 [1 - 0.55 \log(u_r)] \qquad (6)$$

Where:

$$\alpha_0 = (z_0 / 10)^{0.2} \qquad (7)$$

METHODOLOGY

Wind data from Meteorological Authority of Libya are available only at 10 m height above ground level (a.g.l.), as recommended by WMO. For this study wind data at least at three heights are required. So wind speed data at three levels; 10, 20 and 40m (above ground level), for the year 2003 at Magrun town on the Libyan coast was used. Data was provided by Renewable Energy Authority of Libya (REAoL) [27]. It was processed in order to identify, classify, and study the atmospheric stability conditions for the annual, seasonal and diurnal pattern. Wind data was measured every ten minutes and averaged on hourly bases. The daily wind shear variation with time of day was drawn by using daily average wind speeds for each month at three heights 10 (referenced height), 20 and 40 m above ground level (a.g.l.). The wind shear was determined as the difference between hourly wind speeds at elevation 10 and 40 m, normalize by the wind speed at 20 m $((u_{40} - u_{10}) / u_{20})$.

From wind shear curve, the atmospheric stability state can be determined. The highest wind shear occurs during stable condition at night, and the lowest during unstable atmospheric condition near midday.

The surface roughness length z_0 is determined, by plotting the measurement of wind speeds versus heights in logarithmic scale in neutral condition where $\psi_s = 0$, and extrapolated to the best fitted straight line down to the level where the wind speed equal to zero. Using equation (1) the coefficient (u_* / k) for neutral condition could be evaluated. The stability length L_s, for stable and unstable conditions, is determined by using measured wind speeds at 10 and 20 m and substituting in equation (1). By substituting the value of) for each stability u_* / k 1), the value of (in equation (L_s condition is determined. Then wind speed profiles under different stability conditions are drawn. The effect of the atmospheric stability on the wind velocity profiles as well as on the wind energy intensity was studied.

The power density and energy intensity of the wind were evaluated at different heights and stability conditions and its deviation from classic logarithmic law was determined. For the power law calculations, the wind shear exponent α was determined and the wind speed profiles were estimated, according to equation (5) and (6). The power density and energy intensity of the wind at different heights were determined and compared with results of above diabatic profiles.

RESULTS AND DISCUSSIONS

Atmospheric stability analysis was performed using measured wind data at the three heights for the Libyan middle coast represented by Magrun town for the year of 2003. The wind shear, stability parameters, wind speed profiles and wind energy intensity for different stability conditions were calculated. Diurnal, seasonal, and overall distribution of atmospheric stability were determined.

Daily Distribution of Atmospheric Stability Conditions

The daily wind shear ratio pattern for the four weather seasons of the year 2003 at Magrun town, Libya, is illustrated in Figure (1). The wind shear is high during the period from sunset to sunrise, where the ground heat flux is negative, and the air temperature increases with elevation. This period is described as stable atmosphere mode. A ground positive heat flux occurs due to solar thermal radiation during the time period from sunrise to approximately noon time, where the air temperature gradient, $\partial T/\partial z$, near the ground is negative. This period is classified as unstable atmospheric mode.

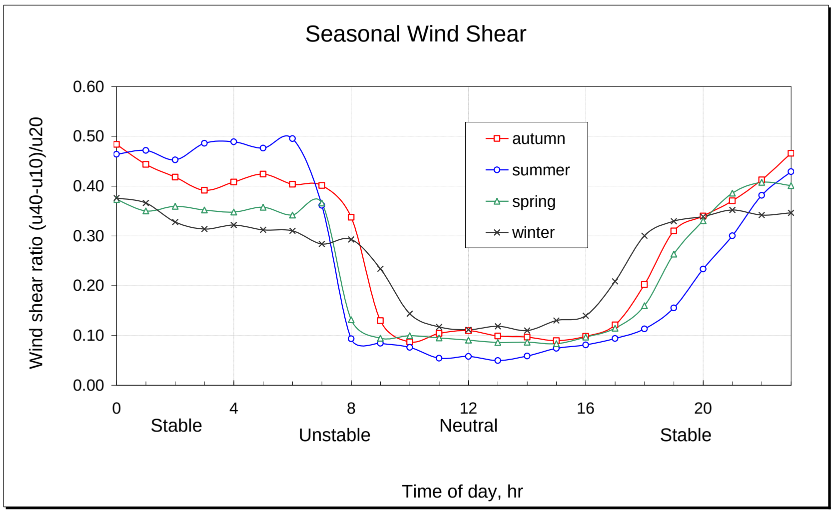

Figure 1: Seasonal cycle of wind shear at Magrun town, 2003.

Seasonal Distribution of Atmospheric Stability Conditions

The seasonal variation in wind velocity profiles for stable, unstable and neutral conditions are illustrated in Figures (2-5). Figure (2) shows the effect of atmospheric stability conditions on velocity profiles in Winter. Referring to this Figure, the unstable condition states that the wind speed gradient is diminished; the vertical mixing creates a generally homogeneous wind profile with higher magnitude. The wind speeds are 7.0 m/s and 7.2 m/s at 60 m and 80 m elevation above ground level (a.g.l.), respectively.

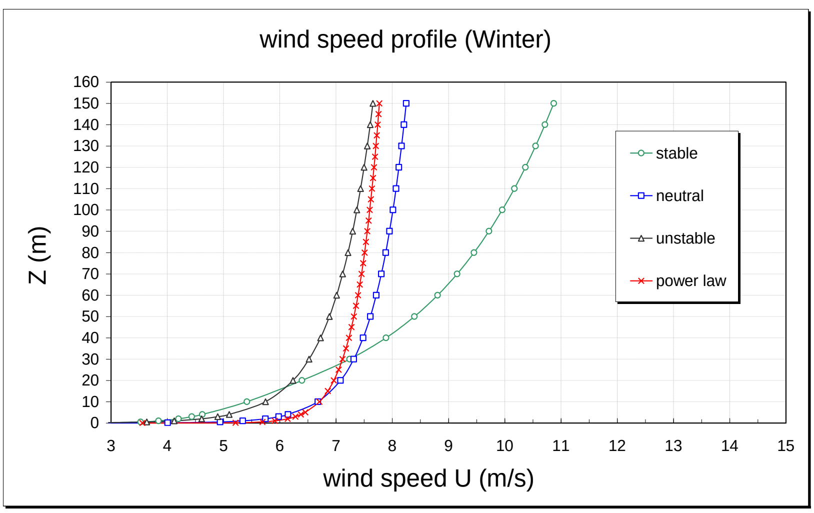

Figure 2: Wind speed profiles for different conditions in Winter.

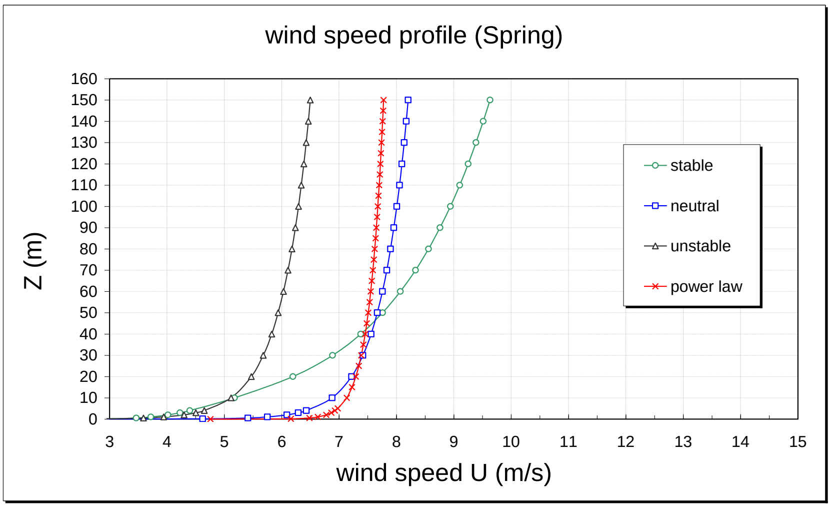

Figure 3: Wind speed profiles for different conditions in Spring season.

However, in the stable condition, the wind speed gradient is increased obviously, because of the reduced mixing process. The wind speeds are 8.8 m/s and 9.5 m/s at 60 m and at 80 m, respectively. In neutral condition, the homogeneous wind speed profile still exists, because the convective mixing layer reaches its maximum value. The wind speed at 60 m is 7.7 m/s, and at 80 m it is 7.9 m/s. It could be noticed in Figure (2) that the wind velocity profile generated by the power law, behaves as the neutral condition, since it does not consider the atmospheric stability effect.

It could be concluded that using neutral stability condition and ignoring atmospheric stability conditions for winter season will result in overestimated wind speeds of 8.9% and 8.5% at 60 m and 80 m., respectively for unstable condition while wind speeds will be overestimated at 60m by 12.5% and at 80 m by 16.6% for stable condition.

Figure (3) indicates the variation of wind speed profiles for Spring season. According to this Figure, the unstable condition states that the wind shear is lower than that in Winter. The vertical mixing creates a generally homogeneous wind profile with higher magnitude. The wind speed was estimated to be 6.0 m/s and 6.2 m/s at 60 m and at 80 m., respectively. For stable condition, the wind speed gradient is increased obviously, because of the reduced mixing. The wind speeds are 8.1 m/s, and 8.6 m/s at 60 m and at 80 m, respectively. In neutral condition, the homogeneous wind speed profile with elevation still exists, because of the convective mixing layer reaches its maximum value. The wind speeds are 7.8 m/s and 7.9 m/s at 60 m and at 80 m, respectively.

It could be noticed that ignoring effect of atmospheric stability condition during Spring season will result in overestimated wind speed at 60 m and 80 m by 22.2% and 21.8%, respectively for unstable condition and underestimated wind speeds by 4.1% and 8.5% at 60 m and at 80 m, respectively for stable condition. These results obviously will affect the technical an economic feasibility studies performed for any proposed wind project.

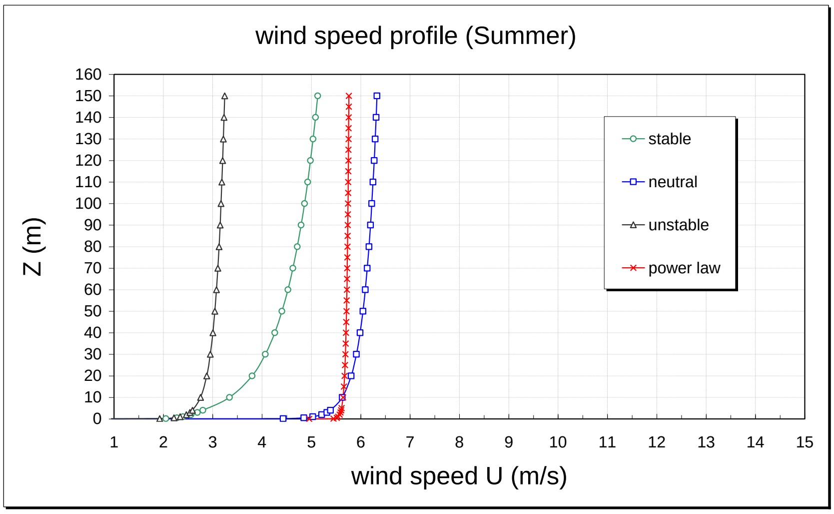

Figure 4: Wind speed profiles for different conditions in Summer season.

Figure (4) illustrates effect of atmospheric stability on wind speed profiles in Summer season. As it could be noticed from this Figure that the wind speeds and wind shear are very low during this season for both stable and unstable conditions because of the large amount of ground heat flux and the high ground convective mixing. The wind speed for unstable condition is roughly 3.1 m/s at both altitudes of 60 m and 80 m. For stable condition, the wind speeds are 4.5 m/s and 4.7 m/s at 60 m and 80 m, respectively.

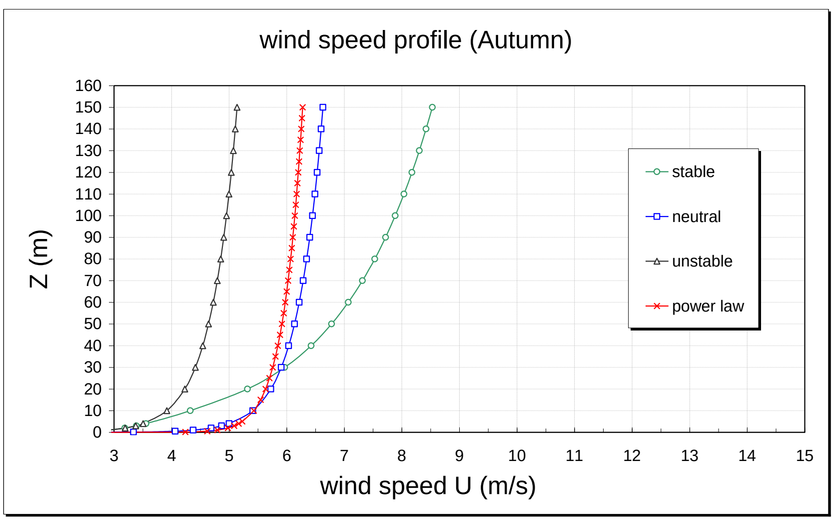

Figure 5: Wind speed profiles for different conditions in Autumn season.

It could be noticed from above graph that the wind speed at high altitudes equivalent to wind turbine heights ignoring stability effect will result in overestimating wind speed for both stable and unstable conditions. For unstable condition the wind speed overestimation is 49.6% and 49.35% at 60 m and 80 m, respectively while for stable condition it is 26.1% and 23.5% at 60 m and 80 m, respectively.

The effect of atmospheric stability conditions on wind speed profiles in Autumn season is presented in Figure (5). It could be noticed the effect of atmospheric stability on wind speed profile in Autumn is close to that of Spring season presented in Figure (3).

As shown in this Figure, the effect of using neutral stability velocity profile and ignoring stability effect will result in overestimating wind speed at 60m by about 24% for unstable condition and underestimation of 14% for stable condition, while for 80 m the wind speed overestimation will be 23.5% for unstable condition and an underestimation of 18.6% for stable condition.

It could be concluded that ignoring atmospheric stability effect on velocity profiles is noticeable. When extrapolating wind speed to heights close to wind turbines hub heights will result in overestimation of wind speeds for unstable condition and underestimation of wind speeds for stable condition for all seasons with different percentages except for summer season where ignoring atmospheric stability effect will result in overestimation of wind speeds for both stable and unstable condition.

Overall Distribution of Atmospheric Stability Conditions

Figure (6) shows the overall distribution of atmospheric stability conditions for the four seasons at Magrun town. It could be concluded from this Figure that during Summer season stable condition contribution represents 42%, while unstable condition represents only 25% of the season and the neutral condition is about one third, 33 %. In Winter season unstable condition shares only 17% of the time, neutral condition represents one quarter of the time (25%), while the highest share of 58% is for stable condition. This means ignoring effect of atmospheric stability will contribute to underestimating wind speeds and therefore the expected available energy from the wind and the expected energy produced by proposed wind turbines.

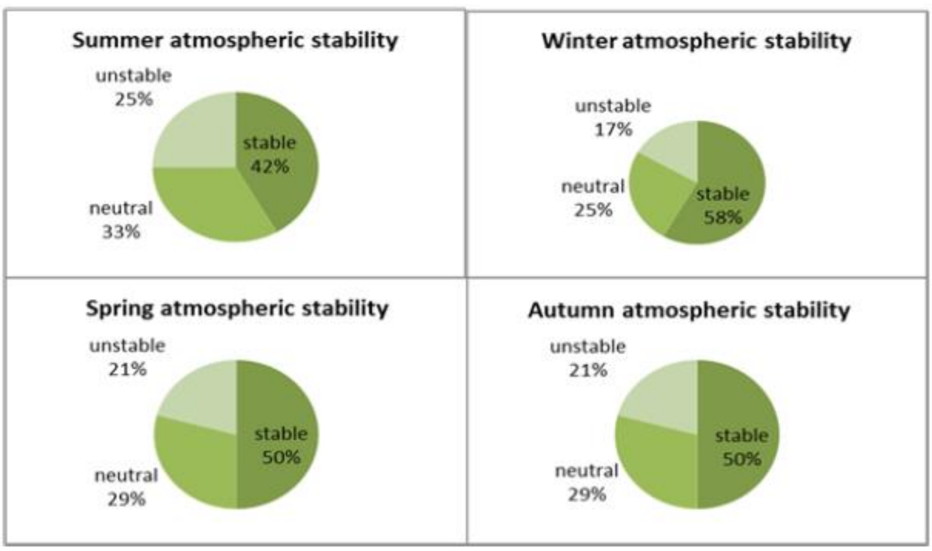

Figure 6: The percentage share of stable, unstable and neutral stability conditions.

The atmospheric stability conditions for spring and autumn seasons are identical. The neutral stability condition contributes 29.2% while unstable shares by 20.8% and stable condition goes for 50%. The results show the importance of considering the effect of atmospheric stability conditions on wind speed and therefore on the expected available wind energy. It could be concluded that atmospheric stability effect is an important issue that should be tackled whenever there is a wind resource assessment or wind project feasibility studies proposed for this city.

Variation of Atmospheric Stability Conditions with Wind Speed

Figure (7) shows the variation of atmospheric stability conditions with respect to wind speed for various seasons. It could be noticed that in Winter, the high speeds are in the range of 10.5-11m/s, which represent only 15% for stable condition, and wind speeds of 9-10 m/s represent 12% while other wind speeds are represent less than 10%, as shown in Figure (7).

Neutral stability condition represents higher frequency with lower wind speed values, where wind speeds of 7- 8 m/s represent about 32%, while wind speeds of 5-7 m/s represent less than 10%. Unstable stability condition dominates wind speeds of about 6.5-8 m/s as shown in Figure (7). For this city, it could be concluded that during winter unstable and neutral conditions are dominating low to medium wind speeds while stable condition dominates high wind speeds. Same applies for other seasons with different frequency values except for summer, where it is characterized with higher frequency that reach 68% for unstable condition for low wind speeds of 3-3.5 m/s, 65% neutral condition for medium wind speeds of 6-6.5 m/s, and 38% stable condition for wind speeds of 4-5.5 m/s. This is due to the large amount of ground heat flux of convective boundary layer effect that characterize this season.

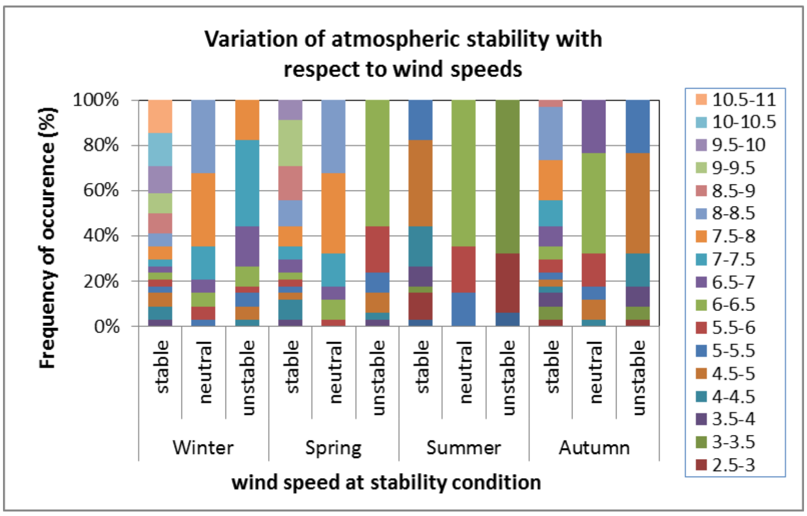

Figure 7: Frequency of wind speed at atmospheric stability conditions.

The Available Wind Energy

Figure (8) illustrates the available wind energy at Magrun in winter season. The maximum wind energy intensity or the available wind energy is obtained at stable condition. It 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. In unstable and neutral conditions, the increase is not as large as that in stable condition with height. It is 1.69 kWh/m^2 at 60 m and 1.8 kWh/m^2 at 80 m in neutral condition.

It could be noticed that for stable condition the available wind energy at 60 m is 246% of the energy at neutral condition and at 80 m it reaches 300% that of the neutral condition. So, it should be brought in mind that stability conditions represent 58 % in winter season which illustrates the importance of considering the effect of atmospheric stability in estimating the velocity profile in wind resource assessment as well as in studying loads and stresses affecting the blades of wind rotors.

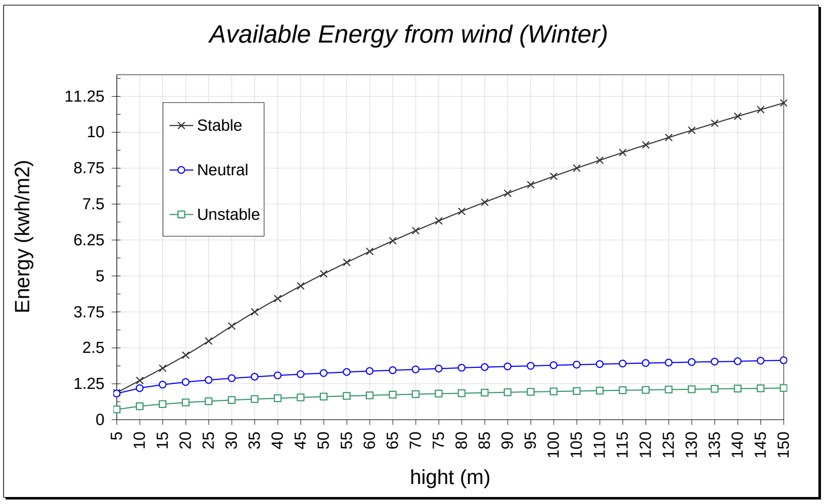

Figure 8: Available wind energy at Magrun town in winter.

The available wind energy is presented in Figure (9) for Spring season. It could be noticed that at stable condition the available wind energy increases with height at higher percentage than that for unstable and neutral conditions. Also, it takes a similar trend for the other seasons but with different values.

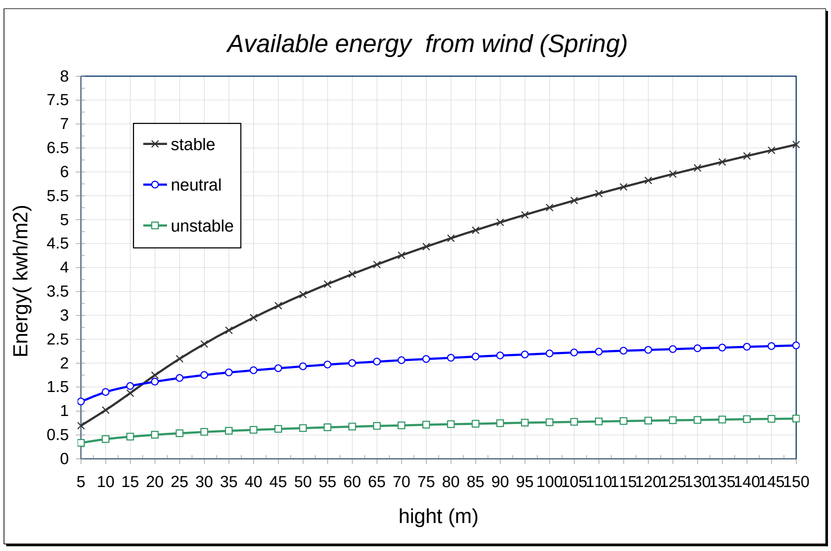

Figure 9: Available wind energy at Magrun town in spring season.

Figure (10) illustrates the effect of seasonal variation of atmospheric stability conditions on wind energy intensity or available wind energy for Magrun town at 80 m. The elevation of 80 m is the typical height of recent wind turbines hub height. According to this Figure, the maximum available wind energy in Winter at stable condition is estimated to be 7.24 kWh/m^2, while the minimum available wind energy in the stable condition occurs in the summer with a value of 0.641 kWh/m^2. From the Figure, the maximum wind energy occurs in the stable condition for all seasons, while the minimum wind energy occurs in the unstable condition.

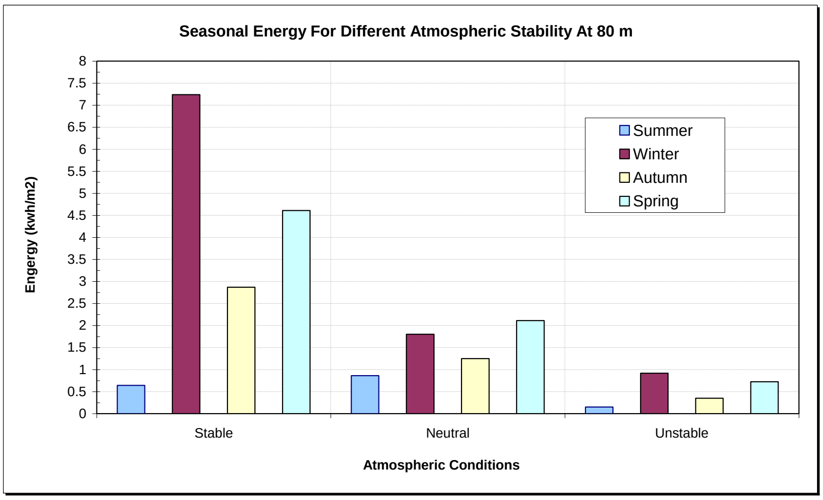

Figure 10: Seasonal available energy from the wind at 80 m for Magrun town

CONCLUSIONS

In adiabatic or neutral conditions wind speed profiles can be described by logarithmic law while for diabatic conditions stability corrections should be considered. Stability corrections can be determined by "MOST" for surface boundary layer. Stability corrections are important for the correction and simulation of diurnal and seasonal patterns as well as for the frequency distribution of wind speed.

The characteristics of the atmosphere at a coastal city in Libya named "Magrun" was investigated. The diurnal, seasonal variation and overall atmospheric stability conditions were determined. Wind power density and wind energy intensity were calculated. The effect of atmospheric stability conditions was investigated. Variation of atmospheric stability conditions with respect to wind speed frequency were studied and illustrated.

It was found that stable atmospheric condition represents the highest share where it reaches 58 % in winter season, 50% in Spring and Autumn seasons, and 42% in Summer season. The highest wind shear for Magrun town is during winter season and its lowest value is in summer. The maximum wind energy available in the stable condition for all seasons, while the minimum wind energy is expected in unstable atmospheric conditions. Referring to the results, in Winter season with stable atmospheric conditions the available energy at 80 m could reach 300% of that at neutral condition. This illustrates the importance of considering the effect of atmospheric stability in estimating the wind speed profile in wind resource assessment as well as in studying loads and stresses affecting the blades of wind rotors.

This study illustrated that during winter unstable and neutral condition are dominating low to medium wind speeds while stable condition dominates high wind speeds in this city. Same applies for other seasons with different frequency values except for summer, where it is characterized with higher frequency that reaches 68% for unstable condition for low wind speeds 3-3.5 m/s, 65% neutral condition for medium wind speeds of 6-6.5 m/s and 38% stable condition for wind speeds 4-5.5 m/s because of the large amount of ground heat flux of convective boundary layer effect that characterize this season. The atmospheric stability conditions have a pronounced effect that represents an important issue that should be tackled whenever one considers wind resource assessment or wind project feasibility studies proposed for this city.

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Nomenclature

k = Von Karman constant, approximately equal to 0.4.
L = A reference height above ground, m.
L_s = Monin-Obukhov stability length, m.
u = wind speed at an elevation, m/s.
u_* = the friction velocity, m/s.
U = A reference wind speed, m/s.
z = the height above ground, m.
z_0 = the empirical surface roughness, m.
ψ = the atmospheric stability function.