Wind Resource Potential in Los Taques Venezuela

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***Abstract*— The Venezuelan government has established more aggressive policies and incentives for renewable energy resources in recent time, especially in terms of wind power. Although several academic efforts to make publically available wind energy resource data in Venezuela, there is a lack of information in terms of local wind resource putting in risk development in areas where potential is good enough for commercial exploitation. The objective of this paper is to presents a very comprehensive wind resource assessment at Los Taques, Venezuela based on on-site observation anemometry. This is unique paper because it is the first ever wind energy assessment in Los Taques using hourly data recorded during three years in an on-site ground weather station contrary to studies based on daily values based on radar or satellite data. The applied methodology has been developed based on the characteristic of the data obtained from the on-site anemometry. Results of wind energy assessment and evaluations on a 100 MW wind farm shows the wind energy resource available in Los Taques is enough for commercial use and the results.**

***Keywords*— Wind data, Wind Energy potential, Wind power generation, Venezuela.**

I. INTRODUCTION

THE BOLIVARIAN Republic of Venezuela is a country which has the largest electricity consumption in South America (4,018 KWh/year per capita) and electrical power system provide electricity to 95% Venezuelan population [1]. The demand peak value varies between 16,500 MW and 18,200 MW depending on seasonal conditions [2], [3]. Electricity consumption rises between 4% and 7% per year, and it is expected to increase with the same or higher rate in the next 10 years [2]. Total generation installed capacity is 26,550 MW and the generation mix is 65% hydropower, 32% thermal power plants and 3% distributed energy resources [1]. Although the proven oil reserves in Venezuela are claimed to be one of the largest in the world, more aggressive policies on the use of environmentally friendly electricity generation have begun in recent years in Venezuela.

Several academic projects have been reported to promote renewable energy sources installations in numerous areas of Venezuela [4], [5], [6] especially wind power. Several small-scale and off-grid wind power projects have been developed and two utility-scale wind have been installed in mainland Venezuela: La Guajira (25 MW) [7], and La Peninsula de Paraguaná (100 MW) [8].

A wind atlas of Venezuela has been recently published by the author in [1] where several areas have been identified suitable for wind energy projects, including the Paraguaná area where the Paraguaná Wind Farm is installed [8]. However, there is not information, publically available to allow enforce more development of wind energy use in the area of *Santa Cruz de los Taques* (or *Los Taques* as known).This paper is a first effort make publically available information about the wind resource potential available at Los Taques-Venezuela, it will allow to local population a valuable insight into the wind resource, its potential development, and its value to a utility utilization of individual use.

The objective of this paper is to presents a very comprehensive wind resource assessment at Los Taques, Venezuela based on on-site observation anemometry. Section II describes briefly the analysis method for the assessment in the study area whilst Section III to V present the results gathered and a discussion of their significance. Data used in this paper is based on the available wind data measurement from on-site observation anemometry. From the results of this paper, Los Taques is identified as suitable site for the wind energy exploitation in Venezuela. Conclusions of this paper suggest further site-specific investigations should be conducted evaluating economical of potential wind energy development.

II. METHODOLOGY WIND POTENTIAL ASSESSMENT

Wind energy site assessment evaluates the potential for a given site to produce energy from wind turbines. There are several approaches to investigate the wind resource within a given area of land [9] and the preferred approach is defined by objectives of the wind energy program. [10]. However, there is a general consensus as to how wind energy site assessment is performed. The *Wind Resource Assessment Handbook* [11], Wind Energy – The Facts (Volume 1, Chapter 2) [12], consulting firms [13], and state guidebooks on site assessment [14], all endorse a similar site assessment methodology. As summarized in [15], there are a number of methods for estimating the wind resource of an area [16], [17]. A detailed review of all of these methods is beyond the scope of this paper. Aspects of wind resource evaluation based on *measurement only* are presented in this paper. This approach has been applied successfully in several locations around the world [18-23].

Figura 1 shows a complete flow chart of the methodology for the wind resource assessment followed in this paper. This methodology has been developed by the author based on the characteristic of the data obtained from the on-site anemometry. This simplify procedure follows a sequence of three steps: (1) *data validation*, (2) *data recovery,* and (3) *data processing*.

The main *input data* for the site wind resource assessment procedure is on-site measurement data, time series, relating to different meteorological parameters: wind speed, wind direction, air temperature, and atmospheric air pressure.

The onsite measured data must be *validated* and *processed* in order to generate adequate information to allow wind

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resource assessment. The *data validation* process consists of the inspection of all the collected data for both *completeness* and *integrity* as well as the elimination of any erroneous values. There is several validation routines designed to screen each measured parameter for *suspect values* before they are incorporated into the archived database and used for site analysis. Manually and automatically routines are used for validation purposes in this paper. Details of validation tests are presented in next section.

When the data validation step is complete, the data set must be subjected to various *data processing* procedures to assess the wind resource [24], [25]. This typically involves performing calculations on the data set, as well as binning (sorting) the data values into useful subsets based on your choice of averaging interval. The processed data can be analysed in many different ways. However, there is a general consensus about the use of descriptive statistic in preliminary assessment and resource description to quantitatively describing the main features of wind resource. In the following subsections, the treatments used for the processing of valid data used in this paper are presented.

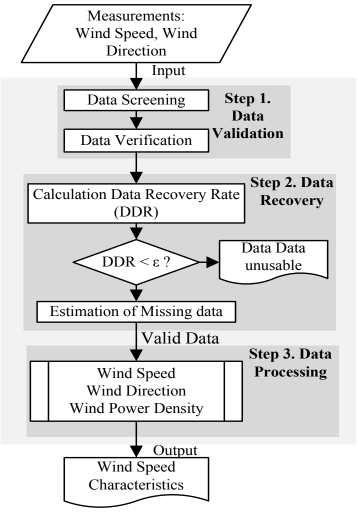


Figura 1. Flow Chart of Methodology for Processing of Wind Data Set and Wind Resource Assessment.

A. Descriptive Statistic Wind Energy

The procedure of determining if a site is suitable for wind power production requires convincing statistical information describing the long-term behaviour of the wind resource. Several statistical indicator of wind energy resource are used in the specialized literature. *Average speed* indicates the overall wind potential at a given site, expected wind speed for a given time interval (first central moment). The variability of wind speed in a given time-series is calculated by the *standard deviation* (σ_m). It indicates the mean amplitude of temporal (or spatial) wind fluctuations (square root of the variance).

Probability density functions (PDF) such as the *Weibull* or *Rayleigh* functions are usually used to determine the wind speed distribution of a windy site for a period of time. Wind speed distributions are used as stochastic representation of the wind resource at the studied site, *Weibull probability density function* is used in this paper and the *maximum likelihood method* is used to obtain distribution parameters [9],[26].

B. Energy Output and Wind Power Density (WPD)

The process to estimate the energy output of a wind turbine in the measured wind regime consists of four main steps. First, it *estimates the wind speed at the hub height* of the wind turbine for each time record in the data set (time step). Second, it uses the hub height wind speed and air density for each time step to *estimate the gross power output* of the wind turbine for each time [9]. Third, it finds the overall mean and the mean for each month of the gross power output, and multiplies this value by the overall loss factor to *calculate the mean net power output*, for each month and for the entire data set. Finally, it multiplies the mean net power output by the number of hours in a year (8760) to find the *net annual mean energy production*. Similarly, it multiplies the monthly mean net power outputs by the number of hours in each month to find the net monthly mean energy production. Full details of this methodology are found several publications [9], [16].

Apart from wind speed, the kinetic energy content of the atmosphere also depends linearly on air density [27]. Near-surface air density is defined as the mass of a quantity of air divided by its volume. It can be calculated using the ideal gas law.

III. DATA SOURCE

The data used in this paper was obtained from the meteorological station of the Josefa Camejo Airport (IATA: LSP), located at coordinates of 11°46′07″N and 70°08′09″W at 23m above sea level. This site is found to be the most suitable information source in the area for developing the preliminary wind energy assessment of Los Taques as there are no obstacles around the measurement area so it is directly open to the Venezuelan Gulf to the west. The collected data covers three years period, from 1st January 2008 to 31st December 2010 (1096 days). This station recorded the wind speed, wind direction, temperature, humidity and atmospheric pressure on an hourly basis. The terrain in the surrounding area is relatively flat and suitable for wind power development with very low surface roughness conditions. A three cup anemometer and a wind vane are mounted individually on cross arm supported by single tubular pole, which was erected in July 2007.

TABLE I. NOMINAL CHARACTERISTICS AND SPECIFICATIONS OF THE MEASURING EQUIPMENT AT ON-SITE WEATHER STATION.

	Measurement range	*Accuracy*	*Resolution*
Anemometer	0-160 mph 0-71 m/s	±0.15 mph or 1%	0.05 mph
Wind vane	0-360°	±2%	< 1.0°
Thermometer	(-40)-(+60) °C	±0.1ºC	0.05 ºC
Hygrometer	0-100% RH	±1.5% RH	0.05%
Barometer	500-1100hPa	± 0.05hPa	0.01 hPa

Temperature, relative humidity and atmospheric pressure data are obtained from a thermometer, a hygrometer and a barometer, respectively. A data logger is connected to the sensors on the mast to collect data in time series. Table I shows the technical specification of the main measurement devices installed at the weather station and all wind sensors are mounted according to the *World Meteorological Organization* (WMO) standard [28].

IV. DATA VALIDATION AND RECOVERY

Three-year data set on hourly basis is used in this paper. This extensive time series has been validated *manually* and *automatically* (using computer-based techniques). Initially is validated automatically by taking advantage of the power and speed of computers and manually validate where more analysis is required. The validation process includes *validation test* of wind speed and direction data series in order to verify a normal operation band (wind speed between 0.0 and 25.0 m/s, and wind direction 0°-360°). The *data screening* is used for the data series validation, *filter by flag* is used to remove questionable or erroneous, e.g. data like prolong calm time-periods. Results of validation process showed that the data series of wind speed and direction are inside the normal operation band. In addition, it is not necessary to apply any shifting to the time series of data based on the criteria concerning the maximum expected change of variable over time.

Missing data is a common problem in statistical analysis. Rates of less than 1% missing data are generally considered trivial, from 1 to 5 % are manageable. However, from 5 to 15% requires sophistically methods to handle and more than 15% may severely impact any kind of interpretation [29]. Missing data is a source of uncertainty in wind energy resource assessment studies. Several publication recommend that missing data should not exceed 10% [10], and this paper assumed 10% value as maximum. The completeness of the collected data is assessed using the *Data Recovery Rate* (DDR), it is a measure of the amount of wind data successfully captured by the data logger and is expressed as a percentage of the *data records available* in a given period of time [10], [30]:

$$\text{Data Recovery Rate (DDR)} = \frac{\text{Data records collected}}{\text{Data records available}} \times 100\%$$

(1)

where records collected is the difference between the data records possible and number of invalid records. The on-site measuring period shall be at least one year and the data recovery rate more than 90 % in order to ensure the quality of the wind energy resource assessment [31]. The total data records possible during 3 successfully measured years is estimated at 26304 which results in a total recovery data of 97.23%, and calculated yearly DDR of wind speed is 99.4%, 95.6% and 96.7% on 2008, 2009 and 2010 respectively. Results of data recovery rate of wind direction during are lower than wind speed during the recording period: 98.7%, 95.0% and 96.2%.

In this paper, a variation of the *expectation maximization* (EM) named *regularized EM* (RegEM) algorithm is used to replace any missing data and therefore complete the data set. MATLAB^{TM} implementation of regularization methods is adapted to fit the framework of the EM algorithm, this is the *EM Regularization Tools* (RegEM) [32].

Results of data imputation and the main statistical index are shown in Table II. The statistical measure, *Root Mean Square Error* (RMSE) is used to indicate how closely the predicted values match the measured values. Results show RMSE below 0.5% for all times-series considered.

TABLE II. RESULTS OF WIND SPEED AND DIRECTION DATA IMPUTATION

Wind	*Year*	*2008*	*2009*	*2010*
Speed	*Iteration Number*	3	8	6
	RMSE (%)	0.365	0.325	0.421
	MSE in Estimated Data (m/s)	2.085	1.139	1.728
Direction	*Iteration Number*	14	6	12
	RMSE (%)	0.395	0.453	0.482
	MSE in Estimated Data (°)	7.624	7.415	8.676

RMSE: Root Mean Square Error, *MSE:* Maximum Standard Error after using the EM algorithm.

V. DATA PROCESSING

A. Temperature, Pressure and Air Density

Figura 2and Figura 3 show monthly and averaged values of temperature and atmospheric pressure for the site, as assessed during the observation time. The temperature average registered is 27.55°C with the minimum diary is 14°C, which is registered in May and maximum diary of 39°C during August. The maximum and minimum monthly mean temperatures are 32.6°C in September and 22°C in August.

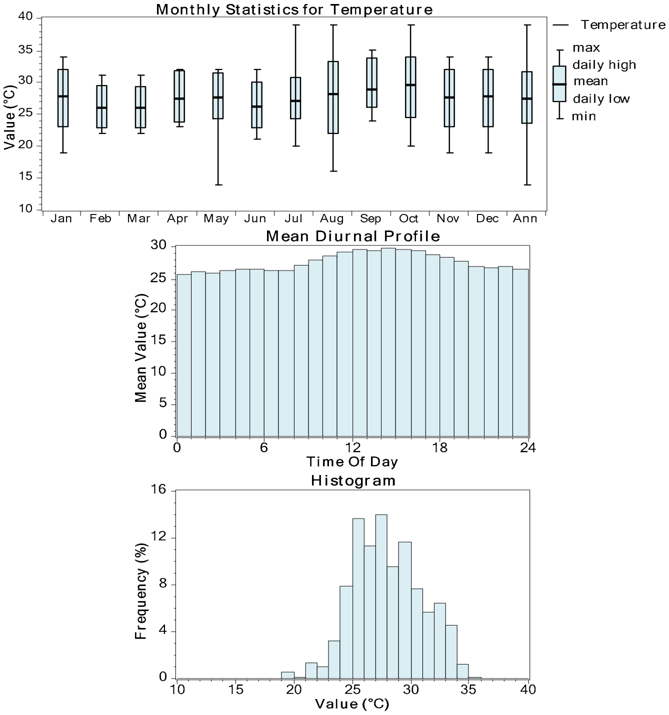


Figura 2. Monthly and daily statistics of temperature.

The average atmospheric pressure varies between 1008.42 and 1013.51 mbar with yearly mean value of 1011.18 mbar. The maximum daily value is 1019 mbar which is registered in January and minimum daily is 1001.00 mbar during June and July. Mean diurnal profile shows small changes in atmospheric pressure and largest values are expected between

11:00 and 12:00 hours (1012.3 mbar).

The site-specific air density is calculated based on on-site measurement of air temperature and atmospheric pressure, the mean values during the observation period is 1.175 kg/m^3. The maximum and minimum monthly average air densities are 1.230 kg/m^3 in May and 1.124 kg/m^3 in August, respectively.

The normal environmental conditions are defined by IEC 61400 and it considers air density of 1.225 kg/m^3 at sea-level at 15°C to be normal [33], [34]. Average air density values at the observed point are below this standard value during the year, this means that the air density of the site would negatively affect the performance of a wind turbine most of the time. The energy in the wind will be reduced proportionally to the density of air and larger wind turbines are required for the same rated power compared with the conditions specified in the standard.

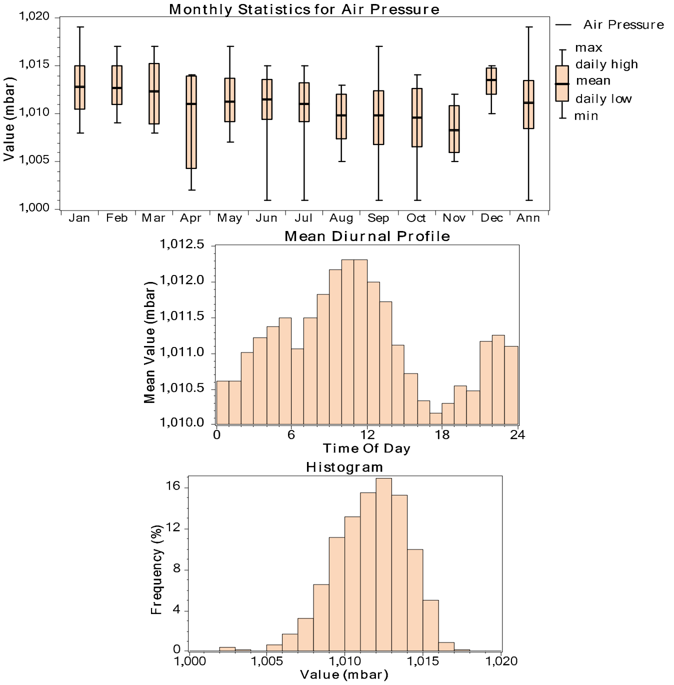


Figura 3. Monthly and daily statistics of atmospheric pressure.

B. *Wind Speed*

The change in wind speed with height above ground, *wind shear*, can be approximated using *Prandtl logarithmic law* (logarithmic law or log law). This law assumes that the wind speed varies logarithmically with the height above ground [35] and uses the *surface roughness* (sometimes called surface roughness length or just roughness length) to characterize the wind shear. In this paper, the logarithmic law is used to approximate the wind shear of wind speed data set to height of 50 m and roughness length of 0.0024 m or *Roughness Class* (*RC*) of 0.5 is assumed. Those values are representatives of open terrain with a smooth surface, such as concrete runways in airports, mowed grass.

A preliminary description of the wind speed at 50 m of the site for the observation period is created using boxplot, as shown on Figura 4 where of five statistical measures: mean, average daily high and average daily low, maximum and minimum values. The monthly mean wind speed varies between 4.92 and 11.78 m/s. The maximum value of the mean wind speed occurs in June whilst the minimum value occurred in November and the average speed for the yearly mean is 8.29 m/s.

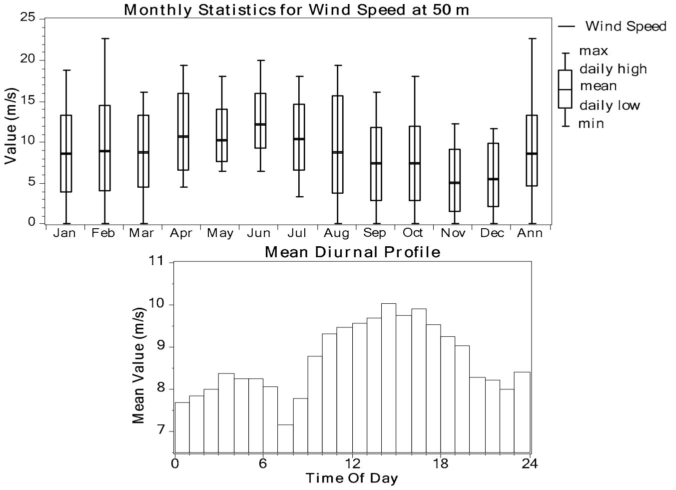


Figura 4. Monthly statistics and daily profile for wind speed at 50 m height above ground.

The wind speed operating range of most horizontal axis wind turbines is defined between cut-in and cut-out wind speeds of about 4 m/s and 25 m/s respectively. It can be noted that the monthly average speeds is over the cut-in during whole year. The average daily high wind speed is 16.25 m/s and occurs in June. The maximum hourly wind speed registration is 22.49 m/s in June and this value is below the cut-out speed of most wind turbines. The wind speeds can be classed as *calm* (<1.0 m/s, below the cut-in wind speed for sensor) at least one hour during every nine months as can be seen in Figura 4.

The diurnal wind speed profile is shown in Figura 5, the mean daily wind speed profile over the observation period varies between 6.72 m/s and 10.20 m/s at 01:00 and 15:00 hours. The diurnal wind speed is 8.29 m/s but the hourly profile recorded in June is the highest as 11.74 m/s.

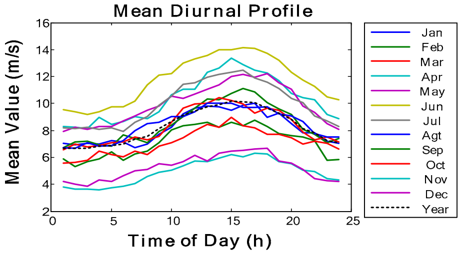


Figura 5. Diurnal Wind Speed Profile.

There are several ways to study a one-dimensional data set. In this study, the statistical boxplot technique described by Wilks [36] is applied to establish the *seasonal* and *inter-annual* variabilities of wind speeds in recorded time series.

In Fig. 6(a)-6(e) the boxplots for the yearly groups are traced. The boxplots for the historical average wind speeds for each season of the year suggest the presence of some apparently atypical values (outliers, represented by the symbol +), especially in summer, Fig. 6(b), for the year 2 and 3. In Fig. 6(a)-6(b), it can observed that summer (June, July, and August -JJA) and autumn (September, October, and November -SON) produce the highest wind speed values for the yearly groups. Year 2 presents a higher median in summer with 9.845 m/s, Fig. 6(b), while in other seasons this value ranges between 5.345 and 9.494 m/s. According to the boxplots values presented in Fig. 6(a) and 6(b), year 1 and 3 have less variability in wind speed for each seasonal transition. The variability of the average annual wind speeds of the groups for the period 2008–2010 is presented in the boxplot of Fig. 6(e).

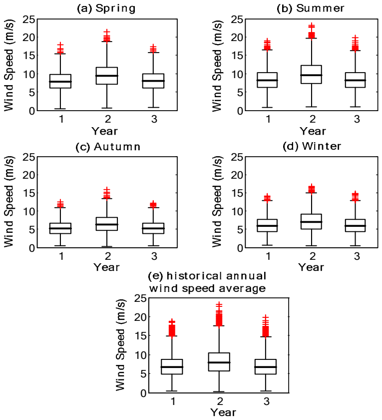


Figura 6. Boxplot showing the variability of the seasonal average wind speed of the groups: (a) Spring, (b) Summer, (c) Autumn, (d) Winter, and (e) the historical annual wind speed average.

Two special time-periods are identified in the specific case of Venezuela: (a) *rainy season* from May to mid-November and (b) *dry season* from December to April. Rainy season presents higher wind speed compared with dry season.

The nonparametric *Mann-Kendall test* has been suggested by the WMO to assess the data trends in time series of environmental variables [37]. This test consists of comparing each value of the time series with the other values remaining in the sequential order. The trend analysis tests with the Mann-Kendall method are summarized in Table III.

TABLE III. RESULTS OF THE MANN-KENDALL TESTS OF THE YEARS FOR SEASONAL AND INTER-ANNUAL VARIABILITIES.

Year	Variable	Summer	Spring	Autumn	Winter	Year
1	Average (m/s)	8.319	7.986	5.345	6.111	6.940
	Mann-Kendall test (Z)	-15.509	7.178	-19.613	18.753	-33.175
2	Average (m/s)	9.845	9.494	6.521	7.191	8.263
	Mann-Kendall test (Z)	-14.597	7.393	-19.864	16.895	-32.713
3	Average (m/s)	8.310	8.012	5.293	6.120	6.934
	Mann-Kendall test (Z)	-15.106	6.823	-19.810	17.651	-33.342

It can be observed that the average annual wind speeds for years 1, 2, and 3 have a negative trend. In autumn, the decrease in speeds is more pronounced in Year 2 and 3, with significance levels of $p<0.05$. This trend is highest in Year 3, with a value of −19.810, representing an impact of climate variability and on wind resources. In some days of Year 2, wind intensity is greater than 6.521 m/s. The highest values in the Mann-Kendall trend test are found for autumn and winter in all years.

C. Probability density functions

The determination of wind speed distributions is carried out considering several probability density functions. Fig. 7 shows the frequency (%) distribution of actual data and the best-fit Weibull probability distribution function considering several methods, and also the estimated parameters derived from the three-year observed data.

The top point of the curve is the most frequent wind speed as depicted in Fig. 9. The peak probability value is 5.67% with a mean wind speed of 7.81 m/s and it corresponds with actual data. The results of the *maximum likelihood algorithm* to fit a Weibull distribution to a measured wind speed distribution shows that the dimensionless shape parameter k is 2.59 while the scale parameter c is 9.36 m/s for the analysed site during the observation time period (R^2 = 0.99091). This value for k indicates that variation of hourly mean wind speed about the annual mean is small. The shape and scale parameters of the Weibull function are calculated for each month.

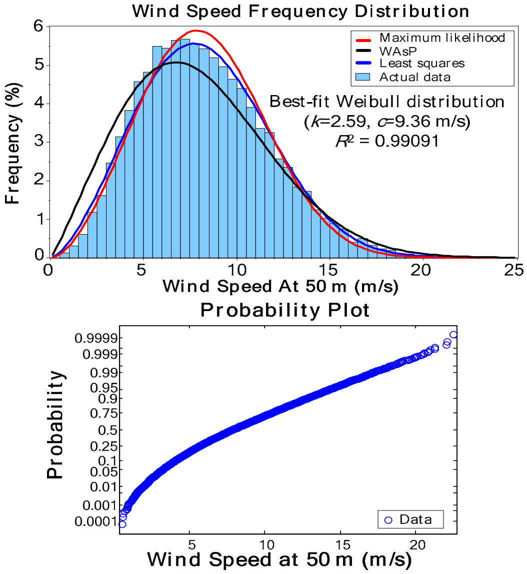


Figura 7. Wind speed frequency distribution and best-fit Weibull distribution in the site assessed.

TABLE IV. MAIN STATISTICS AND PARAMETERS OF BEST-FIT WEIBULL DISTRIBUTION FUNCTION (ALL DIRECTIONS).

	Weibull k	*Weibull c (m/s)*	*Mean Speed (m/s)*	*Standard Deviation (m/s)*
Jan	3.078	9.154	8.208	2.856
Feb	2.694	9.509	8.528	3.468
Mar	3.341	9.285	8.325	2.708

Apr	4.223	11.453	10.272	2.797
May	5.550	10.975	9.842	1.944
Jun	6.243	12.888	11.555	1.968
Jul	4.144	11.097	9.949	2.864
Aug	2.228	9.371	8.401	4.091
Sep	2.175	7.972	7.148	3.533
Oct	2.558	7.956	7.137	2.926
Nov	2.668	5.362	4.809	2.119
Dec	3.296	5.840	5.236	1.686

Table IV shows monthly Weibull parameters, mean speed and the standard deviations are summarized. As seen from this table, the Weibull shape parameter k varies between 2.17 and 6.24 while the scale parameter c varies between 5.36 and 12.88 m/s. The lowest c value is found in November and the highest value in June. The wind at the site is therefore expected to be highly uniform during June. The lowest standard deviation is 1.68 m/s and occurs in December.

Fig. 8 shows the *cumulative probability distribution* (CDF) of wind speed at the assessed site during the observation time period and also the best-fit of Weibull are depicter, Normal distribution is complementary. The *Kolmogorov–Smirnov test* (K–S test) [38] has been used to evaluate goodness of fit. Results of K-S test show Weibull distribution has higher goodness of fit at 5% significance level (KS= 0.0407) than Normal distribution (KS = 0.0204).

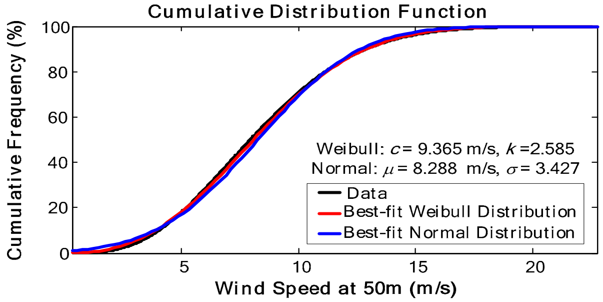


Figura 8.Cumulative probability distribution of Wind Speed at the assessed site.

The time that a turbine can generate power is estimated using the Weibull CDF. For a wind turbine with a cut-in speed of 4 m/s and a cut-out speed of 25 m/s installed at this site, wind resource will generate power for 20.10 hours a day (probability = 0.8378). It is expected the wind speed is within the necessary operating region during 7339 hours per year and the probability wind speed exceed 35 m/s is negligible (probability = 1.116×10^{-21}).

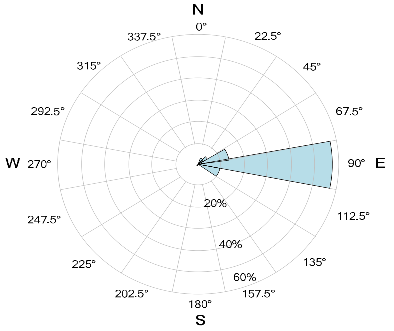
D. *Wind Direction*

The direction of the wind is an important factor when determining the layout of a wind farm or any wind energy conversion system.

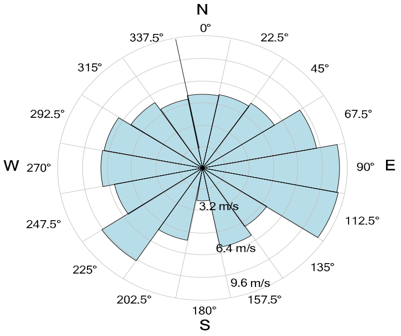
Fig. 9 shows the relative frequency (%) of wind directions and mean wind speed. This wind frequency rose representation is used to show the frequency that wind direction falls within each direction sector. In this case, the Weibull histograms are determined for 16 sectors at 50 m height. According to Fig. 9(a), the frequency at which the wind blows from the East (at a wind speed above the calm threshold) is about 97% and the estimated calm frequency is 3%. This means the wind speed is equal to 0.0 m/s in more than 263.40 hours per year. The prevailing wind direction is the East-West direction.

The mean speed wind rose plots the average wind speed value for a particular wind direction, as shown in Fig. 9(b). According to this figure, the wind rose indicates that winds from the East direction tend to be the strongest, with an average wind speed of over 9.67 m/s and winds from the West direction tend to be the lightest, averaging less than 5.76 m/s.

Table V shows the Weibull parameters for the mean wind speed rose. As seen in this table, the Weibull shape parameter k varies between 1.32 and 4.42 while the scale parameter c varies between 5.75 and 10.33 m/s. The lowest c value corresponds to wind blowing from North, whereas the highest value is for wind blowing from East. Wind rose analysis shows that winds in Los Taques are very unidirectional; more than 74.62% of the year the wind comes from East (62.5°–112.5°), this is likely a result of the thermal effects seen in this region. In this type of site, the wind turbines tend to be arranged in tightly packed rows, perpendicular to the wind, with large spaces downwind to minimize wake effects.



(a) Wind Frequency Rose



(b) Mean of Wind Speed

Figura 9.Frequency (%) and mean speed of wind directions.

TABLE V. PROBABILITY DISTRIBUTION FUNCTION OF MEAN WIND SPEED PER SECTOR.

Sector	*Weibull k*	*Weibull c (m/s)*	*Mean Speed (m/s)*	*Mean (m/s)*
348.75º–11.25º	2.407	6.1091	4.5490	4.9156
11.25º–33.75º	2.376	6.2046	4.6053	5.5240
33.75º–56.25º	2.189	6.5291	4.8476	5.5240
56.25 º–78.75º	2.544	8.7367	6.4976	7.3614
78.75º–101.25º	2.964	10.2607	7.6657	8.5903
101.25º–123.75º	3.033	10.3354	7.7265	9.8192

123.75º–146.25º	4.415	8.1459	4.3439	4.9156
146.25º–168.25º	2.054	6.6779	4.9300	6.1325
168.75º–191.25º	1.319	2.6703	2.0550	2.4578
191.25º–213.25º	1.963	6.1468	4.5325	4.9156
213.75º–236.25º	2.67	8.2719	6.7880	8.5903
236.25 º–258.75º	2.583	6.7588	5.0411	6.1325
258.75 º–281.25º	2.701	7.6355	5.7060	6.1325
281.25º–303.75º	2.265	7.6176	5.6421	6.1325
303.75º–326.75º	2.211	6.3665	4.8061	5.5240
326.25º–348.75º	2.887	5.7597	4.3063	4.9156

E. Wind Power Density (WPD)

A useful way to assessment the wind resource available at Los Taques is the *Wind Power Density* (WPD) because provides an idea about the mean energy content of the wind resource. Fig. 10 shows monthly variations of the mean WPD which is calculated using the wind speed data set during the observation period. Fig. 10 shows the mean WPDs are highly variable during the observation period. Large monthly and daily changes are evident, the minimum daily value is different to 0.0 W/m^2 from April to July and maximum daily, 6740.11 W/m^2 is reached in February. The annual average WPD was 582.08 W/m^2 over the whole period. The monthly mean WPD varies between 141.02 in November to 1169.33 W/m^2 in June.

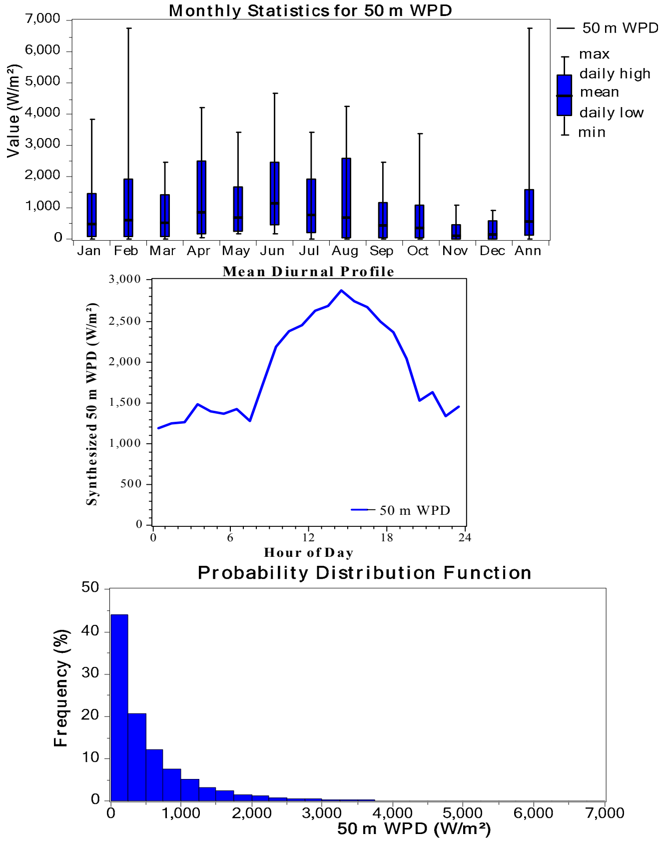


Figura 10. Monthly variation of the mean power density.

The *wind power class* is a number indicating the mean energy content of the wind resource. Wind power classes are based on the mean wind power density at 50 meters above ground, according to Table VI.

TABLE VI. CLASSES OF WIND POWER DENSITY AT 50 M [39], [40].

Wind Power Class	*Description*	*Wind Power Density (W/m^2)*	*Wind Speed (m/s)*
1	Poor	<200	<5.6
2	Marginal	200 - 300	5.6/6.4
3	Fair	300 - 400	6.4/7.0
4	Good	400 - 500	7.0/7.5
5	Excellent	500 - 600	7.5/8.0
6	Outstanding	600 - 800	8.0/8.8
7	Superb	>800	>8.8

According to the wind power classes shown in Table VI, the site assessed exhibits an *excellent* mean power density during the year (>500 W/m^2). It must be noticed the monthly values range between *poor* (<200 W/m^2) and *superb* (>800W/m^2).

Fig. 11 shows empirical CDF of WPD and an as example the best-fit CDF using a *negative binomial distribution* is depicted. It is difficult to give a physical interpretation in this case to the individual parameters, for this reason the empirical CDF is used for results interpretations. It can be observed the power density is *superb* (>800W/m^2) about 21.56% of the total time, 5.17 hours per day, and the WPD is considered *poor* (<200W/m^2) during 9.17 hour per day (38.21%).

The cumulative distribution of wind power density, presented in Fig 11, shows that less than 50% of the time, the wind power density is equal to or less than 309W/m^2, but values above 750W/m^2 are reached less than 25.05% of the time.

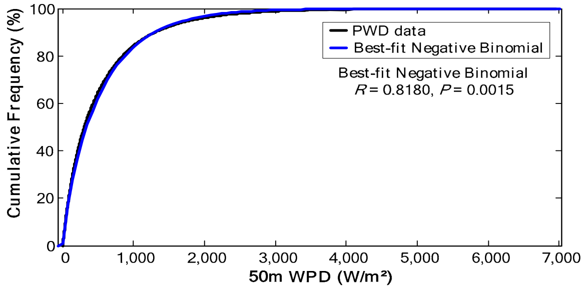


Figura 11. Wind power density cumulative probability distributions in the site.

F. Wind Power of Selected Turbines and Energy Output

Estimation of energy output from a wind turbine to be installed at a selected site will determine if there is sufficient energy available to make the site commercially viable. The annual energy output from a wind turbine depends on the electrical power output from the wind turbine for the wind speed distribution experienced.

In order to select a wind turbine for a specific location, it is necessary to match it with the wind characteristics of the site (it should yield an optimum energy) in order to obtain a high *capacity factor* (C_F) to meet the electrical energy demand.

In this paper, for general evaluative purposes, eight different wind turbines have been selected: (*A*) Gamesa G-52, (*B*) Made AE-61, (*C*) Vestas V-80, (*D*) IMPSA IWP- 83, (*E*) Nordex N-90LS, (*F*) Vestas V90, (*G*) REpower 5M and (*H*) REpower 6M. The main properties of these wind turbines are given in Table VII. The power curves for the four turbines with different rated powers are shown in Fig. 12.

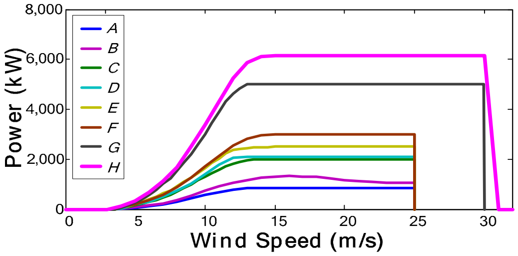


Figura 12. Power curves comparison for selected wind turbines.

TABLE VII. MAIN CHARACTERISTICS OF FIVE DIFFERENT COMMERCIAL WIND TURBINES.

Turbine	*Hub height (m)*	*Rated power P_r (kW)*	*Swept Area (m^2)*	*Power Regulation*	*Generator type*
A	65	850	2124	PAC	DFAG
B	65	1320	2922	SR	AG
C	60	2000	5027	PAC	DFAG
D	100	2100	5410	PAC	DDPM
E	70	2500	7854	PAC	DFAG
F	65	3000	6362	PAC	DFAG
G	100	5000	49875	PAC	DFAG
H	100	6100	49875	PAC	DFAG

Power Regulation: PAC: Pitch Angle Control, SR: Stall Regulated
Generator Type: DFAG: Double Asynchronous generator, AG: Asynchronous Generator, DDPM: Direct Drive Permanent Magnet

Table VIII shows the wind turbine output calculation for selected wind turbines using the wind regimen available in Los Taques.

TABLE VIII. MAIN ENERGY PRODUCTION FOR SELECTED WIND TURBINES

Turbine	*Time at zero output (%)*	*Time at rated output (%)*	*Mean Net power output (kW)*	*Mean Net Energy Output E_{out} (kW/year)*	*Net Capacity Factor C_F (%)*
A	10.01	12.17	362.40	3,174,546	42.6
B	10.14	0.51	478.30	4,190,291	36.2
C	11.57	13.22	828.70	7,259,580	41.4
D	11.22	23.44	910.80	7,978,507	43.4
E	11.40	14.43	1,073.20	9,401,554	42.9
F	9.93	12.29	1,197.00	10,485,328	39.9
G	12.58	23.42	2,057.00	18,019,224	41.1
H	4.23	21.02	2,770.10	24,265,872	45.0

The overall loss factor has been considered equal to 17.70%. An outstanding annual average speed (6.94m/s) is available in Los Taques. However, 3% of calm provides a relatively long period for which the wind turbines are out of service because the wind speed is below their cut-in speed.

The Turbine *C* is the wind turbine with the highest percentage of time at zero output; this is particularly true from September to December: 13.61%, 13.31%, 30.28% and 18.15% respectively. November is the worst month in terms of zero output for almost all selected wind turbines: *C*: 30.28%, *A*: 21.94%, *D*: 21.94% and *E*: 21.94%. In fact, November and December are the worst months in terms of output power production. The poor performance during these months is characterized by the fact that during them none of the selected turbines operate at rated power, as presented in Fig. 13.

The net mean energy output for the selected wind turbines is in the range of 3.17 GWh/year to 24.65 GWh/year. The highest net mean energy output and capacity factor is obtained with a turbine *H* (6100 kW). Sometimes it is advantageous to use a larger generator with the same rotor diameter. This would tend to reduce the capacity factor, but may afford a substantially larger annual production. This is the case in site under consideration because it is a very windy location.

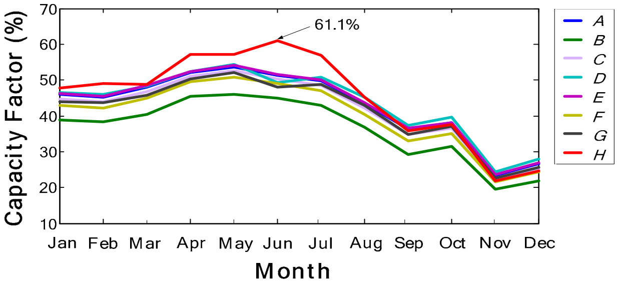


Figura 13. Monthly Capacity Factor (%) of selected wind turbines.

A hypothetical wind farm of 100 MW based on turbine *H* can produce around 395.28 GWh/year. This production is relatively high compared with the 316.22 GWh/year that would be produced by a wind farm based on *B* wind turbine. In this case, the evaluation indicates the best option is use wind turbine *H* in the site under investigation.

VI. CONCLUSIONS

The results obtained in this paper for Los Taques show that the wind energy potential is sufficient for its use as a primary energy to produce electricity commercially, this is an important contribution because defines the starting point for more deeper evaluations. Results of this preliminary assessment have demonstrated an outstanding wind class in terms of annual average wind speed at 50 m in addition to annual wind density of excellent class. This quality of wind resource is suitable for electrical power production through the installation of wind farms. Wind rose analysis shows the winds in Los Taques are very unidirectional and blow strongly and frequently from the east. Although four seasons are not available in Venezuela, two pseudo-seasons, consisting of September to January and February to August, can be used to characterize the wind energy resource. Nevertheless, the one wind farm in this location could not produce electricity whole year. The September to January period mostly consists of wind speeds below those considered as good winds. In contrast the February to August period mostly consists of wind speeds which qualify as excellent. An evaluation of several commercially available wind turbines has shown a good performance for a 6.0 MW wind turbine. However, the power output for this wind turbine is relatively low; it is estimated to be 2.71 MW, which is equivalent to 24.65 GWh/year of exploitable wind energy. Energy production for valuations for a 100 MW wind farm indicates the maximum production is obtained with a 6.0. MW wind turbine. The results obtained in this paper show that the wind energy potential in Los Taques is sufficient for use as the primary energy source for the commercial generation of electrical energy, a further evaluation of wind energy resource is recommended to provide a long term estimation of the wind regime.

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