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Wind Energy Potential by the Weibull Distribution at High-Altitude Peruvian Highlands

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Abstract- Wind energy in recent years has experienced accelerated growth compared to other renewable energy sources, therefore it is important to determine the potential of wind energy available for application in wind systems. The objective of this study was to determine the wind energy potential using the Weibull distribution and the wind rose in the Peruvian highlands at an altitude of more than 3800 m. The two-parameter Weibull distribution function method was used to estimate the profile of the wind speed and the wind perspective, based on observations of the wind during one year by the meteorological station located in the Peruvian highlands of Juliaca. The results show that the wind characteristics are irregular, where the annual mean shape and scale parameters were 2.16 and 2.20 m/s evaluated 24 hours, however, the mean annual shape and scale parameters in the afternoons were 5.01 and 4.46 m/s respectively. Therefore, this site presents a high wind energy potential in the afternoon, because the wind flow is not constant during the 24 hours, but it is in the afternoons.

Keywords Parameters, wind, Weibull distribution, wind energy.

1. Introduction

The scarcity of energy production and the massive use of energy in the world contribute to climate change and global warming [1,2], due to the massive use of fossil fuels such as oil, natural gas or coal, which cause the emission of large quantities of greenhouse gases into the atmosphere [3], affecting the structure of tree vegetation and the dynamics of forest development [4], negatively impacting the environment [5].

Due to population growth, technological progress and other factors, the need for energy increases, and the use of hydrocarbons is insufficient to cover this demand, in addition to the fact that they pollute the environment; therefore, it is necessary to look for other alternative sources of energy that are environmentally friendly [6]. Renewable energies constitute a fundamental factor for the energetic and sustainable development of humanity [7], being an option to reduce climate change problems and avoiding the burning of fossil fuels [8], covering part of the energy demand, mainly solar and wind energy, due to the abundance of solar radiation and moderate continuity of wind speed worldwide [9].

Wind energy is part of the renewable energies, free, inexhaustible and non-polluting, which has experienced a great growth in recent years [10,11], due to the implementation of competitive energy policies with conventional energy sources and environmental sustainability [12]. Energy production depends on wind variability and direction [13], temporal and spatial distribution of wind in flat and mountainous areas [14], climatic conditions and meteorological fluctuations in the area [15]. Therefore, wind energy can contribute to sustainable electricity generation and low carbon economy [16].

Wind turbines convert wind energy into electricity by the rotation of mechanical blades [17], composed of a wind turbine and an electric generator, influenced by factors of wind speed and turbine availability [18], usually is controlled by maximum power point tracking (MPPT), to achieve maximum power at any wind speed and direction [19], up to a maximum of 59.3 % of the wind kinetic energy by the limit of Betz coefficient [20]. These systems are installed as offshore or onshore wind farms [21].

The Weibull distribution function is the most approximate model for the estimation of wind speed [22] and the determination of wind energy potential [23], however the distribution parameters of shape (k) and scale (c) are estimated by numerical methods [24]. The two-parameter Weibull distribution function is the most widely used worldwide, due to its great flexibility and simplicity in the evaluation of the wind resource of a given area, during a period of time, usually monthly or annually [25,26].

Therefore, the objective of this research article was to determine the potential of wind energy by the Weibull distribution method and the wind rose in the Peruvian altiplano at more than 3800 m of altitude, for the application in wind turbines. The determination of the wind potential in the Peruvian highlands is very important, due to the varied climatic conditions during the year, the high altitude of the study, the irregular geography of the area and the few studies conducted under these conditions. In this sense, this study would contribute as a baseline in the implementation of wind generation systems. Meanwhile, the first section shows the introduction and background of the study area, followed by the materials and methods using the Weibull distribution of wind speed in the second section, the third section shows the results and discussions and finally the conclusions.

2. Materials and Methods

2.1. Location

This research was carried out in the Peruvian highlands of Juliaca, Peru, located at a latitude of -15º 29' 27" and a longitude of -70º 07' 37", at an altitude of 3824 m, northwest of Lake Titicaca in the Peruvian altiplano. It has a flat relief composed of extensive pampas with slight undulations (Fig. 1). The average temperature ranges from 4 ºC to 10 ºC, the maximum temperature during all month's averages 18.08 ºC and the minimum temperature reaches -7.5 ºC in July.

Fig. 1. Geographical location of the study area in the Peruvian highlands of Juliaca, Peru

2.2. Measuring equipment

To measure meteorological parameters in the Peruvian highlands of Juliaca, a professional weather station, Ambient Weather WS-2902C, located at an altitude of 10 m in the high Andean city of Juliaca, was used to monitor weather conditions in outdoor areas. The weather station measured wind speed, wind direction, precipitation, temperature, outdoor humidity, solar radiation and ultraviolet rays.

2.3. Weibull distribution model

To estimate the wind energy potential in the high Andean region, the two-parameter Weibull distribution probability function methodology was adopted, with good relationship in the experimental data [24,27], expressed in equations (1) and (2) [28].

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

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^{k}} \quad (2)$$

Where, k is the shape parameter, c is the scale parameter and v are the wind speed in (m/s). $F(v)$ represents the cumulative distribution function and $f(v)$ the probability density function. The parameter k determines the width and shape of the curve with the peak of the wind distribution, and *c* describes the wind regime at *f(v)* and *F(v)*. This distribution has advantages for determining wind potential as flexibility, it uses only two parameters and is represented by a simple equation.

2.4. Estimation of Weibull and wind rose parameters

To model the appropriate Weibull parameter estimation, the mean hourly wind speed (V_m) and variance (σ^2) of the data, which were transformed from wind speed per minute to mean hourly speed [22], for an annual seasonal period, from the month of October 2019 to the month of September 2020, shown in equation (3) and (4), were used.

$$V_m = \frac{1}{n}\left[\sum_{i=1}^{n} V_i\right] \tag{3}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(V_i - V_m\right)^2 \tag{4}$$

The wind rose or polar diagrams were determined using WRPLOT software, to draw the polar diagram of wind speed and wind direction, clockwise from 0° to 360° respectively [26].

3. Results and Discussion

3.1. Wind speed characteristics

The behaviour of wind speed in the high Andean region was very variable, due to the presence of rain between October and March, seasonal variability and sunny days with and without wind. The behaviour of wind speed in the high Andean region Fig. 2 shows the average monthly wind speed during 24 hours, with a minimum value of 1.28 m/s (June) and a maximum of 2.25 m/s (November), however, the average monthly wind speed between 11:00 h to 19:00 h (afternoon), presented a minimum value of 2.41 m/s (June) and a maximum of 4.41 m/s (October), recorded at the meteorological station located at 10 m altitude, the latter being higher compared to the 24 hours average, which means that there was a greater amount of wind flow in the afternoons in the months from August to January.

Fig. 2. Wind speed behavior in the high Andean region Average annual wind speed values recorded during October 2019 to September 2020

3.2. Weibull parameters analysis of the wind speed

The values of the Weibull parameters, are shown in Table 1, where the shape parameter *k* (dimensionless) was found between 1.78 and 2.50 in the months of the year 2019 to 2020, the scale parameter *c* was found between 1.04 m/s to 3.42 m/s respectively, evaluated every 24 hours. Meanwhile, the shape and scale parameters evaluated in the afternoon 11:00 h to 19:00 h, were found to be between 3.47 to 5.95 and 3.02 m/s to 6.01 m/s respectively, observing that the latter parameters were higher. Therefore, the annual mean Weibull shape and scale parameters evaluated at 24 hours were 2.16 and 2.20 m/s, while the annual mean shape and scale parameters evaluated in the afternoons were 5.38 and 5.29 m/s, the latter being higher than the parameters evaluated every 24 hours. Therefore, in the afternoons in the month of October the parameter *c* was higher, on the contrary, this parameter was lower in the month of July evaluated every 24 hours.

Table 1. Meanwhile, the shape and scale parameters evaluated by the Shape and scale parameter values for the Weibull fit from October 2019 to September 2020

Months	Years	Shape parameters and Weibull scale			
		Every 24 hours		11:00 h to 19:00 h	
		k	*c*	*k*	*c*
October	2019	2.33	3.17	4.90	6.01
November	2019	2.50	3.42	5.95	5.65
December	2019	2.20	2.84	4.11	5.14
January	2020	2.48	2.74	4.24	4.58
February	2020	2.36	2.25	5.09	3.69
March	2020	2.21	2.25	4.97	4.27
April	2020	2.24	1.72	5.62	3.49
May	2020	1.97	1.44	4.46	3.44
June	2020	1.90	1.14	3.47	3.02
July	2020	1.78	1.04	5.74	3.22
August	2020	1.84	1.84	6.14	5.70
September	2020	2.09	2.57	5.38	5.29
Annual average		2.16	2.20	5.01	4.46
Annual SD		0.24	0.78	0.81	1.08

The density function of the Weibull distribution of wind speed in Juliaca showed irregular behaviour during the year, with the Weibull parameters varying between the rainy season (October - March) and the sunny season (May - August). In Fig. 3, it is observed that the highest wind density was in the month of November, on the other hand, the lowest density was in the month of July, evaluated every 24 hours, however, Fig. 4, shows that the maximum wind density in the afternoons was in the month of October and the minimum wind density was in the month of June. This means that there is a higher wind speed in the afternoons compared to the 24 hours evaluation in the Peruvian Altiplano, therefore, the highest probability that the wind will be uniform is in the afternoons.

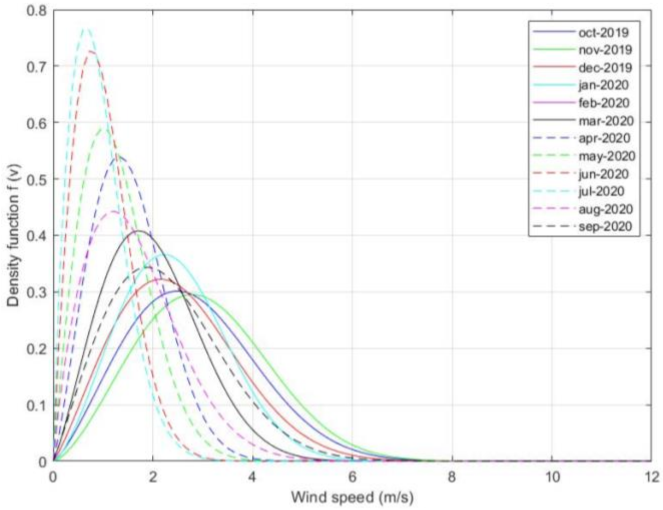

Fig. 3. Wind speed behavior in the high Andean region Average annual wind speed values recorded during October 2019 to September 2020

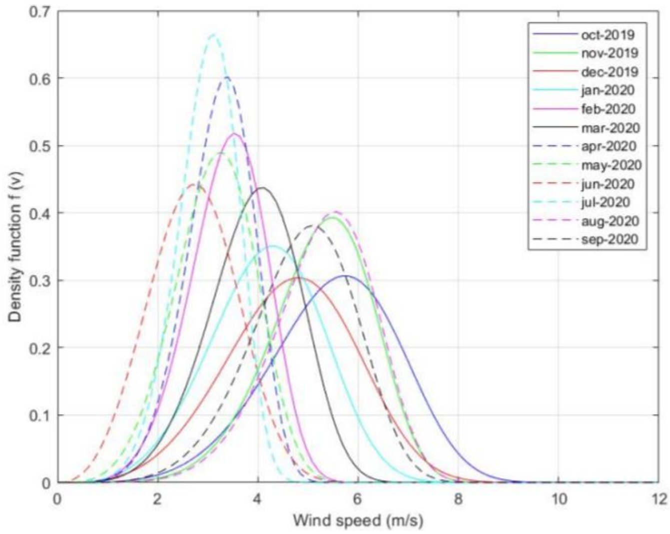

Fig. 4. Wind speed behavior in the high Andean region Average annual wind speed values recorded during October 2019 to September 2020

3.3. Cumulative distribution and Weibull distribution

The annual mean values of the Weibull parameters of the 24-hourly wind speed, for the shape parameter was 2.16 and scale was 2.20 m/s, reflecting in the Weibull cumulative distribution function, shown in Fig. 5, this result is similar to the density function of the Weibull distribution shown in Fig. 3, similarly other studies fitted the Weibull cumulative distribution to the wind speed [26,29].

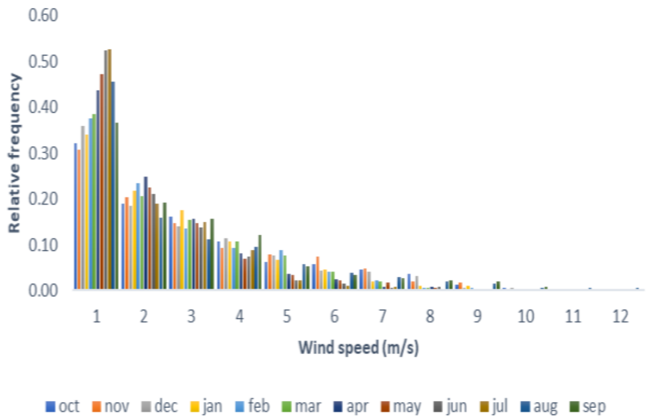

Fig. 5. Cumulative Weibull distribution function during 2019 to 2020

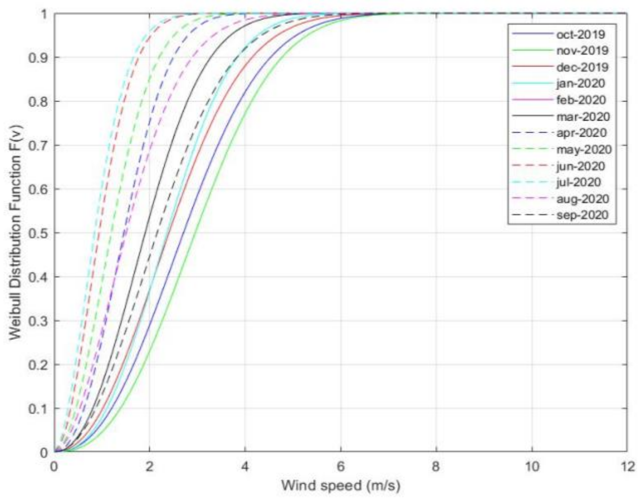

Fig. 6 Weibull distribution function, monthly, every 24 h

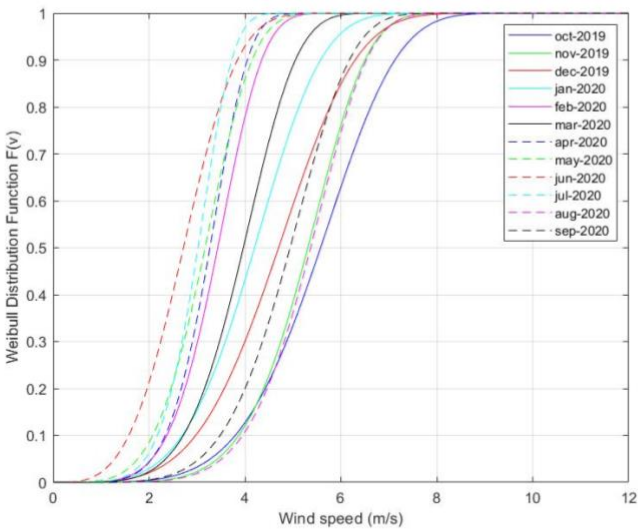

Fig. 7. Weibull distribution function, monthly, 11:00 h to 19:00 h

In the 24 hours Weibull distribution function, the probability of the minimum mean wind speed in the month of July was 0.49 m/s and 1.72 m/s, while the maximum mean wind speed in the month of November was 1.89 m/s and 5.76 m/s, presenting higher wind flow during the day in the month of November (Figure 6). The results of the Weibull function evaluated in the afternoons, determine that the minimum mean wind speed in the month of June was 1.82 m/s and 3.13 m/s, while the maximum mean wind speed in the month of October was 3.25 m/s and 7.09 m/s respectively, observing the highest wind speed in the afternoons (Fig. 7). Through this distribution, the mean annual 24-hourly wind speed was between 1.11 m/s to 3.34 m/s, however, the annual wind flow in the afternoons was between 2.92 m/s to 5.45 m/s respectively (Fig. 8). Therefore, the average wind speed is higher in the afternoons than during the whole day. In another research determined the average wind speed more frequently was between 5.41 m/s to 5.44 m/s evaluated during one year in 2017 in Galati County (Romania), this behaviour is because the wind speed is not frequent during the day [30]. Similarly, on the Indian coast, the parameters of the Weibull distribution *k* and *c* were estimated to be 1.99 and 5.00 m/s [23], being similar to the parameters obtained in the afternoons in this research. Therefore, the wind speed parameters determined by the Weibull distribution in the Peruvian Altiplano are lower evaluated every 24 hours and higher in the afternoons.

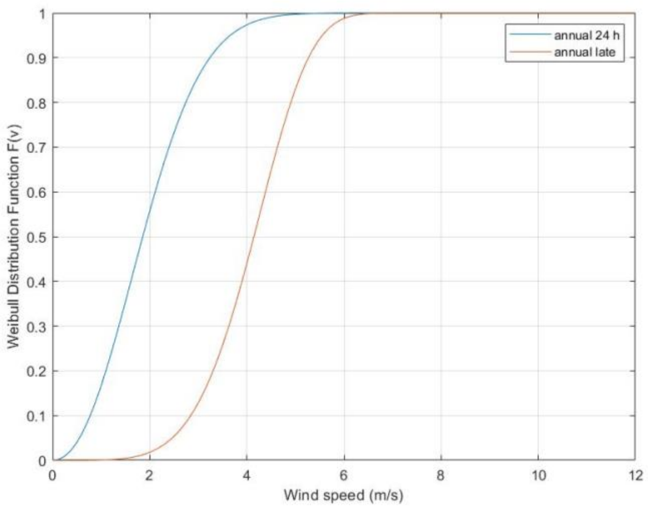

Fig. 8. Weibull distribution function, annual 24 hours and in the afternoons

3.4. Wind direction analysis (wind rose)

The Peruvian highlands present a flat relief in most of its extension, for that reason the wind direction is likely to have few directions. Fig. 10 shows the graphs of the wind roses recorded in the different months of 2019 and 2020. In the months of June to September 2020 there was less wind presence, possibly because these months are in winter and more sunny days, while in the months of October to December 2019 and January to May 2020 there was more wind presence, most of the prevailing wind is in the Southeast direction, being in the rainy season. The average annual wind rose in Juliaca, shown in Fig. 9, shows that most of the wind is in a south-easterly direction, almost 9% of the wind are between 10º and 40º clockwise, in some days with less frequency it was observed that it is in a westerly direction, being possible that the crosswinds are relatively low.

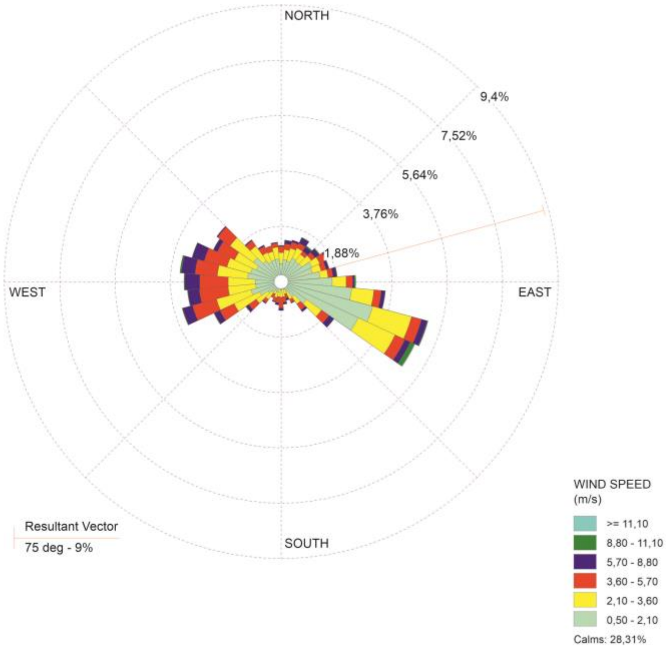

Fig. 9. Average annual wind rose in the Peruvian highlands

3.5. Prospects form wind farms in the Peruvian highlands

The continuity of wind flow in the Peruvian highlands of Juliaca in the afternoons is high, which can be exploited by a wind turbine system, however, the climatic conditions of the area in the rainy season, can hinder its operation, resulting in more frequent maintenance due to mechanical wear of moving parts, increasing operation and maintenance (O&M) costs and reducing the continuity in electricity generation. Therefore, improving maintenance activities is the most appropriate solution to reduce operational risks [31]. The blade of a wind turbine is the main component that can be damaged by wind fatigue [32] and rain load [33].

The main limitation in the operation of wind turbines in this region are rainy days, which can reduce the useful life of the wind turbine, in this area there is high rainfall which can cause erosion of the wind turbine blades, due to high speeds. Rain has effects on the erosion of the mechanical blades, decreasing the yield or energy production up to 1.5% approximately [34], however, heavy rainfall greater than 20 mm can cause wear of the blades in wind turbines [35].

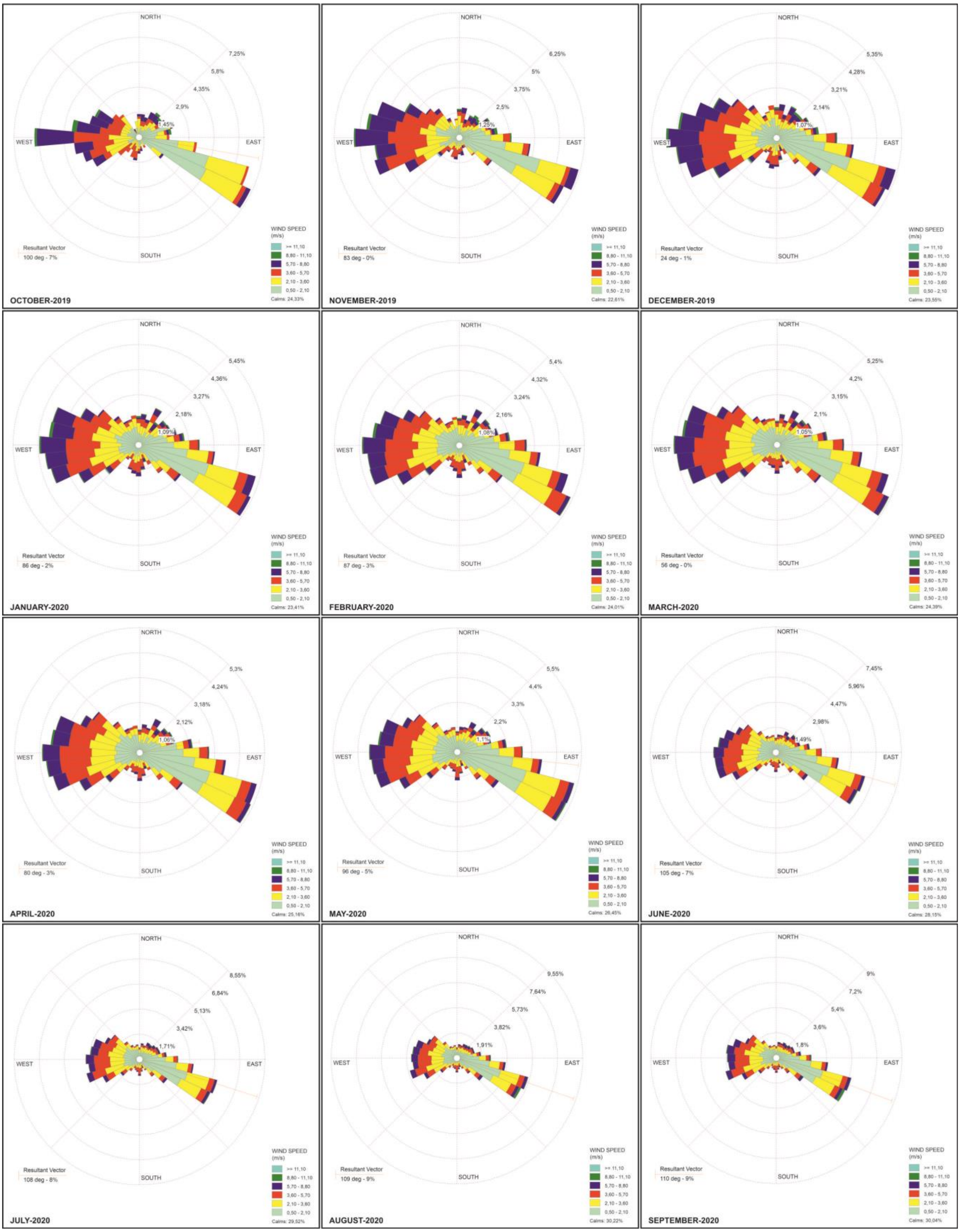

Fig. 10. Wind rose evaluated by month in the Peruvian highlands, October 2019 to September 2020

4. Conclusion

The wind energy potential in the Peruvian highlands, evaluated by the method of the Weibull distribution function of wind speed, where the parameters of shape and annual mean scale were 2.16 and 2.20 m/s every 24 hours, however, by this distribution these parameters evaluated in the afternoons were 5.01 and 4.46 m/s respectively. Consequently, the average wind speed during the 24 hours ranged from 1.11 m/s to 3.34 m/s, while in the afternoons it ranged from 2.92 m/s to 5.45 m/s. Therefore, the wind speed is higher in the afternoons, which can be exploited by low-power wind turbines installed in the residential sector, so that the wind speed throughout the year is not constant, being the wind flow lower in the winter season in some months. Finally, the direction of the average annual wind speed is more significant towards the southeast and on some days towards the west, which would indicate that crosswinds are possibly relatively low.

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