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ABSTRACT

The following study focuses on a spatial analysis of the Colombian territory with Geographic Information Systems (GIS) tools, determining probabilistically the key points with the highest wind energy potential, using a fitted probability distribution function (PBDF), this information was captured along 10 years, by meteorological stations of the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM), installed in a large part of the country. The wind velocity and density data were used to generate the cartography records for the identification of the areas of the country with the most wind potential, locating the areas of the country with high energy potential such as the region of La Guajira and Nudo de Los Pastos. This study provides an estimation of the wind energy capacity of Colombia, arriving to the conclusion that due to its geographical characteristics the country could be able to satisfy its energy demand with the use of wind turbines.

Keywords: Wind energy, Geographic analysis, Energetic potential, Wind speed, Wind density, Geographic information system (SIG).

RESUMEN

El siguiente estudio se enfoca en un análisis espacial del territorio colombiano con herramientas de Sistemas de Información Geográfica (SIG), determinando probabilísticamente los puntos clave con el mayor potencial de energía eólica, utilizando una función de distribución de probabilidad

ajustada (PBDF), esta información fue capturada a lo largo de 10 años , por estaciones meteorológicas del Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), instaladas en gran parte del país. Los datos de velocidad y densidad del viento se utilizaron para generar los registros de cartografía para la identificación de las áreas del país con mayor potencial eólico, ubicando las áreas del país con alto potencial energético, como la región de La Guajira y Nudo de Los Pastos . Este estudio proporciona una estimación de la capacidad de energía eólica de Colombia, llegando a la conclusión de que debido a sus características geográficas, el país podría satisfacer su demanda de energía con el uso de turbinas eólicas.

Palabras clave: Energía eólica, Análisis geográfico, Potencial energético, Velocidad del viento, Densidad del viento, Sistema de información geográfica (SIG).

INTRODUCTION

The use of renewable energy has experienced an important worldwide growth in recent decades, the need to reduce dependence on fossil fuels, lessen environmental impact and seek sustainable development, has massified this type of energy production. The use of renewable energies, in addition to reducing the negative environmental impacts caused by the usage of fossil fuels, can become an economic growth enhancer (Bhattacharya et al, 2016, Albadan-Molano, D., Salamanca-Céspedes, J., & Gallego-Torres, A. 2018, Albadan Molano, D. E., and Salamanca Céspedes, J. E., 2019) demonstrating a directly proportional and long-term relationship between economic growth and renewable energies. In this industry there is a growing interest in investment (McCarthy, J., and Thatcher, J., 2019). Entities such as the World Bank invite countries to implement clean energy projects in their territories and the developing countries are encouraged to implement this type of program and make significant investments in this ambit.

Colombia has important natural resources in its territory; because of its geography and hydrography also has high energy potential, 68% of the power generation comes from hydroelectric plants, 18% from natural gas and 10% from geothermal energy (Norton R., 2017), hydroelectric power has an attractive profitability; it has been estimated from the growth of renewable energy in the country in recent years that large-scale wind and geothermal energy are profitable and ecofriendly, therefore, renewable energy has been able to compete with the prices of the hydroelectric industry (United Nations, 2016), with an electricity price of 35 USD kilowatt-hour (KWh), Colombia is the second country in Latin America in energy consumption by GDP points (Pinilla, E., 2017, Salamanca, 2017).

Recently, the growth of the renewable energy industry in Colombia has been considerable, the country has the challenge of generating greater investment, research and policies that support this industry as is proposed by Law 1715 of 2014, that has as the objective to promote the development and use of renewable energy, this is undoubtedly a great step for the country but at the same time a substantial challenge, Colombia has huge potential for the installation of wind farms, it is estimated that the region de la Guajira has the capacity to generate 21,000 MW sufficient to supply the national energy demand (Pinilla, E., 2017). Colombia, in the field of wind technologies, is a territory to study due to its particular surface roughness, climate, wind randomness, and other features, which implies a specific PBDF and **Ω** for this wind behavior; the need arises to research the geographical and climatic characteristics of the country, to determine its viability and wind potential, and this is the main proposal of this work, which will have as main objective to generate a spatial analysis and an accurately PBDF, determining the areas of the country with the most probable advantages to installing wind farms.

REGION OF ANALYSIS

Colombia has an area of 1'240,192km^2, with near to 50'000,000 habitats, located in the equatorial belt see figure 1, between the Andes mountains, with a great variety of thermal floors, a climate marked by two seasons, the dry season between the months of January, February, July and August and the rainy season located in March-June and September-December, the climate conditions can go from dry to tropical arid, at high altitudes the temperature can be reached 12 ° C while at low altitudes on average it can be between 19 ° C - 25 ° C.

Colombia is strongly affected by the El Niño-Southern Oscillation, generating droughts resulting in large losses in economic sectors of the country, experienced last time in the period 2015-2016, being one of the strongest in the

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country's history, this climatic phenomenon raised the risk of an energy crisis; acknowledging this conditions, the country has the challenge of developing the sector of non-conventional renewable energies and take advantage of the energy capacity given by the favorable geographical conditions of the country. This information about the Colombian features will give an intuition about the relatively broad range of values in **Ω** due to the wind flow process is characterized by a large number of variables which interact with each other simultaneously in a non-linear dynamic (Hernandez et al, 2015).

WIND SPEED DATA IN COLOMBIA

The IDEAM together with other Colombian institutions has 5840 functional stations installed at the date of preparation of this research, which is distributed mainly in the north and center of the country. For the realization of the wind speed map, the IDEAM estimated the monthly and annual averages of the speed and the calculated values were interpolated, obtaining estimates for the other points distributed throughout the country, the coefficient of wind speed asymmetry was calculated using GIS software Based on regional numerical modeling with WRF (Weather Research & Forecasting) with a spatial resolution of km, the boundary conditions for modeling were defined by the IDEAM using the CFSR (Climate System Forecast Reanalysis) model. The results of the wind information layer was categorized into 13 ranges ranging from 0 to 15 m/s, the final data was validated by IDEAM quality controls.

In this way the results of this research are supported by the use of data of IDEAM, having measures from 2000-2010, which allows great precision in the calculations made in this research. It is proposed to determine the areas of the country with the greatest potential for wind energy generation.

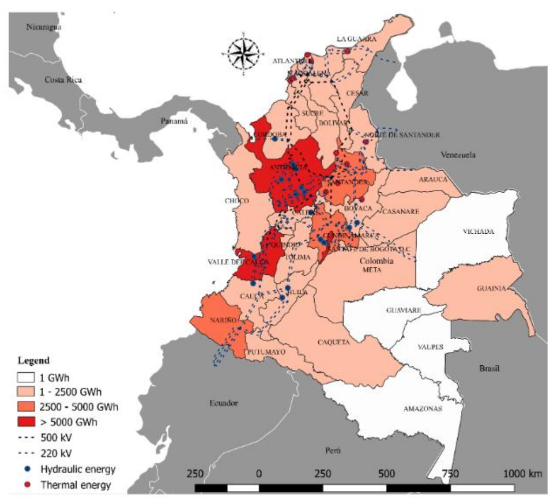

Figure 1. Energy consumption and transmission lines map.Made with data of the Comisión de Regulación de Energía y Gas (CREG)

The highest energetic consumption is given in the main cities see figure 1; Bogotá, Medellín and Cali. Antioquia and Valle del Cauca are the departments with the highest energy consumption by its industrial activities followed by Nariño, Cundinamarca and Santander departments, regarding national transmission lines, this is geographically distributed between the mountain ranges and the distribution substations are concentrated in the country's center.

MATERIALS AND METHODS

Information was requested to the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM by its acronyms in Spanish) of air density and wind speed, this institute has meteorological stations in a large part of the Colombian territory which gives reliability to carry out this study with the data supplied, information was obtained on annual air density for the period 2000-2010 and wind speed at 100 meters high during the period 2000-2010.

The IDEAM calculated the wind speed and air density by estimating the monthly and annual averages of the physical parameters captured by the meteorological stations and using an advanced geostatistical technique such as the Kriging technique, the density and velocity map is constructed. This technique is also ideal to address research problems due to the reliability of its estimation, an empirical semivariogram is determined by calculating the distance between the location of the values to be interpolated:

$$2\gamma(h) = Var(Z(s+h) - Z(s)) \quad (1)$$

Where $Z(s)$is the value of the study variable on the ubications$s$, and $h = s_i - s_j$ The semivariogram model determines the spatial autocorrelation of the values associated with the stations; the *Kriging technique* is based on this model since the objective of this method is to estimate the values for the locations in the space where measures were not made, the prediction of the Kriging is obtained from a theoretical model of semivariogram and its reliability will be subject to the adjustment of the semivariogram to a theoretical model.

$$Z(s_0) = \sum_{i=1}^{n} \lambda_i Z(s_i) \quad (2)$$

In this Kriging formula: n is the number of points for the prediction, are the weights assigned to each measurement, $Z(s_i)$is the observed value of the study variable is a

ubication $s_i$and $Z(s_0)$is the observed value of the variable on the locations_0.
With unbiasedness restriction:

$$\sum_{i=1}^{n} \lambda_i = 1 \quad (3)$$

The IDEAM, based on the Weather Research and Forecasting model, estimated the asymmetry coefficient for wind speed at a spatial resolution of $20km^{□}$. In the preprocessing stage, interpolations were made with terrestrial data extracted from the MODIS satellite and from the United States Geological Survey. The result of the interpolation is a raster layer of 20 km x 20 km, in the post-processing stage the calculation of the wind energy was made using the Weibull function theoretical frame, the power P is the kinetic energy per unit of time (Boumassata, A. and Abderraouf, D., 2014). The extractable power Pe, is the mechanical energy given by the wind propeller per unit of time; for its analysis, the air through a theoretical wind tunnel is studied, applying the momentum theory as well as Bernoulli's equation (Okulov, Valery et al, 2013), the following equation it's obtained:

$$Pe = 2\rho \bar{v}_m^3 Aa(a-1)^2 \quad (4)$$

Where m is the Air mass, ρ is the Air density,$V_m$is the wind speed, is the transversal area by the wind flows and a is the interference coefficient which is the relation between both the velocities: before and after crossing the wind propeller. The Weibull distribution is in general used to measure the certainty about the occurrence of wind speed value (Weibull, W., 1951), considering the **Ω** features, the Weibull probability distribution function is defined as:

$$f(\bar{v}_m, k, \lambda) = \frac{k}{\lambda}\left(\frac{\bar{v}_m}{\lambda}\right)^{k-1} e^{-\left(\frac{\bar{v}_m}{\lambda}\right)^k} \quad (5)$$

The data analysis is focused on fit the shape factor $k$and scale factor λ, to ensure the accuracy of the probability distribution function using criteria as maximum likelihood (Carrillo, C., et al., 2014).

RESULTS

The maps of wind speed and density were made with information based on the IDEAM's data whose meteorological stations collected data from 2000 to 2010.

These maps are of key importance because they allow us to spatialize the characteristics of the wind and this

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information is the starting point for the planning and realization of renewable energy projects in Colombia's wind farms. By having the IDEAM hundreds of stations installed in the country and treating these data through a quality protocol, these maps may be used to characterize areas of the country with high wind power potential as a first approximation of study areas.

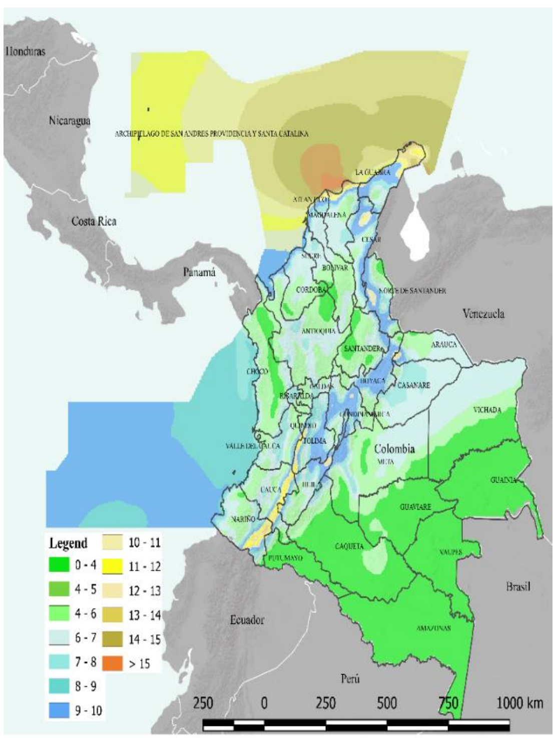

Figure 2. Wind speed map 2000 - 2010

Elaborated with IDEAM's data

The average wind in Colombia since 2000 to 2010 reaches its maximum value of 15 m/s in the coastal area of the Caribbean sea, geographically the La Guajira region has the fastest wind from 12 m/s to 13 m/s, the east mountain range is characterized by wind between 6m/s to 9m/s, the results show the Colombian regions with high wind speed, this region begins in the Nudo de Los Pastos crossing the Nariño and Cauca departments and having wind speeds between 10 m/s and 13 m/s.

Speed m/s	**Location**	**Power Density** $(\frac{W}{m^2}$
6 - 7	Borde cordillera oriental y central	72,32
8 -9	Cima de la cordillera oriental	146,59
10 -12	Nudo de los Pastos	322,25
12 - 13	Guajira	529,88
13 - 15	Mar Caribe	783,56

Table 1. Power Density by location.

The data shown in the table 1 are given by the extractable power modeling equation for a wind turbine; whose power density is the extractable power per square meter, has been calculated this power density for wind turbines with blade length for 5, 15 and 30 meters: the results are shown in Table 2.

Location - Length	**10m**	**15m** W/m^2	**30m** W/m^2
Eastern and central cordillera edge	22720,19	51120,44	204481,75
Top of the eastern ridge	46053,59	103620,57	414482,30
Nudo de los Pastos	101236,25	227781,57	911126,27
Guajira	166465,14	374546,57	1498186,27
Caribbean sea	246163,42	553867,69	2215470,77

Table 2. Power density for different blades lengths and locations.

The eolic resource in the major part of the Colombian territory is not high but there is some locations as La Guajira, much of the Caribbean natural region and Nudo de los Pastos, with high wind speed and air density that make them profitable options with usable resources for the generation and supply wind power. Its known that the La Guajira has the fastest wind speed, **Figure 1** shows the national transmission system which does not cover the department of La Guajira, contrasting with the departments of Atlántico and Magdalena, which have the best infrastructure in the Caribbean area of the country, it is interesting to see that the transmission network in the department of Nariño has a similar route than the route of the zone of wind speed between 10 and 12 m / s that cross the departments of Nariño, Cauca and Valle del Cauca..

CONCLUSIONS

The development of electricity generation through clean and economic energy should be a central part of the country's expansion plans, although there are already some signs of their implementation, it is necessary to increase the capacity of energy sufficiency from clean energy.

It’s necessary to create mechanisms that allow the current interconnected system, the transmission system, to facilitate the incorporation of wind power plants in strategic places such as the Nudo de Los Pastos, La Guajira and The Caribbean Sea. Energy consumption has been increasing exponentially, in the main and medium-sized cities of the country, so in Colombia, the supply of electrical energy must be diversified in order to increasingly depend on renewable energies that guarantee long-term sustainability.

The current production of electrical energy is concentrated in areas of high economic activity, where there is the largest amount of population; this is a remarkable opportunity to increase electrical energy sources in these territories.

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