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SIMULATION OF ELECTRIC ENERGY POTENTIAL FROM WIND SPEED IN THE SAN ANDRÉS ISLAND

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ABSTRACT

In this work, the wind resource of the islands of San Andrés was studied during the years 2011 - 2012 to determine its electric energy potential. Wind speed and direction taken from the mereology station of IDEAM located at the Gustavo Rojas Pinilla airport were used for modeling the electric energy obtained from different types of wind turbines and their location height. The maximum energy obtained was 5496.6 MWh/year using a wind turbine of 3.75 MW power. However, the economic analysis indicated that Neg Micon's 2.75 MW wind turbine has the lowest generation cost of US$ 0.04/kWh and an energy production of 4,919.1 MWh/year. According to this, for a sale price of US$ 0.14 /kWh, the net present value (NPV) would be US$ 5,928,594.9 the internal rate of return (IRR) of 16%, and the investment recovery time (TRI) of almost 4.1 years, making the wind project attractive for investors.

Keywords: wind energy potential, turbine, economic analysis.

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INTRODUCTION

The geographical and technological energy diversification is a key strategy to achieve an economically and environmentally viable energy supply. Renewable energies are contributing to this diversification, as well as reducing greenhouse gas emissions, to consider the electric power production techniques one of the main contributors to its generation. According to key world energy statics in its study about the evolution of the accumulated world consumption of primary energies, fossil fuels such as coal, natural gas, and oil, continue to be the main primary contributors of energy worldwide [1]. In this way, the scientific community has focused its attention on new investigations about clean and sustainable energy sources, standing solar and wind energy [2, 3]. According to the Global Wind Report [4] until the end of 2020, the worldwide capacity to obtain electrical energy from wind sources is 743 GW.

The international wind industry has reached great maturity and continues its expansion due to the upward and unstoppable spiral of fossil fuel prices, and the growing recognition by the world scientific community as well as political, economic, and social sectors that global warming will become irreversible if actions to protect the environment are not multiplied. For its part, in Colombia, the wind energy industry has had an incipient development with an installed capacity of just 19.5 MW represented by Jepirachi Park, in La Guajira [5]. The explanation seems to be that these projects are surrounded by great uncertainties that range from the behavior of the winds to the prices of electricity; in addition, they require large initial investments, so when they are valued based on the traditional discounted cash flow methods, the financial non-viability of the project is concluded [6]. Therefore, a mathematical model and economic study are recommended before the installation of a wind park [7, 8, 9]. For that reason, in this work, a study of the wind source in the San Andrés islands and its potential to produce electricity for the demand in this territory has been presented. The electrical energy produced by several wind turbines was simulated, in addition, through different economic parameters, the economic viability of the implementation of this power generation strategy was determined.

MATERIALS

The data on temperature, relative humidity, wind speed, and direction were obtained from reports from the Institute of Hydrology, Meteorology, and Environmental Studies in Colombia (IDEAM). Microsoft Excel® was used as a tool to process the information, extrapolate the wind speed data at different heights, obtain the parameters of the Weibull distribution, and calculate areas under the curve.

Modeling of Wind Energy Potential in San Andrés Island for Electric Generation

The density of wind power $\bar{P}$ for the different heights that describe the wind profile for each selected year was calculated by equation 1 [10]:

$$\bar{P} = \int_0^{\infty} \frac{1}{2} \rho v^3 F(v) dv \qquad (1)$$

where $F(v)$ is the Weibull statistical probability distribution, v is the wind speed and ρ is the air density.

The air density was determined as a function of temperature, pressure, and humidity, by using the below equation (2) [11].

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$$\rho = \frac{1}{T}\left[\frac{P}{R_0} - \emptyset\, Pw\left(\frac{1}{R_0} - \frac{1}{R_W}\right)\right] \quad (2)$$

where P and Pw are the barometric and vapor pressure (Pa) respectively, $\emptyset$ is the relative humidity (range 0 – 1), T is the temperature of the environment (K), R_0 and R_W are the specific heat constant of dry air (287.85 J/kg K) and water vapor (461.5 J/kg K) respectively.

San Andrés Island is located only one meter above sea level, so the pressure is assumed to be 101.325 Pa and it will remain unchanged. Antoine equation (3) was used to calculate the vapor pressure Pw:

$$\ln P_W = A - BT + C \quad (3)$$

where T is the temperature (K) and A, B, and C are constants and its corresponding values are 16.2620, 3799.89, and 226.35.

Extrapolation of Wind Speed with Height

The wind speed V_Z at a height Z was calculated by

$$V_Z = \frac{V_{Ref} \ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_{Ref}}{Z_0}\right)} \quad (4)$$

where V_{Ref} is the known wind speed at a height Z_{Ref} (generally 10 m) and Z_0 is the roughness length constant and this depends on the type of terrain [12].

Determination of the Parameters of the Weibull Equation

The Weibull function estimates the asymmetry of the probability density distribution that is characterized by two parameters, a scale parameter (β) and a dimensionless shape parameter (α). The Weibull probability density function is given by [13]:

$$F(v) = \frac{\alpha}{\beta}\left(\frac{v}{\beta}\right)^{\alpha-1} \times e^{-\left(\frac{v}{\beta}\right)^{\alpha}} \quad (5)$$

where $F(v)$ represents the statistical probability of the occurrence of a determined wind speed (v). The β and α parameters were calculated by using the Weibull cumulative distribution function [14], defined by equation (6).

$$W(V) = 1 - e^{\left(\frac{v}{\beta}\right)^{\alpha}} \quad (6)$$

Weibull accumulative distribution function $W(V)$ calculates the probability that the wind speed is equal to or less than V. The empirical cumulative probability is represented by the following expression:

$$W(v) = \frac{\text{number of order}}{\text{total number of data+1}} \quad (7)$$

Determination of Two-Component Weibull Mixture Distribution Parameters from Wind Speed Data

An alternative is presented to determine the two-component Weibull mixture distribution given by equation (8), it is used to compare different probability functions and determine which one fits the best.

$$F(v) = x\left[\frac{\alpha_1}{\beta_1}\left(\frac{v}{\beta_1}\right)^{\alpha_1-1} e^{\left(\frac{v}{\beta_1}\right)^{\alpha_1}}\right] + (1-x)\left[\frac{\alpha_2}{\beta_2}\left(\frac{v}{\beta_2}\right)^{\alpha_2-1} e^{\left(\frac{v}{\beta_2}\right)^{\alpha_2}}\right] \quad (8)$$

where α_1 and α_2 are adimensional parameters, β_1 and β_2 are scale parameters (m/s), and x is the mixing parameter (range from 0 to 1).

Simulation of Energy Produced by Different Types of Wind Turbines

Annual power generation was simulated at different heights by using different wind turbines with various nominal power using the following equation [15]:

$$E = N_h \int_{u_m}^{u_M} g(v) \times F(v) du \quad (9)$$

where E is the annual energy produced (MWh/year), N_h is the number of hours per year, $g(u)$ is the turbine power curve that represents the power generated by different wind speeds, u_M and u_m are the values of the connection and cutting speed of the turbine (m/s).

Analysis of the Economic Feasibility

The cost-benefit analysis was conducted to determine the economic feasibility of a wind turbine installation on San Andrés Island. The power of the wind turbine was selected by estimating the cost of the kWh of energy produced with each of the wind turbines. This cost was calculated by dividing the present value of the costs (equation 10) by the energy produced over the useful life of the wind turbines [16].

$$VPC = I + C_{om}\left[\frac{1+i}{r-i}\right] * \left[1 - \left(\frac{1+i}{1+r}\right)\right] - S\left(\frac{1+i}{1+r}\right)^{n} \quad (10)$$

where I is the initial investment, C_{om} is the operation cost, r is the interest rate, i is the inflation rate, S is the salvage value, and t is the useful lifetime of the turbine.

The economic analysis was carried out considering parameters such as an interest rate of 8.3% (interest rate for 2017 in Colombia according to the World Bank), inflation of 3.3 % (indicator in Colombia in 2017), and a useful life for wind turbines of 20 years. Operation and maintenance costs (CO&M) are equivalent to 25% of the turbine annual cost and the scrap value of 10% of the plant cost [17, 18, and 19]. The initial investment was calculated based on the installation of the wind farm, the price of the turbine represents 76% of the required investment, the electrical connections 9%, the foundations 6%, the land where the turbines will be installed 4% and other expenses such as consultancies, electrical installations, road construction and control systems are equivalent to 5% [20].

Economic Study Based on Profitability Indices

• Net Present Value (*NPV*) is a standard that indicates the profitability of the project, it represents the difference between income and expenses equivalent [21]. The *NPV* is calculated using the equation 11:

$$\mathrm{VPN} = -\mathrm{I} + \left(\mathrm{P_v E_g} - \mathrm{C_{om}}\right)\left[\frac{1+i}{r-i}\right] x \left[1 - \left(\frac{1+i}{1+r}\right)^t\right] + s\left(\frac{1+i}{1+r}\right)^t \quad (11)$$

where P_v represents the sale price of the kWh (US$/kWh) and E_g is the generated energy annually by the wind turbine (kWh).

• Investment recovery time (*TRI*), equation 12, indicates the period from the investment was made until it is recovered through the cash flows generated by the facility wind power installation.

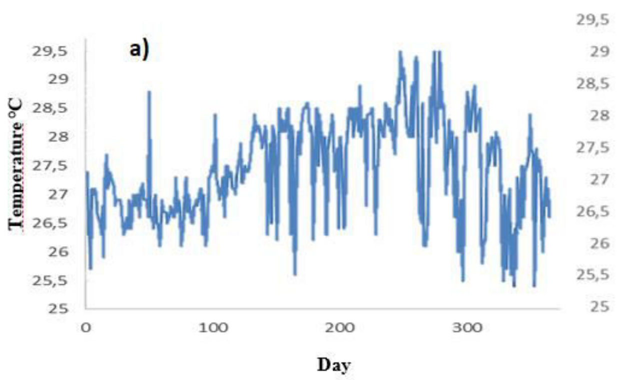
$$TRI = \frac{\log\left[1 - I * \left(\frac{r-i}{P_v * E_g}\right) * \left(\frac{1}{1+i}\right)\right]}{log\left(\frac{1+i}{1+r}\right)} \quad (12)$$

• Internal rate of return (IRR) indicates the value of the interest rate for which the *VPN* is equal to zero.

RESULTS AND DISCUSSIONS

Meteorological Conditions in San Andrés Islands: Temperature, Relative Humidity

Figure-1 shows the daily temperature behavior in San Andres Island during the years 2011 and 2012. According to these graphs, the maximum value recorded for these years was 33 and 29.5 °C respectively, whereas the minimal values were 22.1 and 23.4, respectively.



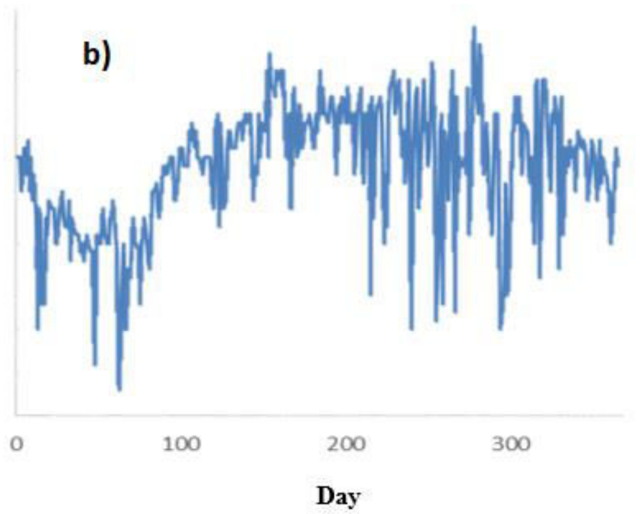


Figure-1. Daily temperature record on San Andrés Island. a). 2011, b). 2012.

Air Density Determination

Air density was calculated through Equation 2; the results obtained are shown in Table-1. These results correspond to the monthly and annual averages of air density. It is possible to observe that the meteorological (weather) conditions in San Andres Island did not change significantly during the two years.

Table-1. Air density in San Andrés Island over the years 2011-2012.

Average air density (kg/m^3)		
Month/Year	**2011**	**2012**
January	1.159	1.154
February	1.157	1.149
March	1.165	1.164
April	1.159	1.168
May	1.145	1.159
June	1.163	1.163
July	1.157	1.159
August	1.149	1.156
September	1.157	1.144
October	1.168	1.159
November	1.157	1.158
December	1.167	1.164
Annual Average	1.158	1.154

Wind Speed and Direction

Figure-2 shows the variation of daily wind speed in San Andres Island during the years 2011 and 2012 respectively at a height of 10 m. The maximum wind

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speed reached was 8.6 and 9.1 m/s for 2011 and 2012, respectively and the minimum value reached was 0.8 and 0.9 m/s. Wind direction is from northeast to east and implementing wind turbines in this area will be an advantage, since it leads to a better use of the wind potential of the wind and facilitates space distribution.

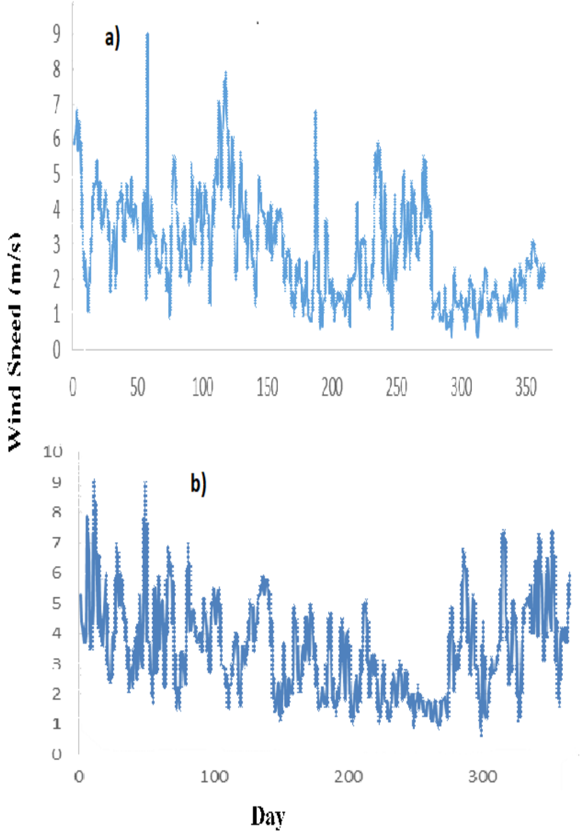

Figure-2. Daily record of wind speed at a height of 10 m on the island of San Andrés. a). 2011, b). 2012.

Estimation of Wind Speed for Different Heights

The wind speed for different heights was determined through equation 4, it was used a roughness length (Z_0) of 1 m. Results of wind speed for 70, 100, and 130 m are presented in Figures 3 and 4 for years 2011 and 2012, respectively.

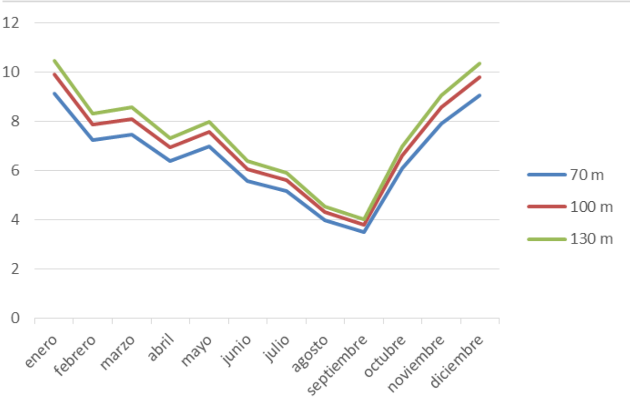

Figure-3. Extrapolation of wind speed to different heights for the area, year 2011.

Modeling the Wind Potential for Electrical Energy Generation in San Andrés Island

Weibull parameters α and β were determined by linear fitting of equation 6. Figure-5 shows the linear adjustment at 10 meters, corresponding to the years 2011 and 2012, respectively. Results obtained present a good fit with an R^2 near to 1.

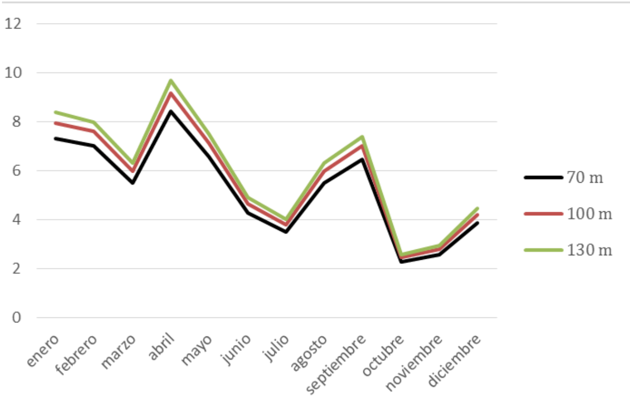

Figure-4. Extrapolation of wind speed to different heights for the area, year 2012.

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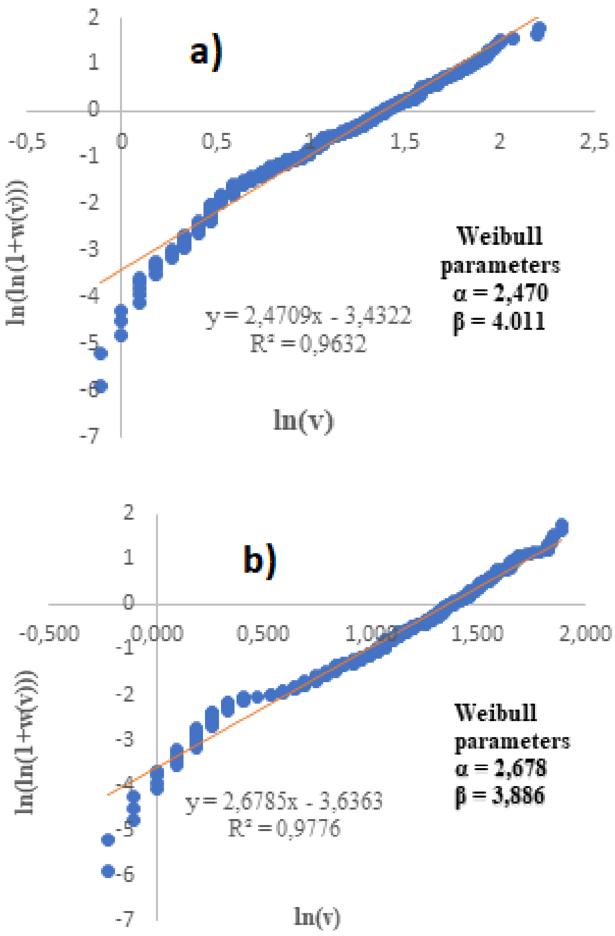
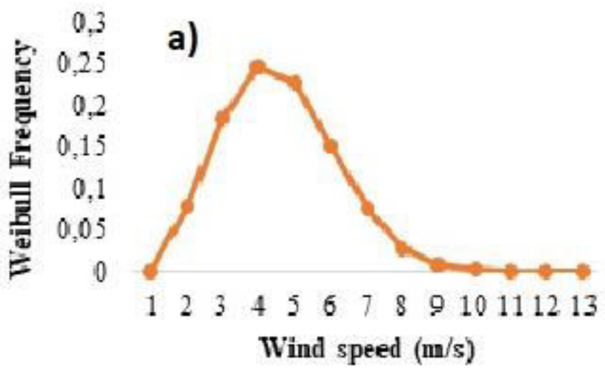


Figure-5. Weibull parameters values, a). year 2011, b). Year 2012.

Taking into account the parameters obtained, the frequency distributions are represented in Figure-6.



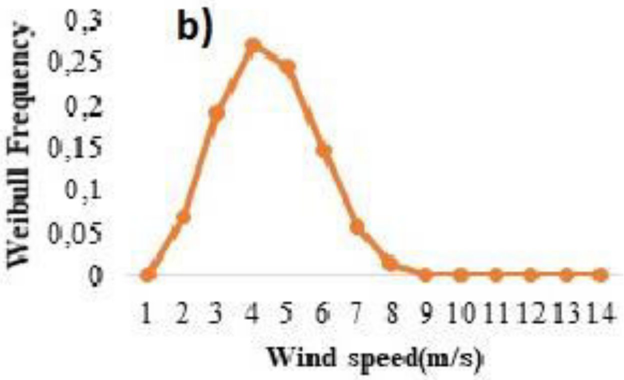


Figure-6. Frequency distribution of Weibull in San Andrés island at 10 m of height, a. year 2011, b. year 2012.

According to Figure-6, the Weibull frequency distributions show the same trend and have pronounced peaks in wind speed between 4 and 6 m/s, according to these results, in San Andrés Island there is a low probability that the wind reaches lower speeds at 2 m / s or greater than 8 m / s at a height of 10 m. It is also noted that there is no velocity probability equal to zero [20].

Simulation of the Electrical Energy Production by Using Different Types of Turbines

The wind turbine brands selected for this study were Neg Micon and Vesta. Figure-7 represents the power curves of the selected wind turbines; other specifications of each turbine are presented in Table-2.

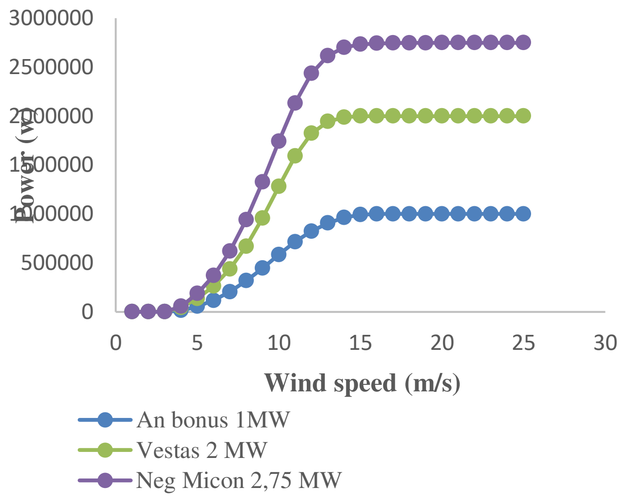


Figure-7. Power curves of the wind turbines.

The annual energy that could be generated on the San Andrés Island by using wind turbines was determined through equation 10. Table-2 shows the energy produced for a year using the Vestas v90/2000 kW wind turbine.

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Table-2. Determination of factor [8760 · g (v) ·F (v)] for different wind speeds (Turbine Vestas a 130 m).

Wind speed	Turbine Potency g(v) kW	Weibull Distribution F(v)	Energy Produced for the year (kW/h)
0	0	0,000000	0
1	0	0,019648	0
2	0	0,052511	0
3	0	0,088306	0
4	50	0,118939	48467,63643
5	160	0,137773	179656,2978
6	330	0,141241	379868,8137
7	600	0,129829	634864,7343
8	880	0,107647	772044,3131
9	1200	0,080706	789308,4545
10	1630	0,054738	727173,2762
11	1900	0,033563	519722,1897
12	1980	0,018579	299801,5159
13	2000	0,009267	151058,8279
14	2000	0,004157	67761,75027
15	2000	0,001673	27273,09417
16	2000	0,000603	9825,850997
17	2000	0,000194	3161,112909
18	2000	0,000056	905,8959242
19	2000	0,000014	230,6824346
20	2000	0,000003	52,06900178
21	2000	0,000001	10,39222085
22	2000	0,000000	1,829557006
23	2000	0,000000	0,283430259
24	2000	0,000000	0,038545605
25	2000	0,000000	0,004591028

Figures 8 and 9 show the energy produced at different wind speeds using three types of turbines for the years 2011 and 2012, respectively. To determine the area under each curve, the Simpson 3/8 method was used. The integration limits for each wind turbine, are the lower limit given by the connection speed (u_M) and the upper limit given by the Cut-off speed data (u_m).

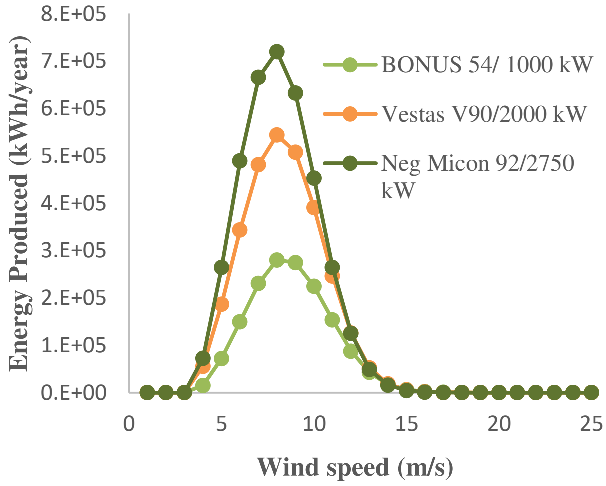

Figure-8. Energy was produced at different wind speeds using three different turbines, in the year 2011.

The area under the curve of Figures 8 and 9 is the amount of electrical energy generated in a year at different heights and three types of turbines for the years 2011 and 2012 as shown in Figures 10 and 11.

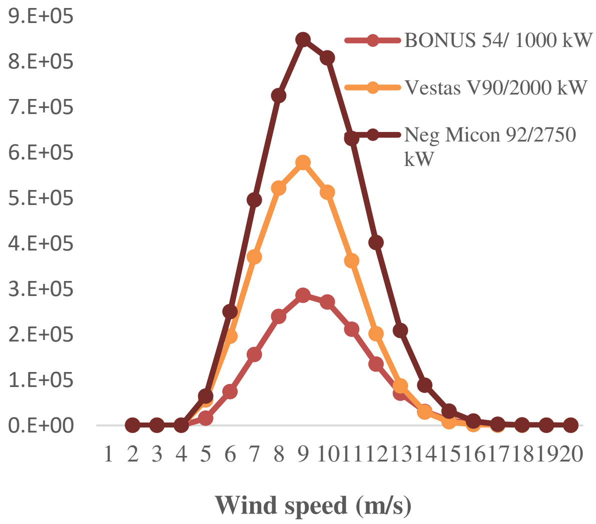

Figure-9. Energy was produced at different wind speeds using three different turbines, in the year 2012.

The area under the curve of Figures 8 and 9 is the amount of electrical energy generated in a year at different heights and three types of turbines for the years 2011 and 2012 as shown in Figures 10 and 11.

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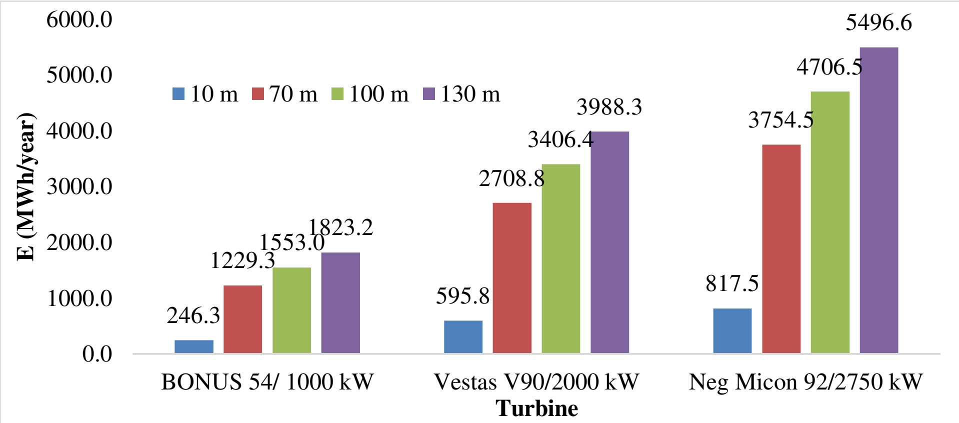

Figure-10. Annual energy generated at 10, 70, 100 y 130 m by using a different type of turbines, year 2011.

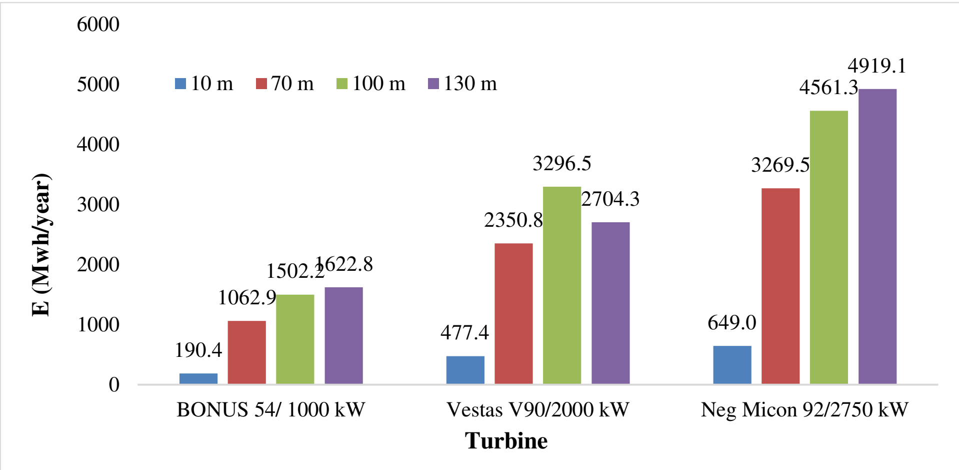

Figure-11. Annual energy generated at 10, 70, 100 y 130 m by using a different type of turbines, year 2012.

Almost the same energy would be produced when installing the Vestas v90 / 2000 kW wind turbine at a height of 100 m, as when installing the Neg Micon / 922 750 kW wind turbine at a height of 70 m, but this in turn produces almost the same as Vestas v90 / 2000 kW 130 m.

Analysis of the Economic Feasibility

Figure-12 shows the specific cost for each of the wind turbines; it was calculated from the energy generated at 130 meters above sea level in 2012. According to this, the cost of each kWh decreases by increasing the power of the wind turbine, the cost results indicate that the NEG Micon (2750 kW) is the more suitable turbine for the production of electrical energy in this area, followed by Bonus (1000 kW) and Vestas v90 (2000 kW) turbines.

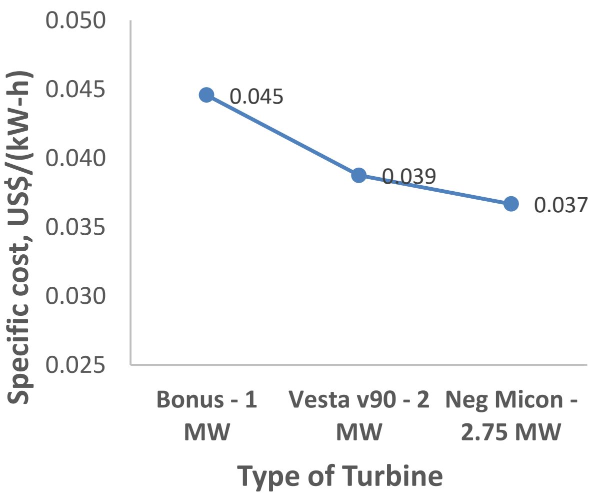

Figure-12. The specific cost of the energy generated by wind turbines at 130 meters of altitude.

Considering the previous results, an economic financial analysis was carried out to determine the pre-

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feasibility of the implementation of a wind farm. Financial indicators such as *VPN*, *IRR,* and *TRI* were taken as evaluation criteria, which depend on variables such as the investor's interest rate, the market inflation rate, the energy sales price, the operation and maintenance costs, the scrape value, and the initial investment cost. All these variables can fluctuate frequently over time and some, such as inflation, also depend on specific conditions of a country's market economies. The present analysis was carried out, especially by varying the interest rate and the sale price of the energy produced. The other required variables were kept constant according to the values calculated and presented previously.

Figure-13 shows the results of *VPN* analysis for different interest rates and sales prices of kWh calculated by using equation 11. According to these results, the *VPN* values greater than zero correspond to the combination of sale prices and interest rates in which the project becomes profitable, under the assumed conditions.

Results obtained from investment recovery time (TRI) analysis are shown in Figure-14, according to this graph, for the different sales prices, the investment recovery time increases with the rate of interest. Furthermore, as long as the KWh sale price is lower, the influence of the interest rate is more significant in the investment recovery time, since the slope of each curve increases as the sale price of energy decreases. In this regard, for an investor with a minimum attractive rate of return (MARR) of 12% (that is, the minimum interest rate from which they decide to invest in a project) and an energy sales price of US$ 0.08/kWh, the initial investment would be recovered in less than 10 years, and If the cost of sale were increased while maintaining the same MARR, the time to recover the investment would be less.

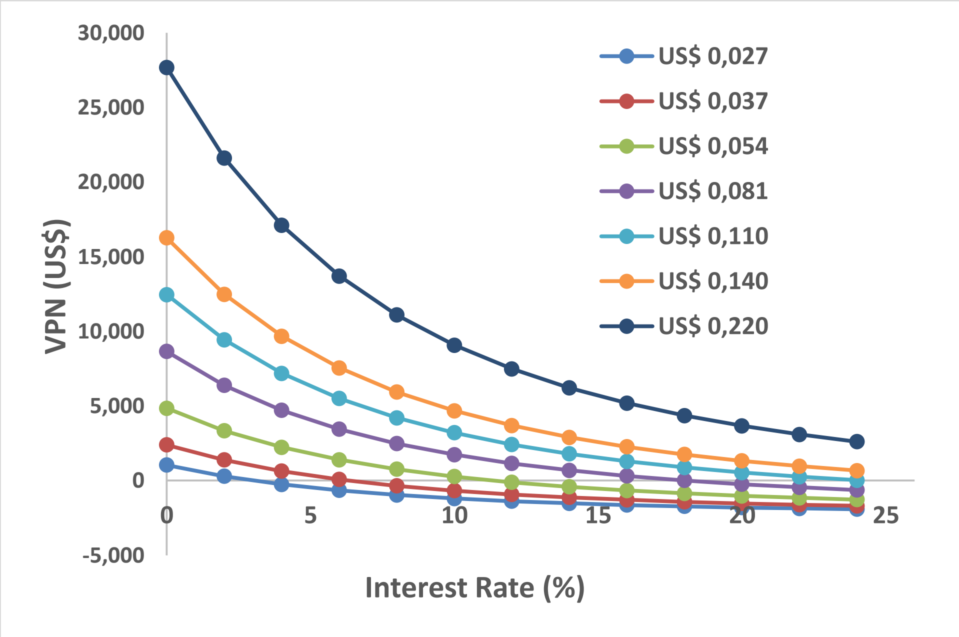

Figure-13. Variation of the NPV according to the interest rate.

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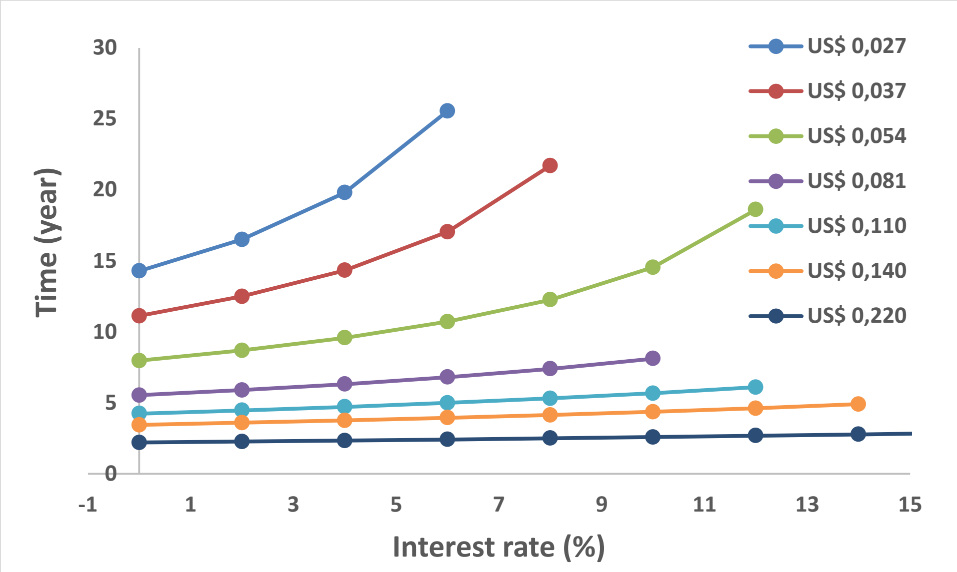

Figure-14. Investment recovery time (TRI).

Table-3 it shows the internal rate of return analysis, according to this, as the sale price of energy increases, the profitability of the project increases.

Table-3. Internal rate of return (IRR).

Energy sale Price (US$/KWh)	IRR
0.027	2.36 %
0.037	4.26 %
0.054	7.12 %
0.081	10.10%
0.110	12.0 %
0.140	13.29 %
0.220	15.47%

These results indicate how attractive the project is for a particular investor, at different sales prices. For example, for an investor, with a Minimum Attractive Interest Rate of Return (TMAR) of 12%, the project only becomes attractive if the energy is sold at US$ 0.11 / KWh onwards, since IRR> MARR.

CONCLUSIONS

For the study of the wind resource in a region, it is necessary to represent the characteristics of the wind using statistical distribution functions, since the average values of wind speed can give wrong ideas of the wind potential because these variables tend to be very random. The Weibull model represented very well the wind speed profile on San Andrés Island with high correlation coefficients. The model indicates that wind speeds of less than 2 m/s or greater than 7 m/s are unlikely to occur at a height of 10 m. According to the results obtained in this work, in the islands of San Andrés, it is possible to generate 4,919.1 MWh/year, at specific prices below the sale prices of the company in charge of the generation, distribution and commercialization of the electrical energy, SOPESA E.S.P., through the use of Neg Micon wind turbines of 2,750 KW at a height of 130 m. Furthermore, from the economic point of view and according to the speed profile of the area, this wind turbine is the most attractive, since it obtains the lowest specific cost of the energy generated at US$ 0.04/KWh.

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