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Efficiency of High Altitude On-shore Wind Turbines: Air Density and Turbulence Effects—Qollpana Wind Farm (Bolivia) †

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Abstract: The wind energy is one of the most important alternatives for renewable and clean electricity generation. During the last decade the number of wind farms has largely increased in South America. Qollpana is only one case of an on-shore wind farm but it is located at 2900 m above sea level over a complex terrain. Due to high altitude, the air density is reduced by 27% compared with sea level and the topographic characteristics induce a high level of turbulence. Qollpana wind farm has ten wind turbines reaching 27 MW of installed capacity. October is the month of highest wind average velocity and February with the lowest one. This work analyses the capacity factor of the wind farm, also the air density and the turbulence effects on wind turbine efficiency. The main results show that monthly capacity factor varies between 0.08 and 0.67 in the wind farm. Moreover, the results have shown a considerable effect of the turbulence intensity on the turbines efficiency.

Keywords: wind energy; high altitude; air density; turbulence; capacity factor

1. Introduction

The current transition from fossil fuel energy systems towards low-carbon energy systems to keep the global warming below 2 °C, that has been agreed in Paris [1], invokes the countries, industry and society, altogether, to take actions to reduce the CO_2 emissions and efficient use of energy [2–4]. In this context, one of the most important alternatives of electrical energy generation, renewal, environment friendly, and non-carbon energy system, has been wind energy systems. The installed capacity of wind turbines growth mainly in Europe, China and US [4–6].

South America is a vast and very diverse territory with different renewable resources for electricity generation where the most important sources are the hydrologic, wind, solar and biomass. This great diversity is due mainly to the Andes cordillera along South America that defines the different potentialities of the resources mentioned before. Along this cordillera the most important rivers in the Amazon meet. This high and long cordillera defines the meso-scale flows of wind along the continent [7–9]. Moreover, the topography, wind patterns, altitude above sea level, and climate are very diverse through the Andes.

In the recent context of reducing the CO_2 and greenhouse gases, and according the new global energy policy, South America has implemented many wind farms incrementing their installed capacity from 1 to 14 GW in the period 2010–2016. The main countries in this labor are Brazil, Chile and Uruguay [6]. Besides, Bolivia has introduced wind energy projects since 2014 with only two wind turbines. During 2016 were installed other eight to establish Qollpana wind farm. Qollpana wind farm is one of the highest wind farms in South America that reaches 2900 m a.s.l. And other wind farms in Ecuador at very similar altitude [10], although in this high altitudes the wind velocity could be higher, the problem is the lower atmospheric pressure that reduces the air density. This diminished density represents less wind energy and challenges for installation of wind farms in the Andes, for instance is necessary to build larger wind turbine blades to compensate the lower density [11].

The wind energy projects could be evaluated with different indicators, such as the capacity factor (CF) that practically measures the economic efficiency and represents the relation of the average power generated between rated peak power. It can vary between 0 and 1. The CF in Europe has had an average of 0.21 that is lower than expected, although other combined technologies, such as wind and compressed air energy storage can reach a CF of 0.7–0.89 [12–14].

This work analyses the CF of the most important wind farm in Bolivia, taking into account the density and turbulence effects in the efficiency of the wind turbines.

2. Data Sources and Methodology

2.1. Description of the Wind Farm

Qollpana wind farm is built on complex terrain that consists in ten wind turbines. It is located in the center of Bolivia (17°37′ 48″ S, 65°17′ W) at 2900 m a.s.l. and to 130 km from Cochabamba city. The wind farm has two types of wind turbines two 1.5 MW and eight 3 MW, The position of those turbines are represented by circles shown in Figure 1. The main wind characteristics in the Qollpana are: wind direction from North to south, 8.2 m/s wind speed average, and highly turbulent flow.

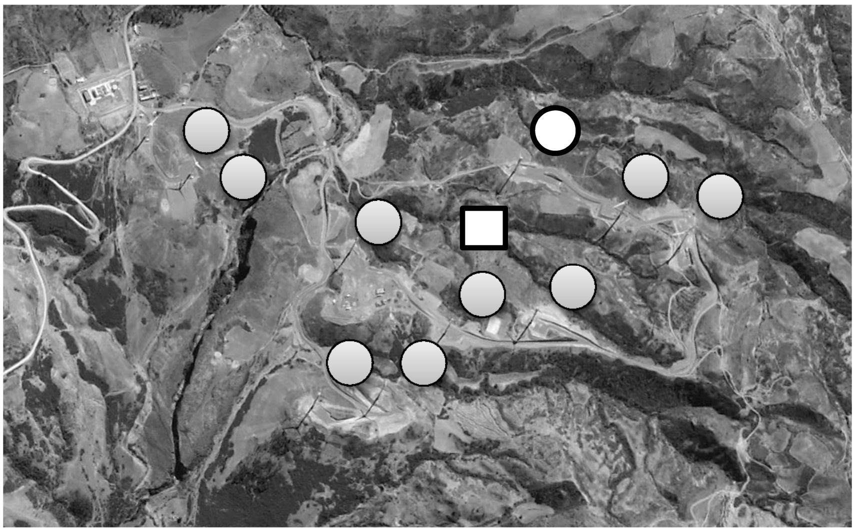


Figure 1. Configuration of Qollpana wind farm, where the circles represent the wind turbines. The circle with thicker border is WT-1 and the square represents the meteorological tower. (Source: Google Maps).

2.2. Capacity Factor

In order to determine the capacity factor of the wind farm and efficiency of wind turbines in Qollpana. We used energy produced data (MWh) from National dispatch committee—CNDC (by his initials in Spanish), and Authority of inspection and social control of the electricity (AE). The CNDC is in charge of the electricity distribution in Bolivia and the AE regulates the electricity market.

The computation and analysis of capacity factor (CF) was performed using the data available in CNDC web page and AE, and computed as is shown in the Equation (1). Then those were analyzed yearly during the period 2014–2017 and monthly for the 2017 period.

$$\mathrm{CF} = \frac{\text{Energy produced of wind farm/turbines (MWh)}}{\text{Rated energy production of wind farm/turbines (MWh)}} \tag{1}$$

2.3. Density and Turbulence Effects

In order to study the density and the turbulence effects, the data consisted in measurements of temperature, atmospheric pressure, power generation, and wind speed during four days (1–4 April 2017). The samples were registered every ten minutes. Those data were used to compute the actual density, turbulence, the wind power in Qollpana, and the actual power generated. In this work the temperature, atmospheric pressure, and wind speed was measured in a meteorological tower at hub level (78 m above the ground level). And the power generated was measured in one wind turbine called WT-1. The position of the meteorological tower is marked with a square in Figure 1 and the WT-1 wind turbine is the first one in the top-left corner of the Figure 1. The density was computed with ideal gas model, using the temperature and the atmospheric pressure measurements. Finally, the turbulence intensity was computed as the relation between the standard deviation of wind speed and the average wind speed, such as is displayed in the Equation (2).

$$\mathrm{TI}\ (\%) = \frac{\sqrt{\sum_0^n (u_i - \bar{u})^2 / n-1}}{\bar{u}} \times 100 \tag{2}$$

In the Equation (2) u_i represents the sampled wind speed that was measured every minute, $\bar{u}$ is the average wind speed, and n is the number of samples.

3. Results

The evaluation of CF was performed for monthly and daily average. Figure 2 shows the CF monthly variability along three different years with the following particularities: During 2014 only 1.5 MW turbines were working, during 2017 both, 1.5 MW and 3 MW. However during 2016 only 1.5 MW wind turbines were working in the period January–July because in August began the operation of 3 MW wind turbines in the wind farm. As the Figure 2 shows the low CF in 2016 in the August-September period is due to test time of the new wind turbines. Additionally is important to mention that the winter time is between June and August, the summer time is between December and February.

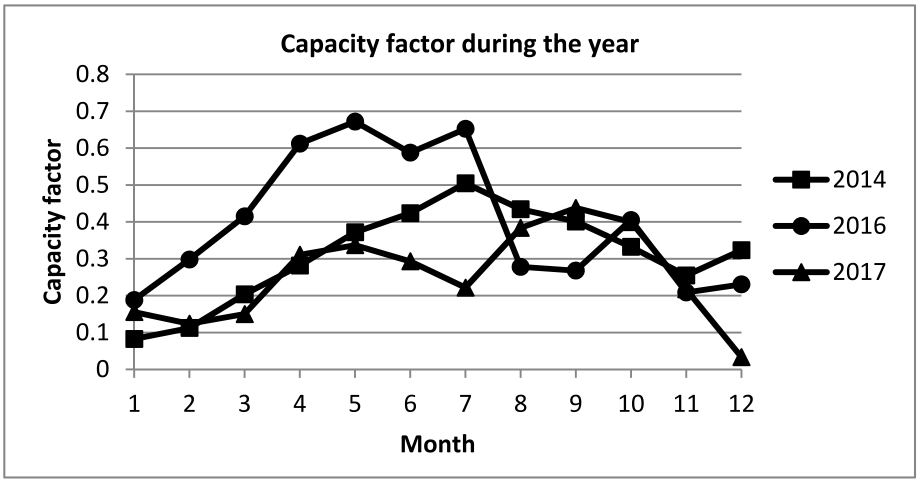
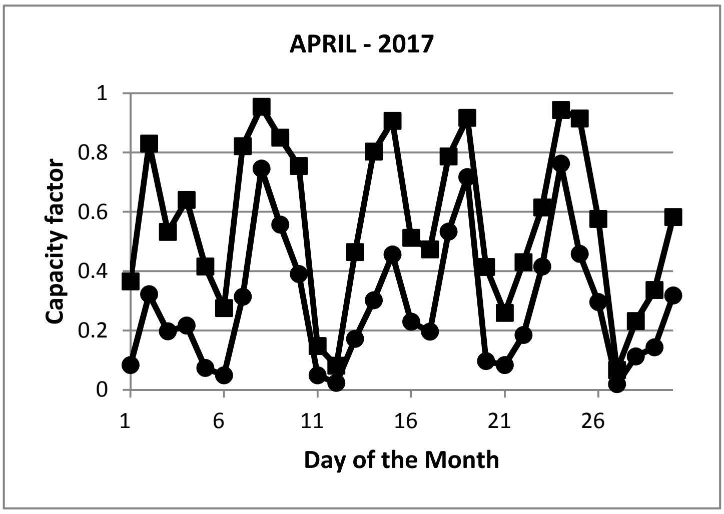


Figure 2. Capacity factor the Qollpana wind farm during the period 2014–2017 without 2015. Where CF 2014 (circles), CF 2016 (squares), and CF 2017 (triangles).

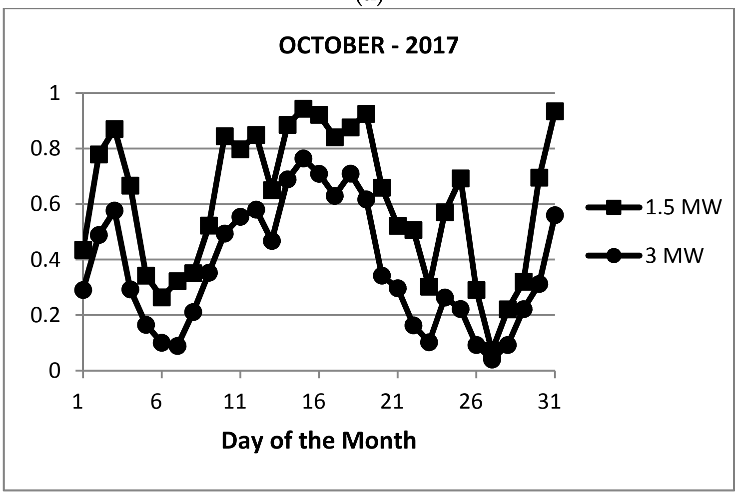
The yearly capacity factor in Qollpana wind farm has varied among 0.25 for 2017, 0.4 for 2016, and 0.31 for 2014, and the monthly CF varies considerably among the months and years as it is displayed in Figure 2. However, we may see some tendencies along the years, such as the period

May-October (winter–spring) is present the maximum CF and December–March (summer) is the lowest CF period.

The Figures 3a,b display the daily variability of CF in the two different sizes of wind turbines, 1.5 MW and 3 MW, where there are differences in the daily behavior and trends, however both of them has a variation between 0.04 and 0.94 along the month. Both Figure 3a,b, shows that CF of 1.5 MW model is higher than 3 MW wind turbine model. The main difference between these figures are the tendencies, for instance the April maximum CF varies periodically along the month with a frequency of approximately of 5 days. In change that periodical variability is different in October where there is a period of 10 day of considerable high CF.



(**a**)



(**b**)

Figure 3. Daily variability of capacity factor for the two different types of wind turbines in Qollpana wind farm (**a**) April 2017; (**b**) October 2017.

The density of the air in Qollpana wind farm has slight variation during the time analyzed. The average density was 0.887 kg/m^3 with a minimum of 0.861 kg/m^3 and its maximum of 0.918 kg/m^3. The variation of the density is mainly due to atmospheric changes than temperature variations.

The calculated turbulence intensity average was 18.35%, however the turbulence intensity varies according the wind speed, for this reason we calculated it in three velocity ranges. The turbulence intensity was 28.4% between 0–6 m/s, 16.2% between 6–10 m/s, and 15.2% between 10–14 m/s.

Figure 4 displays the efficiency—also known as power coefficient—of a wind turbine in Qollpana wind farm (squares) and the manufacturer efficiency (circles). The experimental efficiency could be divided in three ranges. Range I, 3–5 m/s; range II, 5–12 m/s; and range III, 12–15 m/s. In the range I the efficiency is close to the theoretical, however the standard deviation is around 0.2. For the range II the efficiency is lower than the theoretical, its efficiency has a standard deviation of 0.18. Finally, the range III presents a higher efficiency compared with the theoretical and the standard deviation in this range is 0.06, the lowest one.

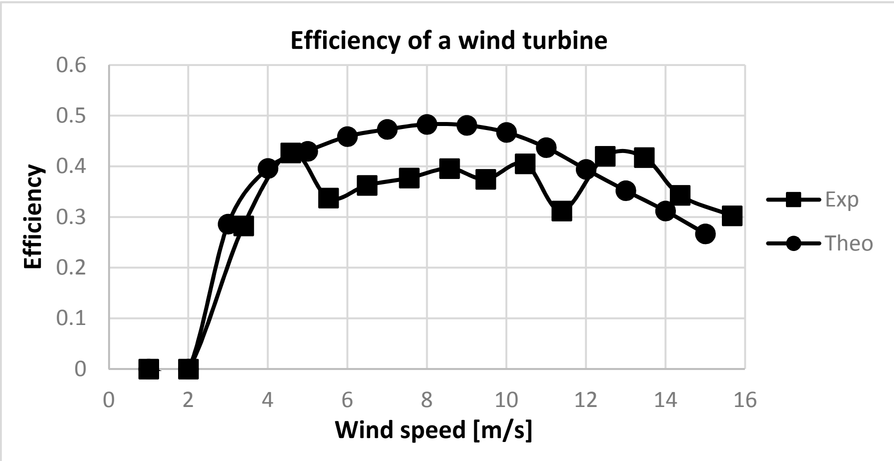


Figure 4. Efficiency of a wind turbine in Qollpana wind farm compared with the standard efficiency. (Squares) and Qollpana conditions (Triangles).

4. Discussion and Conclusions

The results previously showed express mainly the variability in the nature resources from yearly to daily unpredictability. The average of the CF during 2014–2017 was 0.32 that is inside of the estimated range for onshore wind farms [13]. The CF in the years 2014 and 2017 has almost the same trend with small differences proper to nature changes. However the CF during 2016 displayed a considerable high CF between February and June compared with the other years. This atypical high power generation might be related to the end of the mega-drought of the last five years in the region and to the ENSO oscillation in the Andes [15].

According the monthly variation the best period for wind energy generation is between April and November. This period coincides with austral autumn-winter-spring seasons in Bolivia and this period are also known as the dry season. As during this time the sun light is high and longer (for the absence of clouds) there are conditions for convection and thermally driven winds. This is different to the December to March, where the weather is humid and rainy.

The results of yearly and monthly CF represent the meteorological variability in the region; however for the high variation inside the showed months, April and October, the variability might be due to regional flow in South America. This regional flow is caused by moisture transport from the Brazilian Amazonas to the northern of Argentina that produces low-level jets (LLJ)—high wind speed at altitudes above 1000 m. This LLJ is approximately at 1000 m a.s.l. and when is flowing to the west of the Andean cordillera blocks and changes the direction to the south. In Qollpana wind farm (2900 m a.s.l.) there is a direct connection throughout a channel to Amazon and therefore to LLJ that may produce the high wind speed in the wind farm. Finally some researchers found an approximately four-day occurrence of LLJ in the region that might explain this fluctuation in Qollpana wind farm [9,16,17].

The main reason of the higher CF of the turbines of 1.5 MW compared with 3 MW turbines is due to their operations conditions of them. For instance, the rated wind speed of 1.5 MW and 3 MW wind turbines are 12 m/s and 16 m/s respectively. This means, 1.5 MW wind turbine produces a power of 1.5 MW when the wind speed reaches 12 m/s and the another 3 MW it is necessary 16 m/s. However, in this case 3 MW wind turbines are producing more energy with slightly lower CF in comparison to 1.5 MW turbines.

In relation to density variation; this is mainly due to atmospheric pressure oscillation [18]and this does not coincide with the diurnal temperature variability. However the density varies only between 0.91 and 0.861 kg/m^3, which means 3% from the average.

The turbulence intensity is one important variable, because this correlates with reduction of the efficiency of a wind turbine. In the range I and II described previously (Figure 4) there is a high turbulence intensity that correlates with a lower efficiency compared with the theoretical. This lower efficiency in range II could be due to high variation in the flow through to angle of attack in the blades and to the variation of the wind direction [19]; under this off-design conditions the aerodynamic efficiency is considerably affected. Finally, the range III involves a lower turbulence intensity and high wind speed; the efficiency is higher than theoretical one. This could be due to two effects, first the lower turbulence intensity (15.2%) that improves the aerodynamic efficiency and second is due to the lower density that applies less torque and the control system of the turbine identifies as a lower wind speed than the realized one. Under this condition the control system of the turbine is still optimizing the power generation.

In conclusion, Qollpana wind farm has high variability in its power generation from a monthly CF of 0.08 (January) to 0.67 (April). This is mainly produced seasonal changes in the region. In the case of the daily average the CF, this varies between 0.03 and 0.95 and its variations are due to weather and regional flows between the Amazon and the Andes. In this work, the efficiency of one wind turbine in high altitude and complex terrain depends mostly of the turbulence intensity and wind speed. However, these conclusions are only valid for the period studied and it is necessary to develop more studies and measurements to explain the efficiency of wind turbines under high altitude and complex terrain conditions.

Author Contributions: P.H. and R.M. conceived and designed the research strategy; N.H. analyzed the data and results; R.M. performed the calculations and wrote the paper.

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References

1. United Nations. *Paris Agreement*; United Nations: Paris, France, 2016; pp. 1–27.
2. Rogelj, J.; Den Elzen, M.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **2016**, *534*, 631.
3. Schleussner, C.-F.; Rogelj, J.; Schaeffer, M.; Lissner, T.; Licker, R.; Fischer, E.M.; Knutti, R.; Levermann, A.; Frieler, K.; Hare, W. Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Chang.* **2016**, *6*, 827.
4. Wüstenhagen, R.; Menichetti, E. Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research. *Energy Policy* **2012**, *40*, 1–10.
5. Saidur, R.; Islam, M.R.; Rahim, N.A.; Solangi, K.H. A review on global wind energy policy. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1744–1762.
6. IRENA. *Renewable Capacity Statistics 2016*; IRENA: Abu Dhabi, United Arab Emirates, 2016.
7. Nogués-Paegle, J.; Mo, K.C. Alternating Wet and Dry Conditions over South America during Summer. *Mon. Weather Rev.* **1997**, *125*, 279–291.
8. Hoorn, C.; Wesselingh, F.P.; Ter Steege, H.; Bermudez, M.A.; Mora, A.; Sevink, J.; Sanmartín, I.; Sanchez-Meseguer, A.; Anderson, C.L.; Figueiredo, J.P.; et al. Amazonia Through Time: Andean Uplift, Climate Change, Landscape Evolution, and Biodiversity. *Science* **2010**, *330*, 927–931.
9. Marengo, J.A.; Douglas, M.W.; Dias, P.L.S. The South American low-level jet east of the Andes during the 1999 LBA-TRMM and LBA-WET AMC campaign. *J. Geophys. Res. D Atmos.* **2002**, *107*, 8079.
10. Weston, D. Gallery: In the sky, high-altitude wind projects. *Wind Power Monthly*, 3 July 2016.
11. Ini, L. Wind prepares to conquer new heights. *Wind Power Monthly*, 31 July 2014.
12. Cavallo, A.J. High-Capacity Factor Wind Energy Systems. *J. Sol. Energy Eng.* **1995**, *117*, 137–143.
13. Boccard, N. Capacity factor of wind power realized values vs. estimates. *Energy Policy* **2009**, *37*, 2679–2688.

14. Chang, T.-J.; Tu, Y.-L. Evaluation of monthly capacity factor of WECS using chronological and probabilistic wind speed data: A case study of Taiwan. *Renew. Energy* **2007**, *32*, 1999–2010.
15. Garreaud, R.D.; Alvarez-Garreton, C.; Barichivich, J.; Boisier, J.P.; Duncan, C.; Galleguillos, M.; LeQuesne, C.; McPhee, J.; Zambrano-Bigiarini, M. The 2010–2015 megadrought in central Chile: Impacts on regional hydroclimate and vegetation. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 6307–6327.
16. Berri, G.J.; Inzunza, J.B. The effect of the low-level jet on the poleward water vapour transport in the central region of South America. *Atmos. Environ. Part A. Gen. Top.* **1993**, *27*, 335–341.
17. Saulo, A.C.; Nicolini, M.; Chou, S.C. Model characterization of the South American low-level flow during the 1997-1998 spring-summer season. *Clim. Dyn.* **2000**, *16*, 867–881.
18. Haurwitz, B. The diurnal surface-pressure oscillation. *Arch. Meteorol. Geophys. Bioklimatol. Ser. A* **1965**, *14*, 361–379.
19. Butler, R.J.; Byerley, A.R.; VanTreuren, K.; Baughn, J.W. The effect of turbulence intensity and length scale on low-pressure turbine blade aerodynamics. *Int. J. Heat Fluid Flow* **2001**, *22*, 123–133.