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Wind Characteristics and Wind Energy Potential in Andean Towns in Northern Peru between 2016 and 2020: A Case Study of the City of Chachapoyas

Jesús Rascón *, Wildor Gosgot Angeles, Manuel Oliva-Cruz and Miguel Ángel Barrena Gurbillón

Instituto de Investigación para el Desarrollo Sustentable de Ceja de Selva, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Calle Universitaria N° 304, Chachapoyas 01001, Amazonas, Peru; wildor.gosgot@untrm.edu.pe (W.G.A.); manuel.oliva@untrm.edu.pe (M.O.-C.); miguel.barrena@untrm.edu.pe (M.Á.B.G.)

* Correspondence: jesus.rascon@untrm.edu.pe

Abstract: Currently, climate change and population growth have a significant impact on human beings. Furthermore, these factors are generating a great need for energy to sustain present-day pace of life. For this reason, this research aims to determine the wind potential of the city of Chachapoyas, through the study of wind direction and speed using a wind rose. Data were obtained from the Metrological Station located on the University Campus of the National University Toribio Rodríguez de Mendoza (UNTRM) for developing this diagram. The mentioned station had 15% of missing data, therefore a quality control of the data and multiple imputations was carried out to fill in any missing data. The results obtained show that the winds in this area are mostly weak (from 0 to 3 m/s) with an East-Northeast (ENE) and Northeast (NE) direction for both the studied period and for each year of the period. It has also been determined that there is a difference between the wet and dry seasons in terms of wind frequency. Finally, we conclude that, in the city of Chachapoyas, it is possible to generate wind energy by using low-power vertical axis wind turbines.

Keywords: wind resource; energy potential; renewable energy; wind direction; wind speed; wind speed

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1. Introduction

Currently, both climate variability and climate change cause substantial impacts on the population, especially in rural communities dependent on activities such as agriculture or livestock farming. This puts the energy sovereignty and sustainability of the population at risk, especially in developing countries [1,2]. Such climate changes are potentially destructive events with catastrophic consequences for humanity and ecosystems [3]. Studies reveal that agriculture is likely to be severely affected in Latin America, with significant decreases in yields [4–7]. Thus, it is necessary to adapt to these climate changes for sustainable development [8,9]. One way, is to take advantage of climatic elements to obtain renewable energy for activities such as agriculture, livestock, or domestic purposes [10].

One of the essential climatic elements is wind, defined as "moving air" and described by two characteristics: speed and direction [11]. In order to see these two variables graphically, there is the so-called wind rose, allowing to simultaneously represent the relationship between the characteristics that compose the wind [12–14]. The wind rose is a circular diagram that has marked the directional headings into which the horizon's circumference is divided. The wind rose diagram represents the average wind intensity and wind direction in different sectors into which it divides the horizon circle [14,15]. The speed is expressed in m/s, km/h, knots, etc., and the direction in degrees (°) or the components or headings. The headings are divided into four cardinal directions, North (N), South (S), East (E) and West (W/O); in four lateral or secondary headings; North-East (NE), South-East (SE), South-West (SW) and North-West (NW); and eight collateral bearings or secondary intercardinal directions; North-Northeast (NNE), East-Northeast (ENE), East-Southeast (ESE), South-Southeast (SSE), South-Southwest (SSW), West-Southwest (WSW), West-Northwest (WNW) and North-Northwest (NNW) [16,17].

These data can be obtained through the use of climatological or meteorological stations. These generally use the wind vane and the anemometer to obtain wind direction and wind speed values. In climatological records, they are separately registered; however, to study the general wind behavior, a handy and straightforward statistical table is used to find or verify the relationships between two or more variables [18,19]. Wind radar is currently used to determine the speed and direction in a given area. Radiosondes and pilot balloons are used for wind measurement at height. In order to handle and interpret all these data, statistical treatment and representation of the data in a more straightforward and graphical form becomes essential, which allows us to draw conclusions quickly; the wind rose is, therefore, the simplest method for this analysis [20].

Consequently, this type of statistical analysis of wind directions and wind speed through the wind rose consists of using bar diagrams or extensions going from the center of a circle to a certain point that illustrates the wind direction, the length of each extension will indicate the percentage of time in which the wind was directed in a specific direction [21,22]. It is of great utility as it allows determining the most optimal position of a wind turbine, i.e., in that position where it will receive the most significant amount of wind over time [23]. It is also essential for locating wind turbines in non-uniform terrain [24]; for recognizing the directional variability of the wind regime to which a wind turbine's orientation system must respond [25]; even for determining the orientation of blades and turbines to optimize wind energy production [26,27].

There are two types of wind turbines, horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT), each having advantages and disadvantages. Within HAWTs, their main advantages are: (i) their high efficiency, since the height of the tower allows the wind turbine to have access to strong wind currents [28]; (ii) each blade receives wind power at any point during rotation [29]. On the other hand, its main disadvantages are: (i) the visual impact on the landscape [30]; (ii) the high cost and difficulty of construction and maintenance [31]; (iii) HAWTs require solid constructions to support the weight of the turbines; (iv) the generator, gear train and transformer must be elevated to be installed; (v) in addition to requiring an additional control system to orient the blades towards the wind [32]. As for VAWTs, their significant advantages are: (i) they do not need a blade orientation mechanism, so wind capture is better than in HAWTs by harnessing wind from any direction; (ii) the gear train and transformers are installed at ground level, facilitating their installation and maintenance reducing costs [33]; (iii) their impact on the landscape is low [34]. However, their main disadvantages are: (i) the power is low by capturing winds at soil level, that is a low-speed; (ii) if there are large objects near the wind turbine, they can cause vibrations and stress on the wind turbine components [35].

Chachapoyas is the capital of the Amazonas Department—Peru, so it has grown rapidly in the last ten years [36]. For this reason, it needs more services such as electricity; notably, its strategic location gives it excellent potential for the use of wind energy. Given these reasons, it is necessary to analyze the direction and speed of winds to use wind energy efficiently. This study analyzed the winds between 2016 and 2020 using Wind Roses based on the above considerations. This seeks to prove the pattern of winds during this period and if it remains the same during all the years of study. At the same time, it was analyzed if there are differences in wind speed and direction between the wet and dry seasons. This will help enhance the understanding of the winds in this area, for the potential installation of wind turbines or their potential development in Andean areas.

2. Materials and Methods

2.1. Study Area and City Areas

The high Andean city of Chachapoyas is located in the northern Peruvian Andes (Figure 1). It is located at an altitude of 2338 m a.s.l., with approximately 800 mm of annual precipitation and an average temperature of 15.6 °C. There is a very marked seasonality of rainfall in the Andean areas, with wet and dry seasons. For Chachapoyas, the wet season lasts from October to March and the dry season from April to September [37].

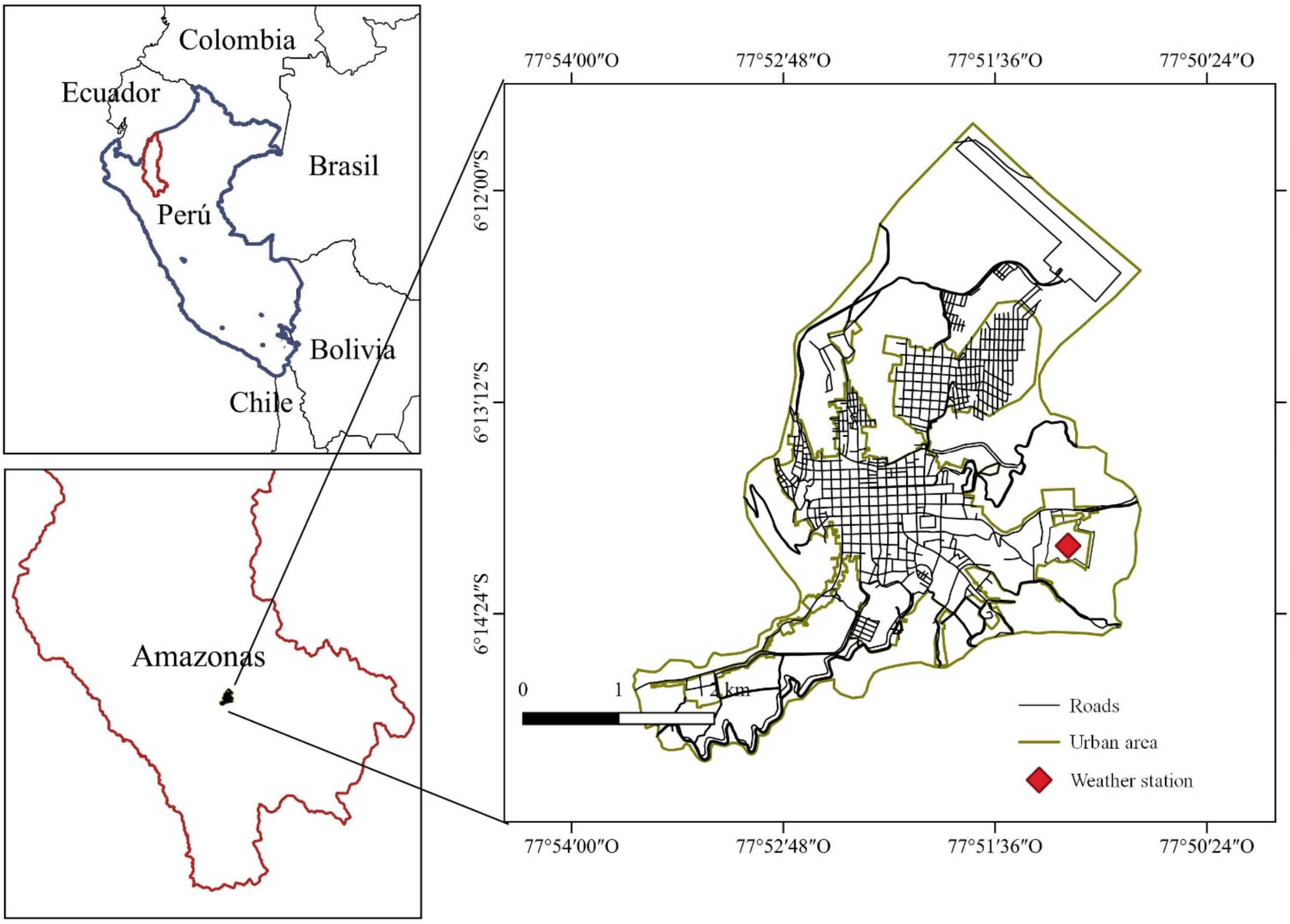

Figure 1. High Andean city of Chachapoyas in the department of Amazonas—Peru.

2.2. Selection of the Period and Weather Station

As a high Andean city, climate studies are scarce due to the lack of a reliable weather station network, which is very common in such cases [38,39]. In the city of Chachapoyas, there are only two meteorological stations. One station is part of the Instituto de Investigación para el Desarrollo Sustentable de Ceja de Selva (INDES-CES) of the UNTRM, and the other belongs to the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI). However, only the INDES-CES station has the necessary equipment to measure wind speed and direction. This equipment is an automatic station, DAVIS Vantage Pro 2 model, located on the campus of the National university Toribio Rodríguez de Mendoza de Amazonas (UNTRM), latitude south 6°14′04″, longitude west 77°51′12″, at an altitude of 2348 m.a.s.l. The anemometer measurements at the station were taken from the standard height of 10 m above the ground level adopted by the World Meteorological Organization. The campus is located at the beginning of a valley, with mountain ranges on both sides. The directions of these mountain ranges are east-west. The data collection period was established in 5 years, guaranteeing optimal representativeness [17].

2.3. Data and Quality Control

The data obtained from the weather station were recorded every hour for the established period, obtaining a total of 43,848 observations for each variable at 10 m height (speed and direction). However, a common occurrence in weather station measurements is missing data due to maintenance, calibration, lack of power, and other causes [40,41]. In this case, there were a total of 6, 762 missing data, accounting for 15.42%. These missing data and the possible errors that the meteorological station may present in the measurement can affect the statistical treatments applied to them to extract information from them [40,41]. Therefore, basic quality control was developed using Microsoft Excel® software. Through a manual review, records of negative wind speeds were identified and discarded, as well as wind directions outside the range of 0° to 360°. Subsequently, a missing data imputation process was carried out using the multiple imputation method with R statistical software version 4.0.4, using the "mice" library [42,43].

Multiple imputation works by creating several versions of the data set. Each version contains different estimates of missing values, which, using a regression model, treat incomplete variables as outcomes and complete variables as predictors. Then, one or more statistical analyses are performed on each complete data set, obtaining standard estimates of imputations and standard errors. Finally, we finish by pooling the estimates and standard errors into a single set of results [44]. Under these conditions, the pooled estimates are unbiased and have correct statistical properties [45]. In addition, multiple imputation solves the problem of minimal standard errors [46].

2.4. Description of Wind Speed and Wind Direction

In order to describe both the speed distributions and the frequencies of wind direction variation, a graphical analysis called "wind rose" was used. Sixteen directions with a range of 22.5° each were considered for their elaboration. Likewise, three wind intervals were established according to the Beaufort Scale: from 0 m/s to 3 m/s (weak winds); from 3 m/s to 7 m/s (moderate winds); from 7 m/s onwards (strong winds) [47]. Using the statistical software R version 4.0.4, using the "openair" library [42,48]. Wind roses were elaborated for the total period, for each year of the period, for each month of the period. With this, whether the wind behavior has a pattern during all years; whether it is suitable to install wind turbines, in such case, which wind turbines may be the best based on the wind speed; or if there are different behavioral characteristics between the wet and the dry season.

3. Results and Discussion

3.1. Wind Behavior in the Period 2016–2020

For 2016–2020, the most predominant winds are from the East-Northeast (ENE) direction with 20% of the data, the Northeast (NE) direction with approximately 12.5% of the data. Weak winds are most common in wind speed, followed by moderate and strong winds (Figure 2).

Regarding the wind distribution pattern, the predominant winds throughout all the evaluated years are ENE and NE directions (Figure 3).

In the case of Chachapoyas, both wind direction and wind speed are mainly due to the area's topography, as the area is located in a "mountain corridor" with an east-west orientation. The geographical peculiarities and the flow of the atmosphere greatly influence the wind direction and can cause the wind direction to fluctuate frequently [49,50]. Usually, the wind direction pattern will follow a region's mountain ranges [51]. To this, we must add the influence of the wind channeling effect, because the station is situated at the beginning of a valley [52]. Also, the influence of factors such as pressure gradients caused by altitudinal differences, or thermal forcing by local heating-cooling of airflows going up and down nearby mountain slopes [53,54].

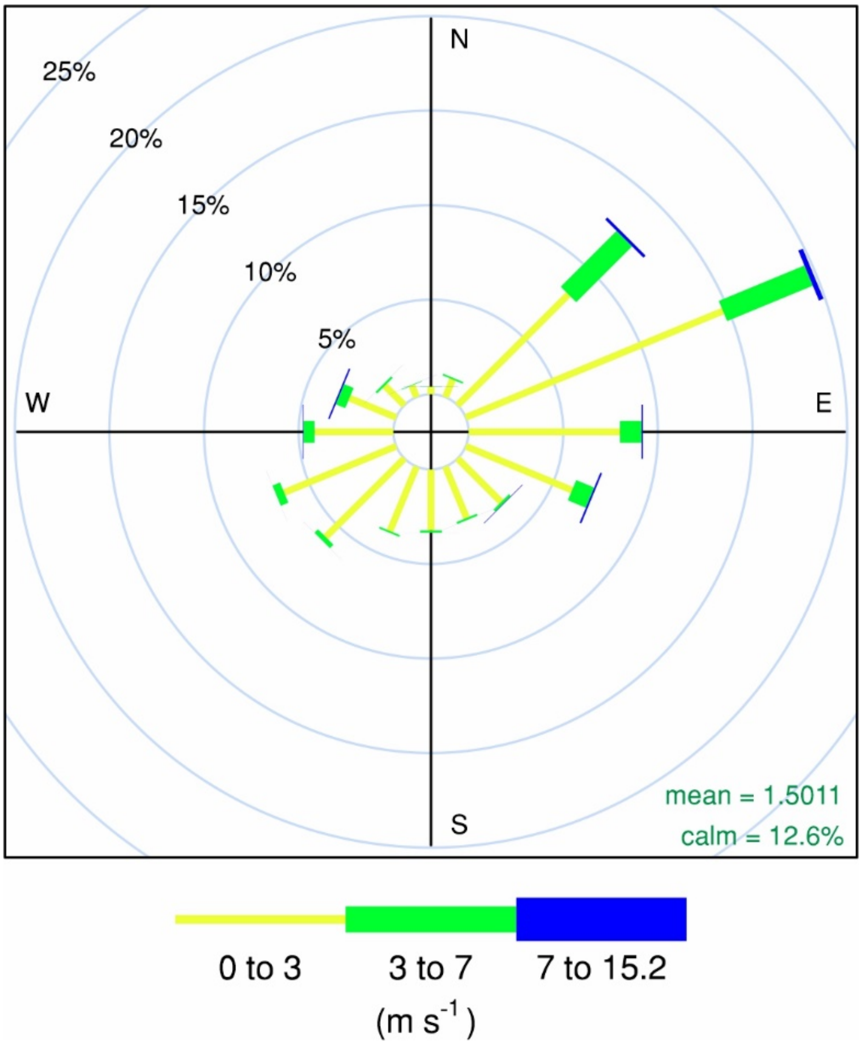

Figure 2. Wind rose for the period 2016–2020.

It should be added that wind direction also varies according to location since atmospheric circulation depends on the forces generated by the atmospheric pressure gradient due to temperature differences. This circulation is also subject to different forces that influence the vector components of the wind at a global level. One of the most important is the Coriolis effect, which generates the deviation of the wind trajectory due to the earth's rotation [55]. However, the wind behavior found in the city of Chachapoyas, in terms of wind speed, is very similar to those found in other South American cities located at more than 2000 m.a.s.l., such as Bogota (Colombia), Quito (Ecuador), and La Paz (Bolivia) [56–58]. These results have also been observed in Asian or North American cities at more than 2000 m.a.s.l. such as Xining (China) or Texcoco (Mexico), which also reach these speeds [59,60].

3.2. Seasonal Wind Behavior

As mentioned above, the Chachapoyas area has a marked seasonality that depends on rainfall. It has a wet season from October to March and a dry season from April to September [61]. During the wet season, the frequency of winds is lower than in the dry season. The months with the highest wind frequency are June, July and August, which are ideal for wind energy generation (Figure 4). These three months have the same distribution pattern observed in the previous figures.

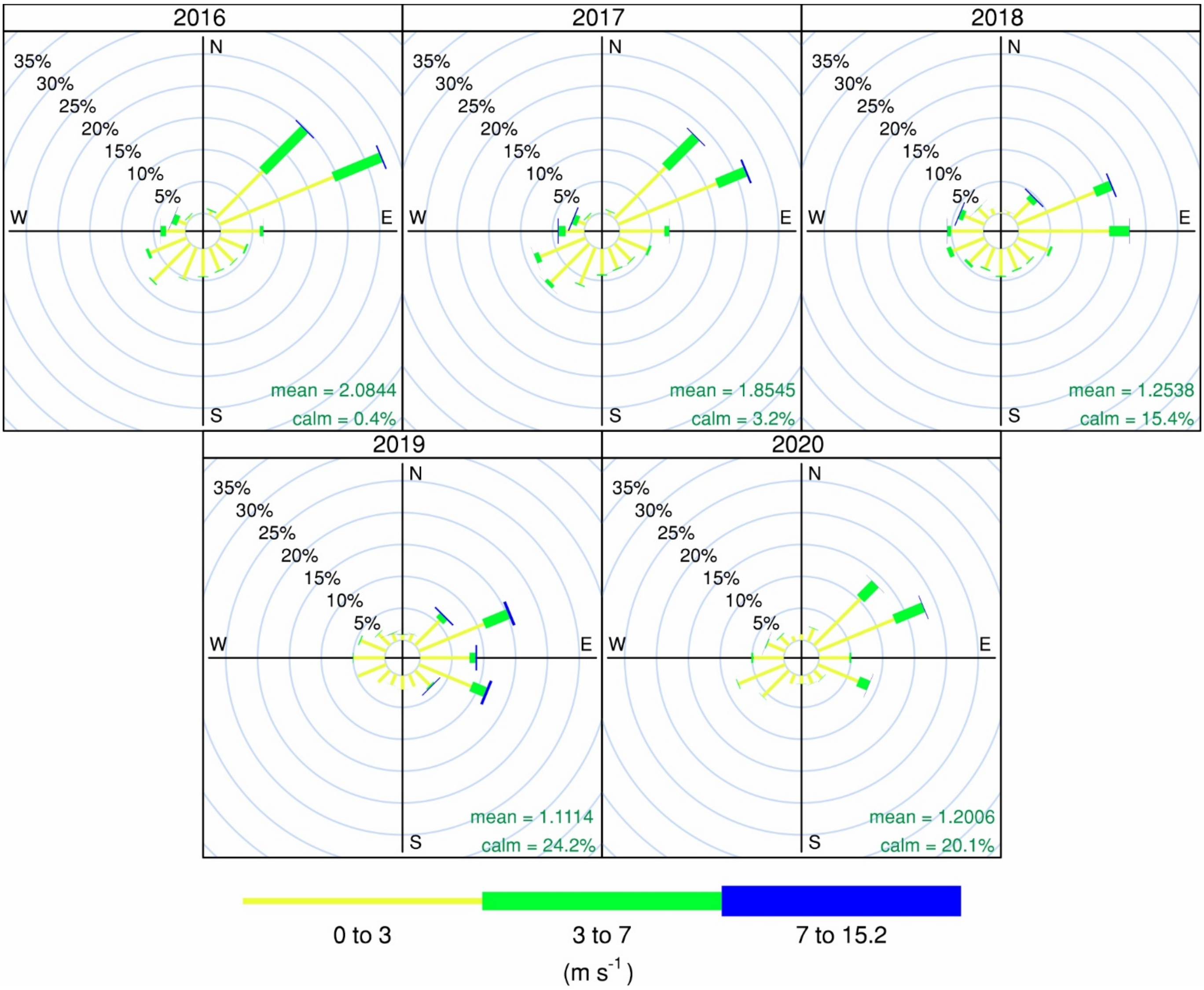

Figure 3. Wind roses of each year for the period 2016–2020.

This distribution of winds in the wet and dry seasons is mainly due to the dependence between precipitation and wind speed [62]. For wind to be generated, the airflow needs to move. This movement is given by the tendency of cold air to go down and warm air to go up [63]. Therefore, these differences in the wet and dry seasons are due to the temperature differences in these seasons and the orography of the area [64]. Accordingly, there is a decrease in wind speed in the wet season. This behavior was also observed in other areas with wet and dry seasons, such as Mexico or Nigeria [65,66]. Therefore, the seasonality of an area is a factor to take into account when conducting this type of research, either to study the distribution of pollutants or particulate matter (PM 2.5 and PM 10) or to determine the suitability when installing wind turbines [67–69].

3.3. Wind Turbines Based on Wind Speed

Once the wind speed and distribution patterns are identified (Figures 2–4), it is possible to evaluate the potential wind energy potential in the city of Chachapoyas. The use of tools such as the wind rose, which determines the patterns of wind speeds and direction, plays a fundamental role in the optimal and adequate positioning of wind turbines and even of a wind power farm [21,22,70]. In addition to the importance of wind systems' design, knowing the wind direction enables the wind turbine to have a permanent rotational movement by positioning itself facing the wind [71]. This information also allows for determining the operating and maintenance costs of the installed systems.

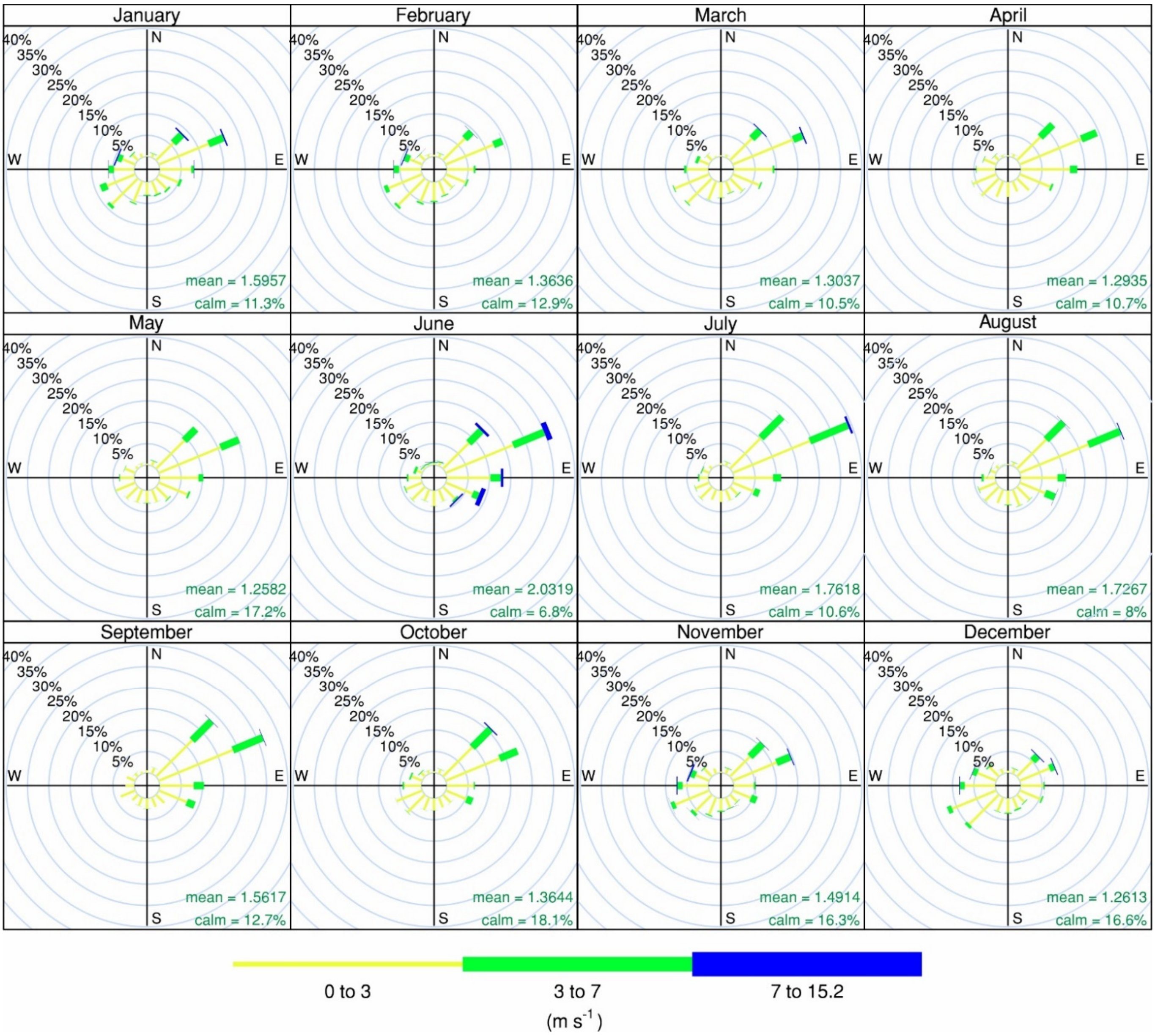

Figure 4. Wind roses for each of the months in the period 2016–2020.

In Chachapoyas, weak winds (from 0 to 3 m/s) predominate in ENE and NE directions. This factor is of great importance since usually, all wind turbines need a start-up speed, usually between 3 and 4 m/s, especially in the typical horizontal models. VAWTs are ideal, as they do not require a start-up speed or have a multiplication system [72,73]. At the same time, since the research was developed in a low-resource area, VAWTs, are much cheaper to install and maintain [35].

Within WATs, we can highlight two types. These are the Savonius and Darreius wind turbines. These models are vertical, somewhat less efficient than horizontal ones, but operate at low and moderate wind speeds, without the need for large surfaces and without generating noise pollution [74–78]. Their use would be ideal on a small scale, without the need for strategic sites, which are often scarce [79–81]. The energy generated by these wind turbines can be used for water pumps, signal lights, or as a supplement to the electrical network, reducing the expense of power upgrades for a single building [82,83].

On the other hand, the city of Chachapoyas is located in the department of Amazonas, which is the department with the most significant number of Conservation Areas in Peru, where the aim is to conserve the tremendous biological and climatic diversity [84–86]. In many of these areas, many activities are developed, such as livestock, agriculture or tourism, under a sustainable approach and where energy requirements are not very high [87]. Therefore, applying this technology in these areas is ideal for taking advantage of the energy potential in them, especially wind energy.

4. Conclusions

For the period studied, the city of Chachapoyas has a prevalence of low to moderate winds with ENE and NE directions. This pattern is maintained in each of the years separately. Likewise, this pattern is kept during the dry season, especially in June, July, and August. At the same time, the wind speed was generally weak, although at times, especially during the dry season, it exceeded 7 m/s.

The variables studied influence the type of structures to be built in this area and the type of wind turbines installed, especially if sustainable development is to be achieved in the area. All in all, it can be affirmed that the city of Chachapoyas has potential for wind energy generation through the installation of low-power wind turbines. VAWTs of the Savonius and Darreius types are the most recommended. The energy generated can be used to supply activities that require small energy consumption or complement the electricity network, reducing the expenses of families or institutions. Nevertheless, wind speeds found in Chachapoyas do not support the establishment of a wind power park.

Finally, this research would be ideal for replication in areas with high biological and climatic diversity, but with low economic resources, looking for sustainable development. This makes VAWTs ideal for these areas, given their low visual impact and low installation and maintenance costs. However, more research is needed on the potential use of renewable energies, such as wind energy, in these areas.

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