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Statistical Analysis of Wind Power and Analytical Methods for Wind Persistence in Magdalena and Cesar Departments in Colombia

Jonathan Fabregas Villegas[1], Guillermo Valencia Ochoa[2] and Marley Vanegas Chamorro[3]

[1]Ms. Ing. Mecánico, Grupo Interdisciplinario de InvestigaciónenEnergía y Medio Ambiente, GIIMA, Facultad de Ingeniería, Universidad Autónoma del Caribe; Jonathan.fabregas@uac.edu.co

[2]Ms. Ing. Mecánico, Grupo de Investigación Gestión eficiente de energía, Kaí, Facultad de Ingeniería, Universidad del Atlántico; guillermoevalencia@mail.uniatlantico.edu.co

[3]PhD. Ing. Químico, Grupo de Investigación Gestión eficiente de energía, Kaí, Facultad de Ingeniería, Universidad del Atlántico; marleyvanegas@mail.uniatlantico.edu.co

Abstract

Background/Objectives: Efficient energy management and its rational use have contributed to the development of statistical studies in the field of the wind resources. **Methods:** Based on the measurement of wind's direction and velocity in the Colombian Caribbean Region, in order to promote the implementation of wind farms, capable to supply energy to the national grid system. **Findings:** These studies are conducted based on the hourly, monthly, and annual characterization, additional to the application of the autocorrelation function for the study of wind persistency and the calculation of the probability of density functions such as the Normal, Gamma, Rayleigh, and Weibull appliedto historical data recorded between 2003-2013 by the Instituto de Hidrología, Metereología y EstudiosAmbientales de Colombia (IDEAM) for the departments of Cesar and Magdalena. **Application:** To achieve a rational use of wind energy, it is necessary to analyze the wind obtained in the weather stations when applying the analysis of wind persistency and Weibull distribution.

Keywords: Autocorrelation Function, Probability Density Function, Wind Persistency, Wind Velocity, Wind Potential

1. Introduction

Nowadays, the effects of the environmental pollution are noticeably increasing. These consequences, which are caused by the climate change, are lived as in Colombia as in many other countries, such as natural disasters and so on and so forth, suggest that the country is going through a critical moment, deserving the assessment of wind energy potential in each of their regions, looking forward to determine the most favorable places for the generation of renewable energies, promoting the rational use and preservation of the environment as well as the diversification of the national energy matrix.

Meeting energy demand while reducing environmental damage caused by harmful emissions of greenhouse gases from burning fossil fuels, has prompted the scientific community to conduct researches about the use of natural resources such as clean and renewable energies as alternatives of electricity generation. In 2012, the Colombian grid system had an installed net capacity of 14,361 MW, attending an energy demand of 59,370 GWh, with a 64 % supplied by hydroelectric generation, 30.8 % by thermoelectric plants, and 4.8 % supplied by lower generation plants. At present, the net installed capacity is around 16,500 MW, supplying an increased demand of 65,000 GWh[1].

In 2002, the wind farm Jepírachi began operations in the Department of La Guajira with 20 MW of net capacity, it is currently the only wind power generation plant and contributes with 0.1 % of the electrical needs of Colombia[2]. Similarly, other projects involving indigenous communities such as Wayuu are in primary phase. In 2010, the license for construction and operation of a wind farm project called Jouktai in Cabo de la Vela was granted,

* *Author for correspondence*

which is still under study, with an expected capacity of 31.5 MW[3] wind power in Colombia is not able to currently guarantee firm power because an accepted methodology to calculate its potential firm capacity does not exist. In this paper we argue that developing such methodology would provide an incentive to potential investors to enter into this low carbon technology. This paper analyzes three methodologies currently used in energy markets around the world to calculate firm wind energy capacity: PJM, NYISO, and Spain. These methodologies are initially selected due to their ability to accommodate to the Colombian energy regulations. The objective of this work is to determine which of these methodologies makes most sense from an investor's perspective, to ultimately shed light into developing a methodology to be used in Colombia. To this end, the authors developed a methodology consisting on the elaboration of a wind model using the Monte-Carlo simulation, based on known wind behaviour statistics of a region with adequate wind potential in Colombia. The simulation gives back random generation data, representing the resource's inherent variability and simulating the historical data required to evaluate the mentioned methodologies, thus achieving the technology's theoretical generation data. The document concludes that the evaluated methodologies are easy to implement and that these do not require historical data (important for Colombia, where there is almost no historical wind power data. Additionally, in 2014 the Law 1715 which regulates the integration of non-conventional renewable energy to the national energy system was enacted (Congreso_Colombia, 2014),thus increasing the registration of similar projects at the UPME. For instance, the sponsor Jemeiwaaka'I S.A.S. has presented three projects in power generation, corresponding to wind farms as follows: Casa Eléctrica, Irraipa, and Carrizal, which will be located in Uribia-La Guajira, with a capacity of 475 MW[4]. However, it is necessary to identify other places with similar wind potential in the Colombian Caribbean Region.

To characterize the wind potential, a statistical analysis is performed based on the historical data recorded by meteorological measurement stations, in addition to computational models that consider the conservation of momentum proposal in the Navier-Stokes equations so that the movement of the wind and the models proposed by WASP can be studied, thus correcting the influence of local effects presented by the roughness of the surfaces, the topography and so on and so forth, which allow settling a logarithmic profile of the wind speed with respect the height[5]. In order to perform a statistical analysis of the wind's speed, direction,persistence, and potential at different heights and places, a variety of studies have been carried out leading to the selection of areas with the highest wind potential from the results of the wind power density, curves of speed duration, and the adjusting of Weibull's theoretical curves, among other which stands out.

In[6] developed a study using data of electrical demand required by the Mexican electricity sector, where the effect between different power generation methods is compared, concluding with the use of wind potential as the most viable method for power generation, thus performing analyzes for wind power measurement in the region of Veracruz-Mexico, collecting data for five meteorological stations and two anemometer stations. In[7] studied the wind properties through a persistence analysis using methods of autocorrelations functions and duration curves of wind speed evaluating properties for the construction of wind farms, resulting that the five areas of study are optimal for wind power generation. In[8] conducted the study of the wind's behavior through a persistency analysis to areas located in the northwestern Turkey based on the autocorrelation function methods, conditional probability, and curves of wind speed duration, clearly evidencing that the behavior of the wind perfectly correspond to these areas for the persistency analysis. In[9] makes a comparative analysis between Weibull distribution and Lognormal methods, based on the comparison of primary parameters such as average speed and wind potential and secondary parameters such as standard deviation of wind speed and wind energy distribution, this comparative study was conducted during twelve months, highlighting the benefits of the Weibull distribution over lognormal.

Since the behavior of the wind depends on specific factors such as latitude and topography, the study is conducted in specific areas of the Colombian Caribbean Region belonging to the departments of Magdalena and Cesar of which statistical analysis and persistency analysis are developed for the wind.

2. Wind Analysis Methods

2.1 Description of the Region

The Colombian territory is located on the northwestern top of South America at latitude 04 ° 00 'N, 72 ° 00' W. Is conformed for Caribbean, Andean, Pacific, Orinoco and Amazon regions. The Caribbean region corresponds to 11,6 % of the total geographic area of 132.288 km^2 , and is located between 12 ° 60 'and 7 ° 80 ' north latitude, 75 ° and 71 ° longitude west of Greenwich and the Caribbean islands. It consists of seven departments as follows: La Guajira,Atlántico, Bolivar, Cesar, Cordoba,Magdalena, Sucre, and a department on the island area, San Andres, Providence and Santa Catalina, distinctive for its location in harnessing the wind resource[10].

A meteorological study was conducted for the departments of Magdalena and Cesar by the IDEAM based on the historical dataof measurements for wind's speed and direction since 2003 until 2013 recorded in the stations Motilonia, Apto Simon Bolivar, Apto Alfonso Lopez, and Prado Sevilla, which allowed the characterization of wind potential in the period. The geographical location of the stations belonging to the departments studied are shown in Table 1 and Figure 1.

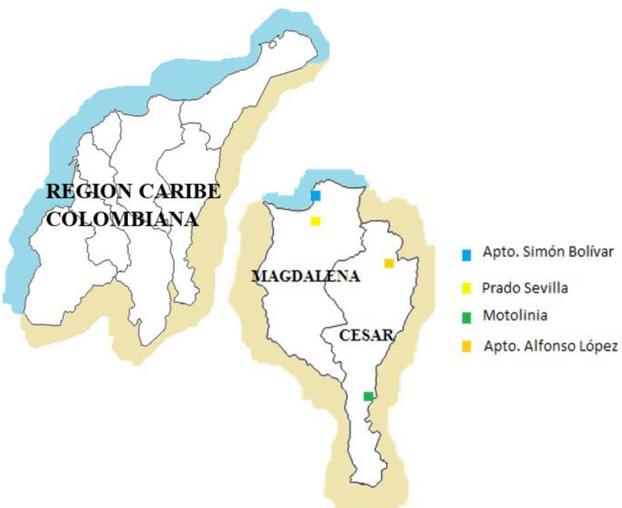

Figure 1. Locations of weather stations.

Table 1. Locations of the regions

Station	Department	Latitude	Length
Apto. Alfonso López	Cesar	10°26'06"N	74°14'58"W
Apto. Simón Bolívar	Magdalena	11°07'10"N	74°13'50"W
Motilonia	Cesar	8°52'50"N	72°58'44"W
Prado Sevilla	Magdalena	10°45'51"N	74°09'26"W

2.2 Wind Analysis at Different Heights

Wind behavior as well as the continuous flow depend on shear effect, where the displacement of the wind is related to the horizontal velocity variation with the height. When studied, the shear effect with respect to atmospheric characteristics of the place where the measurements are recorded,resulted in extrapolations that would allow the estimation of the wind's speed at other heights,setting a group of variables such as the force of the Earth's surface, causing opposition to the movement of the wind. Therefore the Hellman's law of exponential type is applied to estimate the wind at different height, as in the equation (1):

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^{\alpha} \tag{1}$$

Where v is the wind's speed evaluated at a height h. v_0 and h_0 corresponds to values of reference, which it established at 10 m of height to calculate the extrapolations. The value of α refers to the effect of the roughness that cause opposition to the wind's displacement, so it is advisable to record measurements in areas of flat surfaces, as a result of equation (1), increases in wind speed at greater heights are expected.

2.3 Wind Persistence

The data collected by the instruments located at the meteorological stations are an important factor for the measurement and characterization of the wind, however, due to the large amount of data collected hourly, monthly, and annually, is necessary to involve the use of a method of estimation for the wind behavior for specific climatic conditions. The persistence analysis provides extensive information about wind's speed in determined periods of time which implies its consideration in such a manner as to study the wind potential. The methods used to develop the persistency analysis are related to the use of an autocorrelation function for series of time and conditioned probability. Among other methods, the analysis curves for wind speed duration is used.

The ACF is implemented so that the wind's persistency can be characterized in order to identify repetitive patterns in series of estimated data in a time slot. Thus, the equation (2) shows the methods for the estimation of persistency analysis using the ACF[11].

$$r_k = \frac{\sum_{i=1}^{n-k}(v_i - \bar{v})(v_{i+k} - \bar{v})}{\sum_{i=1}^{n}(v_i - \bar{v})^2} \tag{2}$$

Where r_k is the autocorrelation coefficient, n represents the selected data, k is used as a delay value and v is the wind's average speed. Notably, the autocorrelation coefficient always starts from the unit, presenting a decreasing to zero as long as the delayed value k is increased. Afterwards the autocorrelation coefficient is obtained, the ACF calculation is described by equations (3,4):

$$P_{ACF} = \frac{1}{2} r_1 (k_0 - 1) \tag{3}$$

$$P_{ACF} = \frac{1}{2} r_1 (k_m - 1) \tag{4}$$

Identifying the delay value for each autocorrelation coefficient is established through the variablesk_0 y k_m, which are graphically observed in Figure 2 and correspond to the delay value when the autocorrelation coefficient is zero and for the first identified minimum delay value respectively.

Where the triangular area delimited by the delayed values k and the autocorrelation coefficient r is used as an indicator of the wind's persistency, indicating that the use of these values to calculate the persistency through the autocorrelation function will result in high values of persistence whether PACF is high and low values whether PACF is low.

2.4 Frequency Distributions

Due to the fact that wind behavior presents variability among multiple measurement data for each station, is necessary to calculate the probability distributions for each estimated value. The probability functions used to wind behavior are the following: Normal, Gamma, Weibull and Rayleigh[12]. Each function is highlighted by climatic factors at each station such as temperature behavior for a Normal distribution corresponding to tropical climates, the relative humidity of the environment do not have normal behavior and daily precipitation in which a distribution of extreme or Gamma distribution is implemented, and the behavior of the wind's speed which differs from a Normal distribution, that is why the distribution of Weibullis used.

The Rayleigh's distribution function is presented in the equation (5):

$$f(x) = \frac{2x}{b^2} \exp\left(-\frac{x^2}{b^2}\right) \quad x \geq 0 \tag{5}$$

The function f(x) represents the probability, where the wind's speed x is in an interval between x and x+dx, where the area under the function is the unit. The Weibull distribution function is presented in the equation (6):

$$f(x) = \frac{k}{c}\left(\frac{x}{c}\right)^{k-1} \exp\left[-\left(\frac{x}{c}\right)^{k}\right] \quad (k > 0, x > 0, c > 1) \tag{6}$$

The Weibull distribution function depends on two parameters called c and k, which are used for the calculation when the wind's speed reaches a maximum point, which is obtained by differentiating and equating to zero[13].

Gamma distribution function is presented in the equation (7):

$$f(x) = \frac{(x/\beta)^{\alpha-1} \exp(-x/\beta)}{\beta\Gamma(\alpha)} \quad x > 0, \alpha > 0, \beta > 0 \tag{7}$$

The Gamma distribution is approximation to the normal distribution in its form. Where α is a dimensionless parameter value and β has the function either lengthen or shorten the Gamma function to the right or left.

The frequency analysis or probability distribution is calculated from a series of data including wind speed among a maximum and a minimum value, an average

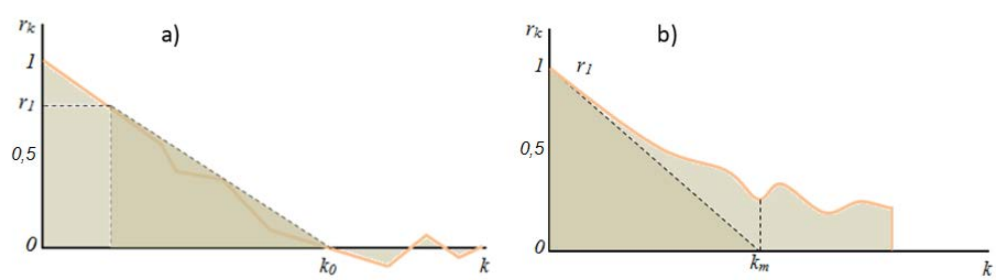

Figure 2. Autocorrelations coefficients a) The function cut in $r_k = 0$ to k_m b) the function reaches its first minimum to k_m.

value is estimated, besides a standard deviation, which is measured in dimensionless units with respect to the relative dispersion. It is important to consider the value of standardized bias and kurtosis, which can be used to determine whether the behavior of the sample is adjusted to a normal distribution. Considering the value of standardized bias, can be affirmed that the value is or is not within the expected range for data from a normal distribution, moreover from the value of standardized kurtosis can be obtained a leptokurtic distribution with respect to the normal. A frequency analysis for the four distributions is shown in Figure 3.

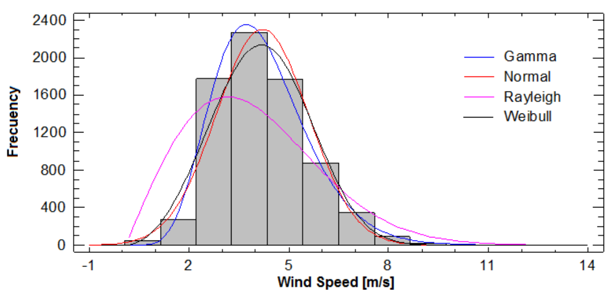

Figure 3. Frequency distributions for wind speeds.

3. Results

3.1 Wind Readings Analysis

The stations AptoAlfonso López , Apto Simón Bolívar, Motilonia, and Prado Sevilla studied by IDEAM in the periods 2003-2013, have recorded the wind behavior in short periods of time. The average wind's speed obtained since 2010 until 2013 is presented in Figure 4.

Thus, the average speeds obtained in the Figure 3 represent the monthly average wind's speed, the estimated calculation for the annual average speed since 2003 until the end of 2013 is shown in Figure 5.

The values of the average annual wind speed represent the estimate for each station to a reference height of 10 m with specific values of surface roughness where the research was conducted as shown in Graphic 1, being these values α = 0,2 for Motilona, α = 0,28 for Apto Alfonso Lopez, α = 0,28 for Apto Simon Bolivar, α = 0,16 for Prado Sevilla. The estimated wind's speeds at different heights were obtained involving the use of the equation (1), as shown in Figure 6.

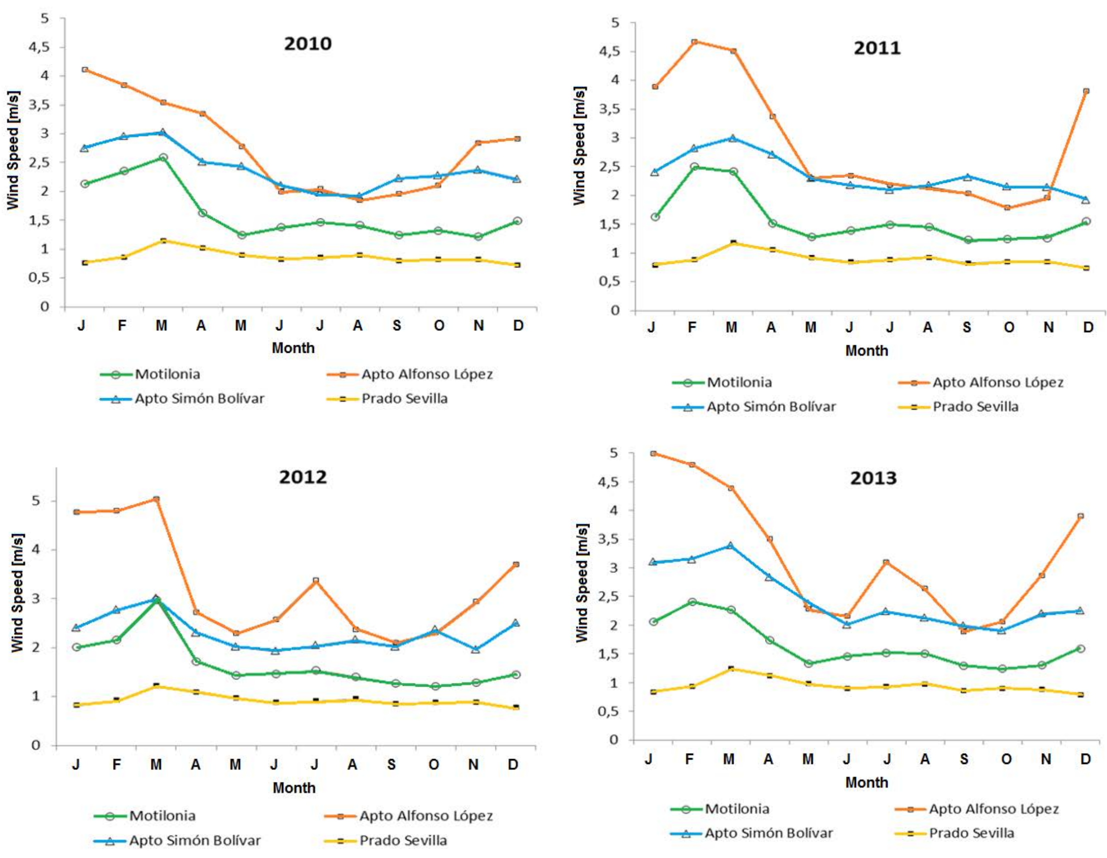

Figure 4. Average wind speed in monthly periods.

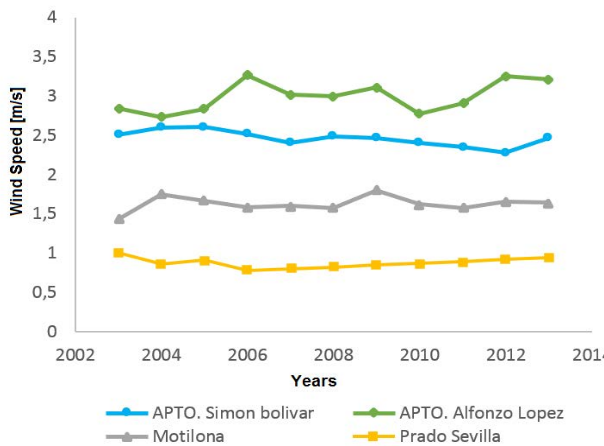

Figure 5. Annual average wind speed.

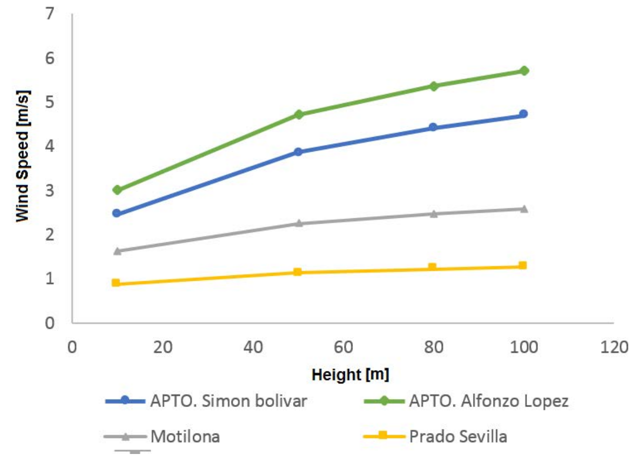

Figure 6. Average wind speed at different heights.

Average wind's speed was calculated for intervals of one hour during 24 hours per day, since 2003 to 2013, where the charts for each station were obtained as shown in Figure 7.

Since the behavior of the wind has direction and sense, is necessary to represent this behavior for a successful location and utilization of wind potential present in the station. Wind roses were obtained for each meteorological

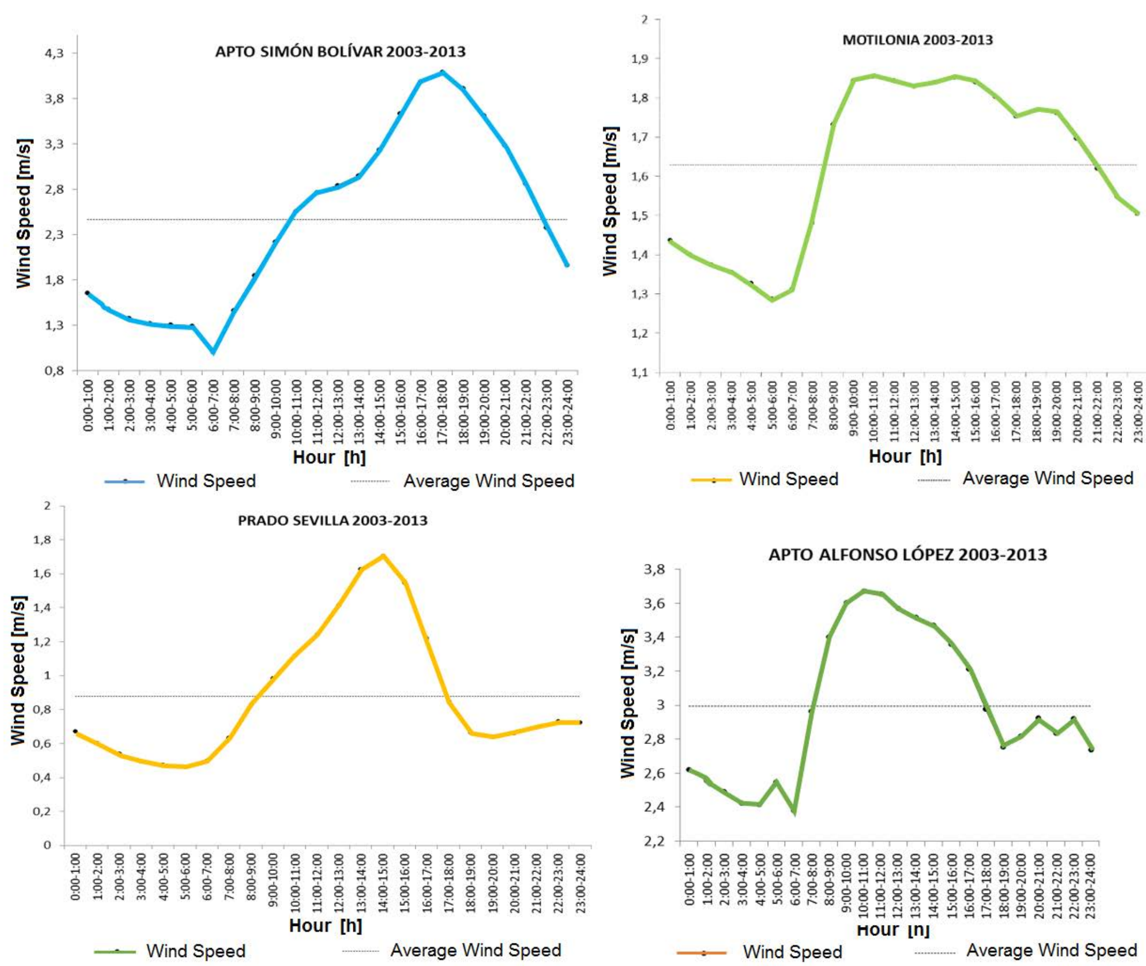

Figure 7. Average wind speed per hour.

station for a period since 2003 until 2013. Wind roses for February in the 4 stations are shown in Figure 8.

3.2 Wind Persistency Analysis

Involving the use of the ACF functions to analyze the wind persistency, the values of the autocorrelations coefficients r_k and delay values k were obtained, allowing the calculation of the wind persistency values through the highlighted areas, as shown in Figure 9 and Table 2.

Table 2. Wind persistence, autocorrelation coefficient and delayed value

Station	r_1 (Y)	K_0 (X)	P_{ACF}
Apto Alfonso López	0,8861	13	5,32
Apto Simón Bolívar	0,8206	6,956	2,44
Motilonia	0,8495	60	25,06
Prado Sevilla	0,8361	178	73,99

Consequently, the station with greater persistence of the wind is Prado Sevilla followed by Motilona, Apto Alfonso Lopezand Apto Simon Bolivar.

3.3 Analysis of Frequency Distributions

After performing the functions of Normal frequency, Gamma, Rayleigh and Weibull distribution, were obtained monthly histograms for the estimated values of wind's speed in the 4 stations, as shown in Figure 10 and Table 3.

Table 3. Parameters set of the adjusted distributions from 2003 to 2013

Apto. Alfonso López			
Gamma	**Normal**	**Rayleigh**	**Weibull**
form = 8,04441	mean = 4,27389	scale = 4,32778	form = 3,07874
scale = 1,88222	desviation estándar = 1,45815	threshold inferior = 0,199116	scale = 4,76998

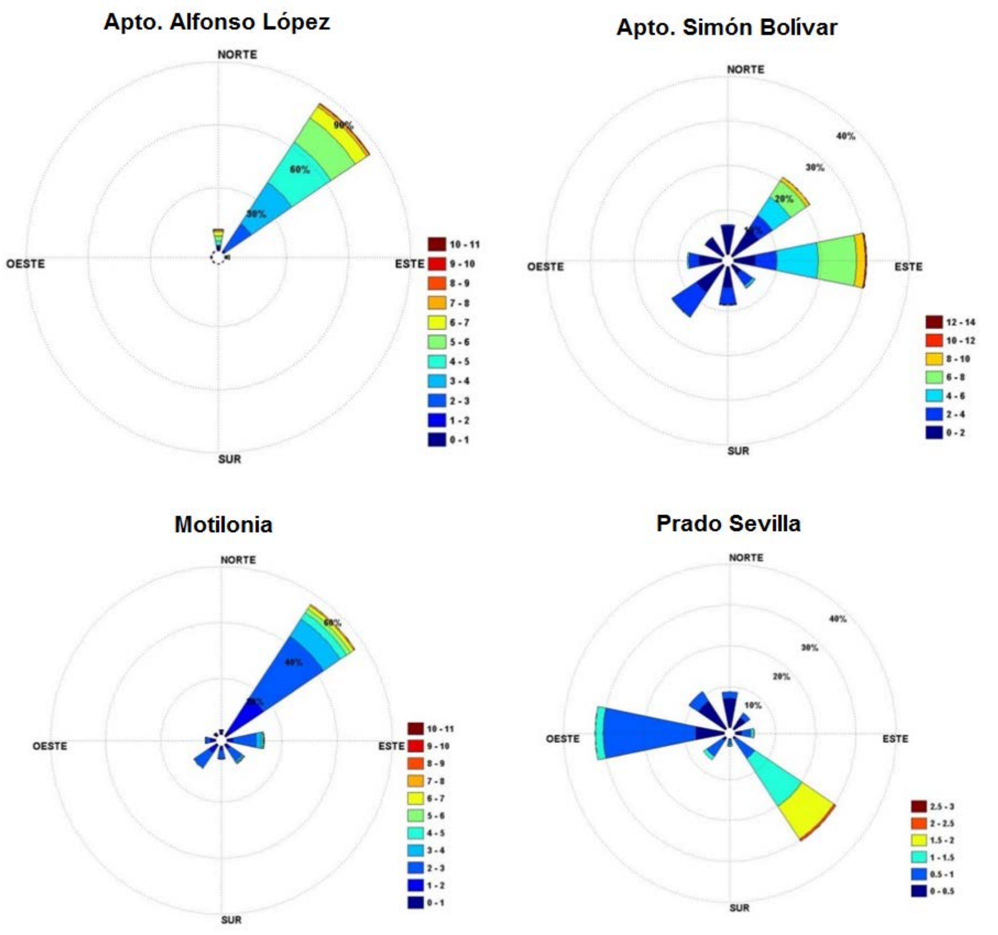

Figure 8. Wind roses for the month of February.

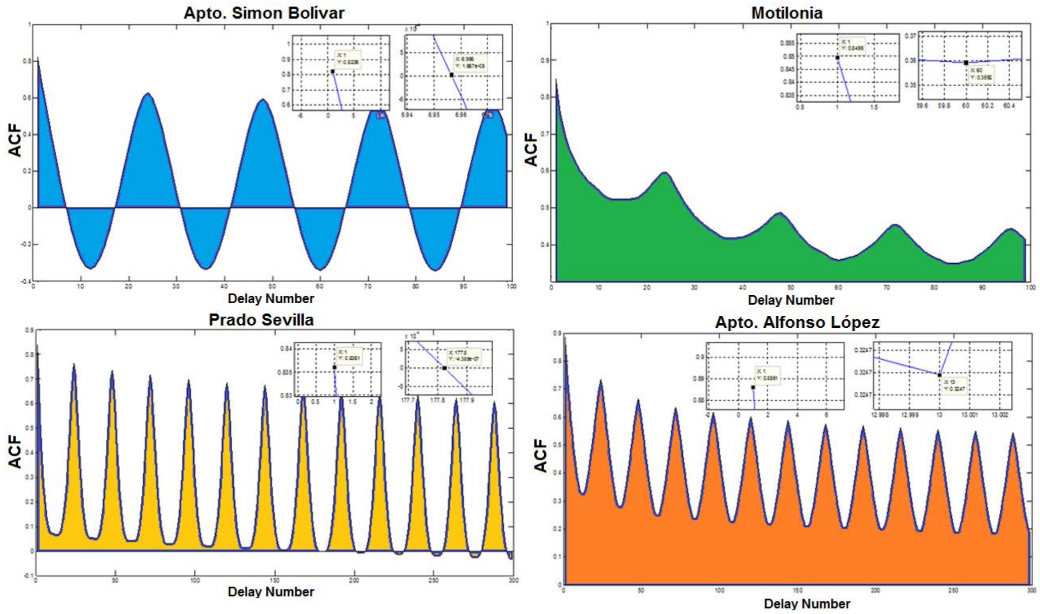

Figure 9. Autocorrelation functions.

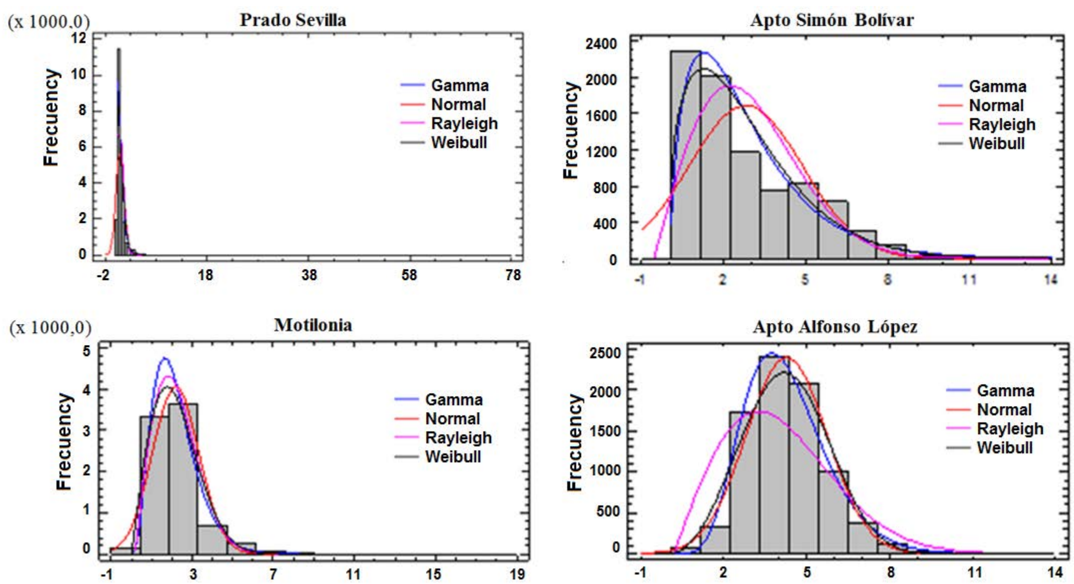

Figure 10. Functions of frequency distribution for the month of January from 2003 to 2013.

4. Conclusions

From the analysis developed during the research can be observed that, for each station where the characterization of the wind's speed was applied, presents favorable results to the proper utilization of wind potential as a source of electricity generation. Alfonso Lopez Airport and Simon Bolivar Airport reported higher average speeds from 2003 to 2013.

Characterized stations present relevant results as the monthly direction where the movement of wind observed as profiles of wind roses is predominant, thus granting a better use of the wind resource. The stations with the highest persistence in wind's speed are Prado Sevilla and Motilonia.

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