The impact of wind shear and turbulence intensity on wind turbine power performance

O impacto do cisalhamento do vento e da intensidade de turbulência no desempenho da turbina eólica

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Abstract: Wind power is already a consolidated global power source. It is essential to study wind power efficiency by means of the evaluation of wind parameters effects on the power production system. This study aims at investigating the influence of wind shear and turbulence intensity in a North American Wind Farm through wind data analysis that was collected using LiDAR and SCADA data. Vertical wind shear is directly correlated to the wind turbine productivity and hardly influences the power performance of the turbine. The turbulence intensity impact on wind power was parameterized as the ratio of the standard deviation and the mean value for the 10-minute wind speed data interval. High turbulence intensity associated with large wind shear may reduce wind turbine performance. Therefore, increasing turbulence intensity, the power output is overestimated at moderate wind speeds and underestimated at higher wind speeds. Meanwhile, the wind shear coefficients were found to vary between 0 and 0.2 at higher inflow velocities. High wind shear values, close to 0.4, were recorded for lower inflow velocities.

Keywords: Wind energy, wind shear, turbulence intensity, wind power, LiDAR.

Resumo: A energia eólica já é uma fonte consolidada de energia elétrica, com abrangência global. É essencial que se estude a eficiência da geração eólica através da avaliação dos impactos dos parâmetros do vento sobre esse sistema de produção de energia elétrica. Este estudo visa a avaliar a influência do cisalhamento do vento e da intensidade de turbulência em um empreendimento eólico na América do Norte mediante análise de dados de vento coletados em LiDAR e na base de dados SCADA. A variação do cisalhamento do vento segundo a vertical está diretamente correlacionada à produtividade do aerogerador. Para estudar o impacto da intensidade de turbulência na geração eólica, parametrizou-se a turbulência pela razão entre o desvio padrão e a média dos registros de vento no intervalo de dez minutos. As elevadas intensidades de turbulência, associadas aos altos valores de cisalhamento do vento podem reduzir o desempenho dos aerogeradores. Portanto, aumentando a intensidade de turbulência, a energia gerada é superestimada em moderadas velocidades do vento e subestimada em altas velocidades do vento. Enquanto isso, os coeficientes de cisalhamento do vento variaram entre 0 e 0.2 para altas velocidades.

Palavras-Chave: Energia eólica, cisalhamento do vento, intensidade de turbulência, geração elétrica, LiDAR.

1 Introduction

The demand for energy has been expanding over the past decade due to the global economic progress. Wind power is a clean resource, which has gained a significant share in global power production. Global availability of wind resources and technological improvements are the main reasons for the growing number of wind farm developments. Moreover, wind power is considered one of the cleanest energy sources, with high economic feasibility due to both equipment and installation falling costs. Therefore, a large number of wind farms have been developed both onshore and offshore over the last decade. The largest expansion rate of wind power development has been registered in Brazil, Mexico and South Africa according to the 2014 Global Energy Council Outlook [1]. The wind resource in Brazil is represented by an enormous potential. The country achieved 10 GW of wind power installed capacity in 2016 [2]. The wind power efficiency depends on the atmospherics processes that produce high winds in a given location, and also on the local turbulence effects on the wind turbine generator [3].

A thorough assessment of wind resources at the potential development site is crucial for wind power feasibility. On site, wind measurements should be made at least for three different heights, which are the hub height, the highest and lowest tips of the blades. The wind velocity at a given site increases with height by a power factor called the wind shear coefficient. The other two wind related parameters that influence energy production are the turbulent kinetic energy and turbulence intensity, which are related to atmospheric stability. The development of accurate simulation of the atmospheric stability through computer models may improve the power output production estimate [4] [5] [6].

Wind shear might be defined as the local variation of the wind vector and surface roughness. The wind shear for a given direction is the variation of wind speed over the normal direction. For the wind power industry, wind shear is assumed to be the variation of the incident wind speed with height above ground level [7]. Wind shear vertical variability is a crucial parameter in wind energy projects, because it is directly correlated to the productivity of wind turbine output [8].

The tendency to endure vertical motion or to restrain existing turbulence is defined by stability. The boundary layer turns its stratification stable on any occasion of the elemental surface has lower temperature compared to the air. High wind shear indicates a faster variation in wind velocities with height [9] [10]. However, in stable conditions, hub height wind velocities point to be greater than under winds, thus its huge gradient generates torque across the rotor, which can lead to power losses. Therefore, a low wind shear exponent produces greater wind speed recovery than a high wind shear exponent [11].

Turbulence is the velocity fluctuations superimposed on the mean flow. Such fluctuations are induced by the shear stresses caused by layers with different relative mean velocities. In stable boundaries, turbulence intensity is typically lower than in the neutral and unstable boundary layers [12] [13]. Low turbulence intensity is associated with stable conditions. High turbulence is associated with unstable conditions, in which there are abrupt changes in wind speed with height [14].Sheinman and Rosen [15] demonstrated that neglecting the effect of wake turbulence in the incoming wind speed can lead to an overestimation of turbine output slightly more than 10%. Barthelmie et al. [13] mentioned a power loss interval between 10 and 20% of total power generation related to the wake effect, when measured by a SODAR (SOnic Detection And Ranging). Moreover, high-level power losses by wake influence can reach 50%, as presented by Chu and Chiang [16]. In particular, the velocity deficit, which is highly related to power losses in wind farms, recovers faster when the turbulence intensity level of the incoming flow is higher, and close to the turbine is the place where the maximum turbulence usually occurs [17]. This affects the power performance of the downwind turbines in substantial wind farms.

It is crucial to study the performance using the evaluation of wind parameters that will influence the whole system. Therefore, in this study, the main characteristics of the wind power generation efficiency are estimated from the data analysis at a wind farm in North America. In order to understand how the wind characteristics can affect the power generation, the wind shear, turbulence intensity and power performance analysis of the wind turbine are discussed in this paper. Brazilian wind power technology is growing fast, and in order to achieve optimal performance, it is pivotal to develop specialized studies on the wind flow through wind turbines.

2 Materials and methods

The influence of wind shear and turbulence intensity on wind power performance was quantified by wind data analysis. The dataset was collected using LiDAR and SCADA technology in a North American wind farm. The following subsections provide a description of the study area, LiDAR characteristics and the analysis methodology applied in this work.

2.1 Study area and LiDAR

The study area is located in the United States of America. The site consists of a flat terrain with annual average temperature in the region close to 22°C and approximately 10m above sea level. Due to contractual agreement, it was not possible to describe the site location and its detailed information.

In order to capture the freestream velocity, the Galion was deployed. Such equipment is a LiDAR (Light Detection and Ranging), which works with the Doppler Shift principle, emits light waves from a laser and receives the signal back from airborne particulate matters. LiDARs identify the Doppler shift in the laser emissions frequency, which is back-spread by aerosol particles heading in the wind. Such movement establishes a Doppler shift on the frequency of the back-spread discharge expressly equivalent to the element of the wind speed vector ahead the line of sight (LOS) wherever the laser discharges radiate. The gradient acquired by changing the direction of the beam in relation to the wind direction must be analysed in order to collect the wind velocity from Doppler shifts and equivalent LOS radial wind speed vector elements [18].

The measurement campaign consisted of nine months of data in 2014, which presented around 41300 samples of 10 min average data, presenting standard error of 0.02. The wind turbine generator (WTG) of interest had an arc scan deployment trying to understand the behaviour of the freestream wind parameters that reaches the turbine, in order to characterize the atmospheric conditions around the swept area of a WTG, where the hub height is 80 m above the ground. A G4000 Galion unit installed on the ground was used for the measurement campaign, which is capable to range up to 4000 m with 30m spatial resolution, the accuracy is close to 0.1 m/s that permits to capture a maximum velocity up to 70 m/s. The measurement characteristics, depicted in Figure 1 scan geometry of five beams, incremented at 30° intervals in azimuth, and Figure 2 angle of 18.32° on the vertical plane.

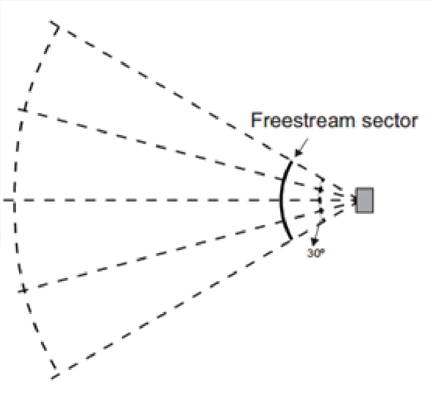

Figure 1: Scan geometry of 5 beams.

Figure 2: Vertical plane with elevation angle.

2.2 Data analysis

The data collected by the LiDAR was used as input the Windographer software, in order to describe the wind attributes over the site field campaign.

Once the measurements occurred, the data were screened to eliminate redundancy or insufficient period record. Due to the varied formats of the data sets, preliminary data evaluation and analysis was performed for data consistency. The first step in any evaluation is performing a basic screening of the measured wind data. This basic screening was important to look for the following occurrences such as: extreme wind speed values and sectors with extreme wind gradient exponents which are typically seen when the data is of poor quality.

Acquiring a valid data set of the wind direction during the period of production is very important due to the large variation in wind farm production over just a few degrees. Wind rose diagrams help to visualize wind patterns at the site, being the most common instrument to display wind data in terms of wind velocity and frequency distribution.

The statistical analysis of wind speed was performed considering the diurnal variation of wind characteristics, frequency and the distribution of wind speed. LiDAR measurements of wind profiles allowed for a satisfactory data base for representing wind statistics. Those wind profiles also help to understand the importance of wind shear and stability as a whole on the power production. In terms of wind energy assessment and analysis of wind speed, the Weibull distribution is a typical technique applied and wind speed distribution study for the area supports in order to understand the wind characteristics of the area. The Weibull parameters k and c are responsible for representing the dimensionless shape parameter and the scale parameter (m/s) respectively. Such parameters are obtained from a wind velocity data employing the Least Squares Technique (LST), characterized as one of the most well-known technique utilized in statistical evaluation approach [19]. Nevertheless, it is important to point out that such a method excels when applied to grand sample sizes, because of that it was implemented in this work.

The Weibull distribution function can be represented as equation 1:

$$\mathrm{f(u)} = \left(\frac{\mathrm{k}}{\mathrm{c}}\right)\left(\frac{\mathrm{u}}{\mathrm{c}}\right)^{\mathrm{k}-1} \exp\left[-\left(\frac{\mathrm{u}}{\mathrm{c}}\right)^{\mathrm{k}}\right] \qquad (1)$$

where $f(u)$ stands for wind velocity probability of occurrence, k is the dimensionless Weibull shape parameter and c is the Weibull scale parameter in units of velocity [20].

2.3 Wind shear

A dimensionless wind shear exponent (α) was calculated from wind speed at two heights, 1 and 2, using the simple power law [21], as described in equation 2:

$$V_2(z) = V_1\left(\frac{Z_2}{Z_1}\right)^{\alpha} \qquad (2)$$

where Z_2 and Z_1 are heights in (m), above the ground level, where will be quantified the wind shear exponent between the two heights; $V_2(z)$ is the mean horizontal wind speed (m/s) at height Z_2 (m); V_1 is the wind speed (m/s) at the reference altitude Z_1(m); and α is the wind shear exponent. The wind shear exponent estimates atmospheric stability, but it is not a straightforward measure of stability [22]. Different wind shear exponents were calculated in three distinct heights from LiDAR measurement data, such heights are the 127, 80 and 33 m above the ground.

2.4 Turbulence intensity

The influence of wind speed parameters is important to wind turbine performance. Turbulence measurements are frequently made by employing equipment placed within the flow, such as cup or propeller anemometers, sonic anemometers and LiDAR. Another detail worth mentioning is that the International Electrotechnical Commission (IEC) [23], IEC 61400-12-1, demands the measurement of only wind horizontal component, therefore the turbulence intensity can be analysed from the horizontal component of the velocity. The turbulence intensity (TI), obtained from straight measurements of horizontal turbulence fluctuations at the site, was also considered in the analysis. It was calculated by the ratio of the standard deviation of the wind speed (s) in (m/s), divided by the corresponding mean wind speed (V), in (m/s), at the height of 80 m, as shown in equation 3.

$$\mathrm{TI} = \frac{\sigma}{\mathrm{V}} \qquad (3)$$

3 Results and discussion

The data presented in this section are important for the profile characterization of the wind farm.

The mean wind speed from LiDAR dataset was 7.66 m/s. Thus, the measurement campaign was implemented during a long period where the mean wind speed is characterized as a high value in terms of power generation.

The mean wind direction was 139° in the southeastern quadrant. The mean temperature around 21.5°C means that the Galion LiDAR was inside of the viable range of the 40°C during the deployment period. A mean air density of 1.18 kg/m³ was also obtained, which was a little bit higher than

Normal Temperature and Pressure at sea level with 20°C. The variables measured by LiDAR are presented in Table 1.

Table 1: Wind variables measured by LiDAR.

Variable	Unit	Mean
Wind speed at hub height	m/s	7.66
Wind speed standard deviation	m/s	3.02
Maximum wind speed	m/s	19.49
Wind direction	°	139.22
Temperature	°C	21.5
Air density	Kg/m³	1.18

Evaluating the energy that can be produced at a particular wind farm is vital. Part of the evaluation is related to the estimation of a probability density function (PDF), which is fundamental for assorted wind power purposes. The Weibull distribution is widely applied to determine wind frequency distribution on wind energy and other renewable energy sources. The wind temporal variability is shown in Figure 3, through the comparison of the wind velocity histogram with the fitted Weibull distribution.

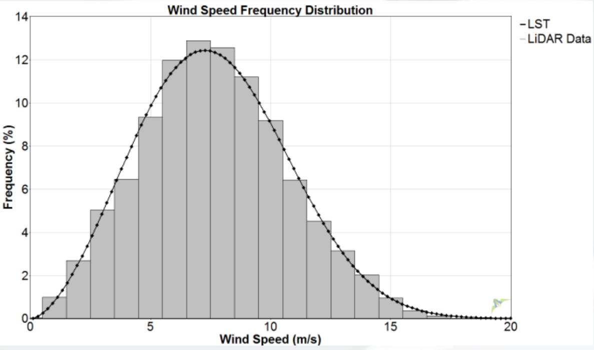

Figure 3: Wind speed distribution.

The shape parameter k is equivalent to 2.70, which means that a lower number is related to a wide distribution, where the wind velocity is likely to vary considerably. The Weibull parameter c = 8.63 m/s can affect the distribution in terms of changes on the abscissa scale.

The wind rose obtained from LiDAR measurements data is shown in Figure 4.

Winds from the southeast sector were dominant, corresponding to 78% of the events. The highest frequency was 35% for the 150° direction, followed by 15% for 120° and 180° directions.

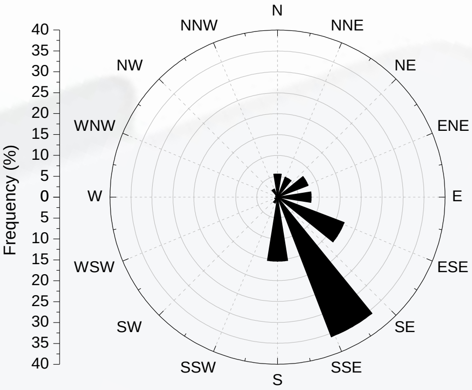

Figure 4: Wind rose.

3.1 Wind shear

The wind shear coefficients (α) were determined following equation 2 for three different heights, corresponding to the base, centre and top of the blades' circle, which yielded the event mean shear coefficient. Such coefficients have been binned in six ranges in order to have enough data to plot the power performance. Those ranges are presented in Table 2, alongside occurrences and median wind shear.

Table 2: Wind shear ranges.

Wind Shear Ranges	Ocurrences	Median
< 0	1655	-0.053
0 to 0.1	6806	0.059
0.1 to 0.2	4701	0.144
0.2 to 0.3	3563	0.246
0.3 to 0.4	2668	0.346
> 0.4	2782	0.483

As seen from the table, the band with lower data counts was $\alpha < 0$ and the range with higher data counts obtained was 0 to 0.1. Thus, a considerable part of the data was related to low wind shear values. Such density of data counts at each range of wind shear can also be seen in Figure 5, which depicts scatter plots of the power generation over the wind speed at hub height for distinct band of wind shear exponents.

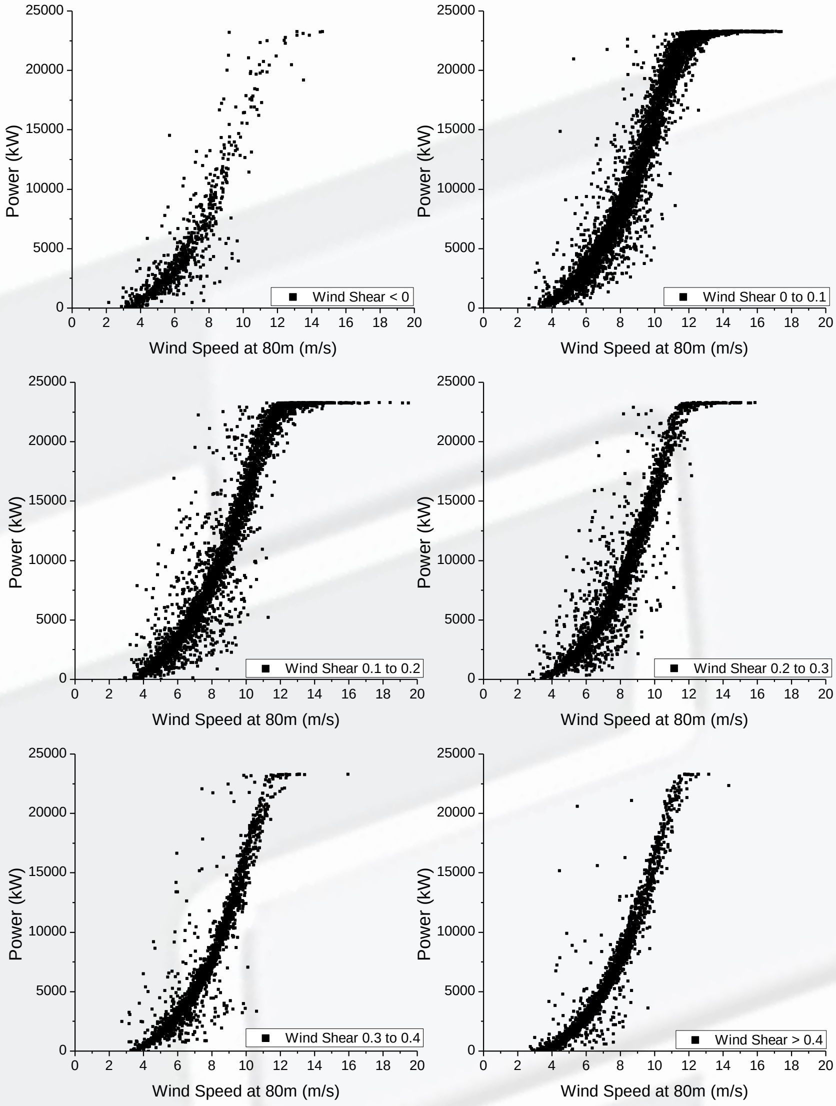

Figure 5: Power curves with wind shear scatter plots.

Figure 5 also shows that the events are concentrated on lower wind speeds. Most of the high wind speeds ($V > 14$ m/s) produced shear coefficients in the [0.1 - 0.2] range, whereas the negative shear coefficient has almost not occurred for high speed winds.

Figure 6 depicts the wind speed histogram conditioned on wind shear coefficients, which was designed to enhance the understanding of the wind shear coefficients behavior for different wind speeds. The wind speed bins of 5 to 10 m/s, comprised 65% of the events, where most of the data was associated with the 0 to 0.1 shear range.

The highest single occurrence for a particular wind shear range occurred for 8 m/s with a value of 832 counts at 0 to 0.1 wind shear coefficient. As soon as the wind speed develops exceeds the coefficient between 0 and 0.1, it becomes more substantial than other ranges. The wind speed bins of 3 and 4 m/s are characterized to be the unique bins that presented a high number of occurrences at wind shear greater than 0.4. Such value is a large coefficient, but might not affect considerably the wind turbine performance due to lower wind speeds. Rehman et al. [24] presented a wind shear coefficient greater than 0.3 for a suburban in Rawdat Ben Habbas, where roughness influences the production more than the open flat terrain. Farrugia [25] found exponents that reached 0.45, that reported to have influences of high wind speeds in an agricultural land roughness.

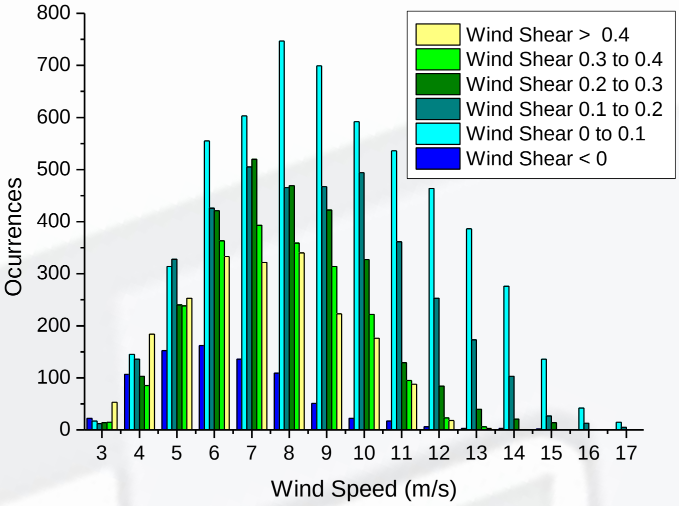

Figure 6: Wind shear histogram.

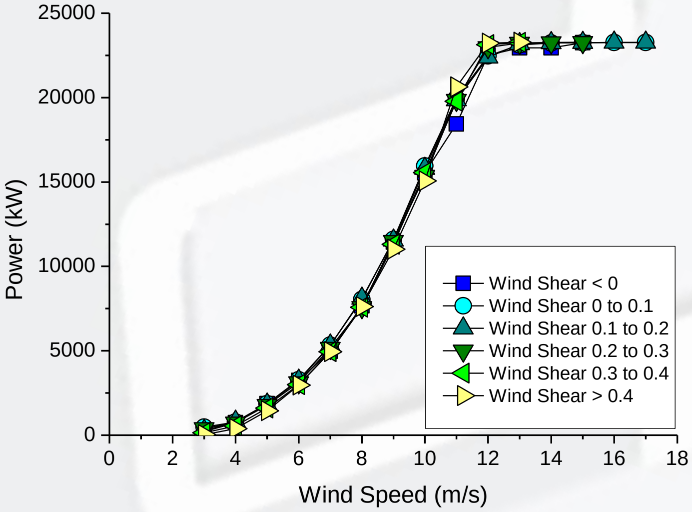

Figure 7: Relationship between power performance and wind shear coefficients.

Figure 7 shows the performance curves which demonstrate how the wind shear ranges performed against power generation for each particular wind speed bin.

All wind shear ranges show similar pattern in terms of power curves. However, the negative shear range demonstrates a visible underestimation of 11 m/s while the range greater than 0.4 seems to have an overestimation at the same wind speed bin.

Therefore, the wind shear range of 0 to 0.1 was taken as the power curve base, due the highest data counts, 6806 samples, which demonstrates good representativeness, with more than 100 data points for every single wind speed bin from 4 m/s to 15 m/s. These data are used to calculate the performance of negative and higher shears in the power output of the wind turbine. The wind speed bin that presented greater difference was the 3 m/s, which deviated more than 10% for all of the wind shear ranges in relation to the base shear range of 0 to 0.1.

In addition, for wind speeds higher than 3 m/s, the power curve conditioned on negative shear performed similarly to the base curve. However, wind shear ranges of 0.3 to 0.4 and greater than 0.4 displayed two wind speed bins in which there was at least 14% power underestimation with respect to the base curve. Both bins, at lower wind speeds of 4 and 5 m/s, were associated with power underestimation of 30% and 14%, respectively, for shear between 0.3 and 0.4, and power underestimation of 50% and 23% respectively for wind shear coefficients greater than 0.4.

The power underestimation of the site agreed with Bardal et al. [26] and Honrubia et al. [8] for high shear events, where the effect of wind shear reduces the efficiency of WTG in high shear conditions when the curves converge below rated wind speed. It can be inferred that higher shear exponents bring large uncertainty to the power produced.

3.2 Turbulence intensity

By means of wind speed standard deviation analysis, showed in equation 3, it is possible to note a rising standard variation of the power generation. Therefore, as velocity oscillate around the rated velocity, the power output is restricted to the rated power.

Only when the immediate velocity values are below rated velocity, the wind is converted into power oscillation. As a consequence, mean power associated with a particular turbulence intensity is typically lower than the power output with hypothetical turbulence intensity equals 0%, for the same wind speed [14]. Figure 8 is represented by four TI ranges in order to demonstrate how the power curves behavior with different turbulence bands and the occurrence distributions pattern.

Table 3 summarizes the statistics of turbulence intensity ranges used in Figure 8.

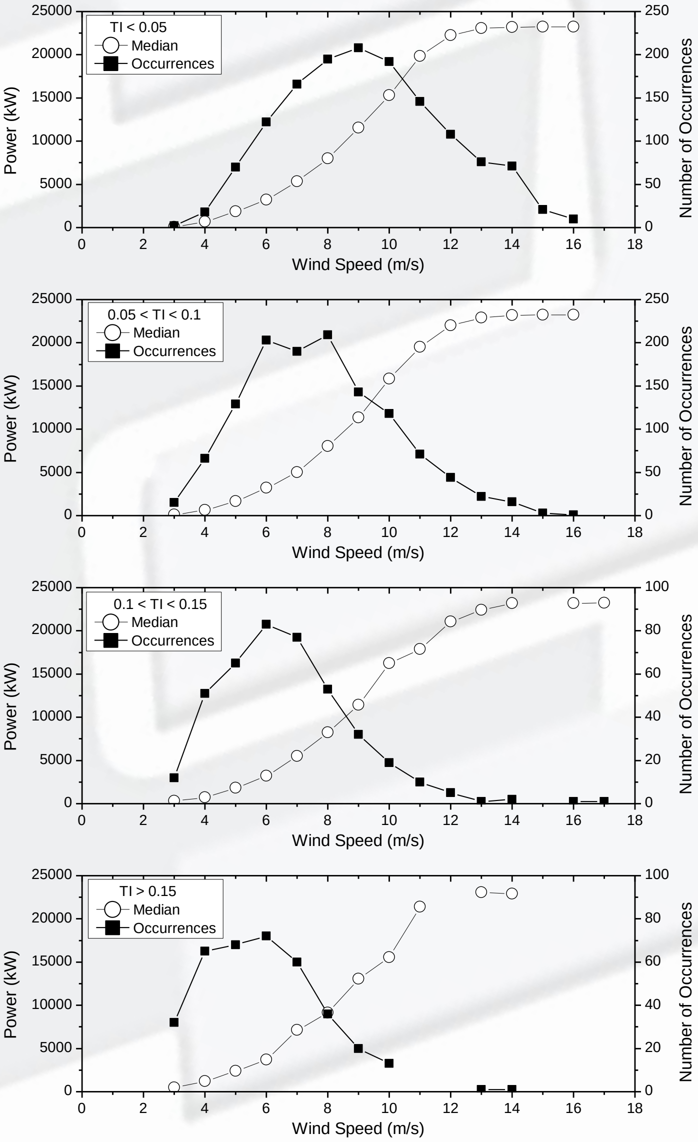

Figure 8: TI median and number of occurrences for different inflow wind speeds.

Table 3: Turbulence intensity ranges.

Turbulence Intensity Ranges	Ocurrences	Median
< 0.05	1405	0.033
0.05 to 0.1	1230	0.070
0.1 to 0.15	412	0.121
> 0.15	370	0.200

Figure 8 and Table 3 show that low turbulence events occur more often (77% of time) than high turbulence events (23% of time).

In order to understand the influence of turbulence intensity at certain levels of wind speed, Figure 9 is presented with four turbulence ranges for each wind speed bin from 3 to 17 m/s.

High velocities are associated with low turbulence, as one can see for the wind speed bins from 9 to 17 m/s, the turbulence intensity is dominated by the range lower than 0.05. Wind speed bins of 7 and 8 m/s are characterized by a close develop of turbulence intensity by < 0.05 and 0.05 to 0.1, with a difference between both ranges lower than 50 counts. Therefore 5 and 6 m/s bins are dominated by 0.05 to 0.1 turbulence band. At 4 m/s, there is almost a tie in terms of occurrences between 0.05 to 0.01 and > 0.15 turbulence range, where the difference happened to be only one count. However, at 3 m/s wind speed bin the high turbulence intensity level dominated the occurrences.

In summary, low turbulence intensity events were dominating in higher wind speeds conditions. In contrast, high turbulence intensity increased at lower wind speed bins.

Finally, in order to compare the turbulence intensity ranges performed against the power output that is generated at each wind speed bin, Figure 10 attempts to illustrate such performance among the turbulence intensity levels. It is important to note that close to the cut-in velocity, the power output tends to intensify according the turbulence intensity. However, the power output is likely to drop as the turbulence intensity intensifies.

All turbulence intensity ranges demonstrated relatively similar pattern in terms of power curves, but high levels of turbulence occurred to have an intensification of the median power at lower wind speeds, and the opposite occurred to higher wind speeds, where an underestimation on the median power output was shown., It is worth mentioning that due to the lack of data counts, the TI range greater than 0.15, and power output at 12, 15, 16, 17 m/s wind speed bins, were not possible to obtain. The same occurred -for the 0.1 to 0.15 turbulence intensity range, for the wind speed bin of 15 m/s. Also at 17 m/s wind speed bin there was a lack of data for <0.05 and 0.05 to 0.1 turbulence intensity range.

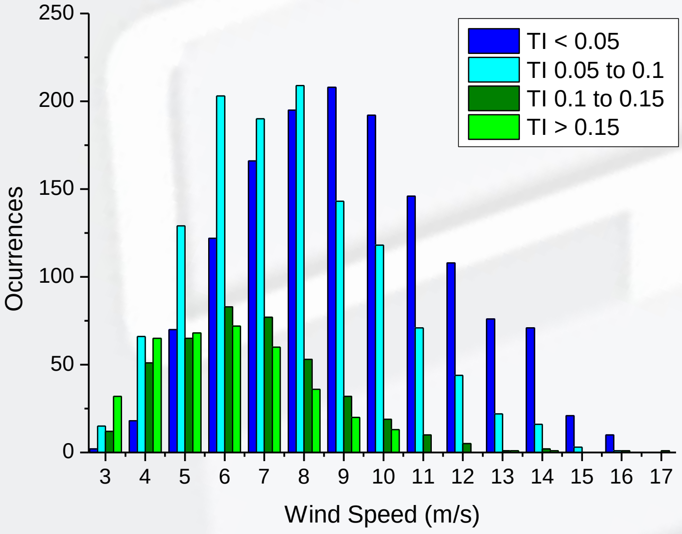

Figure 9: Turbulence intensity histogram.

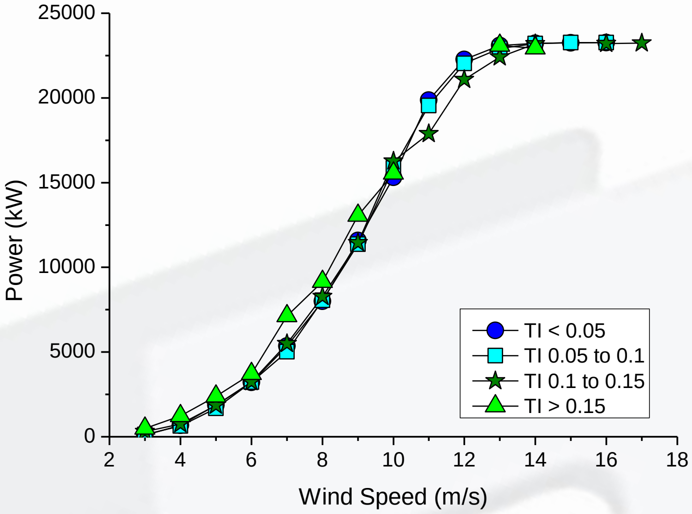

Figure 10: Power performance of TI coefficients.

The turbulence intensity between 0.05 and 0.1 was taken as the power curve base, due to the high number of data counts, with 1405 occurrences, but also due to the International Electrotechnical Commission [23], IEC 61400-12-1, which points out that the normal value of turbulence intensity (based on 10-min average) would vary from 0.03 to 0.12 in an open flat terrain.

For low to medium wind speed bins, from 4 m/s up to 9 m/s, the turbulence intensity bin greater than 0.15 average overestimated in 31% the power output, when compared to the power curve base. On the contrary, at high wind speed levels, over 9 m/s, the power output is underestimated in the turbulence intensity range between 0.1 and 0.15, and achieved the single high underestimation of 10%, at 11 m/s.

In summary, Bardal et al. [26] presented similar pattern, where the power output had an overestimation in lower wind speeds and underestimation on higher wind speeds. Such work also emphasizes that turbulence intensity has a huge impact in reducing power output in higher wind speeds. This is due to pitching the blades for gusts caused by high turbulence, coupled with negative fluctuations.

4 Conclusion

This work investigated the wind characteristic parameters that can influence the power performance of a wind turbine at a wind farm in the United States of America. The wind resource was evaluated exploring the scan geometry of Galion LiDAR mounted close to the wind turbine. LiDAR technology permits straight measurement of unfavourable wind conditions instead of relying on assumption through examination of their effects.

Analysis of LiDAR data demonstrated mean wind speed of 7.76 m/s. The wind speed frequency distribution was supported by the Weibull distribution with shape parameter k equals to 2.70 and the scale parameter c equivalent to 8.63 m/s. The predominant wind direction was 139^{O} in the southeast direction. The mean temperature was around 21°C, which is a moderate temperature that the Galion LiDAR can work with satisfactorily.

According to the results obtained, it is possible to conclude that neglecting the turbulence intensity effect in the wind speed that reaches the wind turbine might overestimate the power production over 20%. Meanwhile, the wind shear coefficients fluctuate between 0 and 0.2 at higher velocities. However, high values close to 0.4 were detected at lower velocities, which in most cases presented an underestimation greater than 20%. Therefore, when low turbulence intensity develops in conjunction with high values of wind shear, the power production might be significantly affected.

Such work grants the application of using a modern technology of acquiring data that can influence the wind power market and academic purposes in order to contribute to the Brazilian wind energy. Sensitivity analysis and longer sampling periods indicate the importance to get full advantage of the LiDAR technology, in order to acquire a high performance in validation.

References

[1] GLOBAL WIND ENERGY COUNCIL. Global Wind Energy Outlook 2014. Disponível em: < http://www.gwec.net/wp-content/uploads/2014/10/GWEO2014_WEB.pdf >. Accessed on 13th Sep 2015.

[2] ASSOCIAÇÃO BRASILEIRA DE ENERGIA EÓLICA. Avaiable in: <http://www.portalabeeolica.org.br/>. Accessed on 05th Oct 2016.

[3] ROY, S. B., SHARP, J. Why Atmospheric Stability Matters in Wind Assessment. **North American Wind Power**, v. 9, n. 12, 2013.

[4] REHMAN, S., AL-ABBADI, N. M. Wind Shear Coefficients and their effect on Energy Production. **Energy Conversion and Management,** v. 46 n.15-16, February, 2005.

[5] WHARTON, S., LUNDQUIST, J. K. Atmospheric stability affects wind turbine power collection. **Environmental Research Letters**, v. 7 n. 1, January, 2012.

[6] MANWELL, J., et al. Wind Energy Explained-Theory, Design and Application. **John Wiley & Sons**. February, 2010.

[7] MCLAUGHLIN, D., Wind Shear and its Effect on Wind Turbine Noise Assessment. **SgurrEnergy**. 2012.

[8] HONRUBIA, A. et al. The Influence of Wind Shear in Wind Turbine Power Estimation. **European Energy Conference**. 2010.

[9] SATHE, A. et al. Can Wind LiDARs Measure Turbulence? **Journal of Atmospheric and Oceanic Technology.** v. 28, n. 7. July, 2011.

[10] ROHATGI, J., BARBEZIER, G. Wind Turbulence and Atmospheric Stability – Their Effect on Wind Turbine Output. **Renewable Energy**, v. 16, n. 1-4. January – April, 1999.

[11] LI, Q. et al. Experimental and numerical investigation of the effect of turbulent inflow on a Horizontal Axis Wind Turbine (part II: Wake characteristics). **Energy**. v. 113, n. 1. August, 2016.

[12] POPE, S. B. Turbulent Flows. **Cambridge University Press**. v. 1. August, 2000.

[13] R. J. BARTHELMIE, R. J. et al.. Comparison of Wake Model Simulations with Offshore Wind Turbine Wake Profiles Measured by Sodar. JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY. **Journal of Atmospheric and Oceanic Technology**. v. 23, n. 1. July, 2006.

[14] KAISER, K., et al. Turbulence Correction for Power Curves. **Wind Energy Proceedings of Euromech Colloquium**. 2007.

[15] SHEINMAN, Y., ROSEN, A. A Dynamic Model of the Influence of Turbulence on the Power Output of a Wind Turbine. **J. Wind Eng. Ind. Aerodyn**. v. 39, n. 1. May, 1992.

[16] CHU, C., CHIANG, P. Turbulence effects on the wake flow and power production of a horizontal-axis wind turbine. **Journal of Wind Engineering and Industrial Aerodynamics**. v. 124, n. 12. December, 2013.

[17] WU, Y., PORT'E-AGEL, F. Atmospheric Turbulence Effects on Wind-Turbine Wakes: An LES Study. **Energies**. v. 5, n. 12. December, 2012.

[18] Clive, P. J. M. Offshore Power Performance Assessment for Onshore Costs. **SgurrEnergy**. Avaiable in: http://www.sgurrenergy.com/wp/wp-content/uploads/2016/05/Offshore-Power-Performance-Assessment-using-LiDAR1.pdf. Accessed in: 01/02/2017. May, 2016.

[19] KIDMO, D. K. et al. Statistical analysis of wind speed distribution based on six Weibull Methods for wind power evaluation in Garoua, Cameroon. **Revue des Energies Renouvelables**. v. 18, n. 1, March, 2015.

[20] SPERA, D. A. Wind Turbine Technology, Fundamental Concepts of Wind Turbine Engineering. **ASME Press**. May, 1998.

[21] CHEHOURI, A. et al. Review of Performance Optimization Techniques Applied to Wind Turbines. **Applied Energy**. v. 142. March, 2015.

[22] WHARTON, S., LUNDQUIST, J. K. Assessing atmospheric stability and its impacts on wind characteristics at an onshore wind farm. **19th Symposium on Boundary Layers and Turbulence**. July, 2010.

[23] INTERNATIONAL ELETROTECHNICAL COMISSION. IEC 61400-12-1. Power performance measurements of electricity producing wind turbines. **International Electrotechnical Commission**. December, 2005.

[24] REHMAN, S. et al. Empirical correlation between hub height and local wind shear exponent for different sizes of wind turbines. **Sustainable Energy Technologies and Assessment,** v. 4, n. 1, September, 2013.

[25] FARRUGIA, R. N. The wind shear exponent in a Mediterranean island climate. **Renewable Energy**. v. 28. May 2002.

[26] BARDAL, L. M. et al. Performance test of a 3MW wind turbine – effects of shear and turbulence. **Energy Procedia**. v. 80. 2015.