# Production of Energy in the Villonaco Wind Farm in Ecuador

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***Abstract.* — This document describes the available wind resource analysis is performed on the Villonaco wind farm in the period Mar - 2017 to Mar - 2018 , on the mathematical foundation Weibull distribution ; based on this energy production of the plant in the mentioned period by applying two methods it is estimated : the mathematical formulation ( Betz limit ) and using the power curve of the wind turbine mounted on the center , with this is to make a comparison between these including the annual production report issued by CELEC E.P, Business Unit GENSUR.**

***Keywords*— Wind energy, Weibull, wind, often Betz Limit, modeling, renewable energy.**

## I. INTRODUCTION

Wind energy is an energy that is produced by the wind, it is an indirect form of solar energy that ranges from 1% to 2% of the energy that comes from the sun, is converted into wind. It is the result of unequal heating of the earth's surface causing the movement of air, which has the ability to transform into electrical energy [1].

The wind energy is transformed into electrical energy with a wind turbine, it is mainly focused on the production between the wind speed and its energy. Wind turbines are described with the power curve, this curve is characterized by being unique for each wind turbine.

In wind turbines for the most part, the minimum wind speed at which it generates its usable power is 3 to 4 m / s and at very high wind speeds of 25 m / s, there is a stop but the wind turbine is still energized. One of the causes of its stop is that the anemometer is damaged, damaged the vane, decalibration in the control system for production. Taking into account this information the wind turbines in operation always maintain their power curve [2].

Wind energy has now aroused interest in most countries for its implementation as a source of electricity generation [18] - [25].

### A. *Wind Energy in the Ecuador.*

In Ecuador, wind power is being exploited, the first wind farm in the country was inaugurated in October 2007 on the island of San Cristóbal with a capacity of 2.4 MW and in the province of Loja, on the Villonaco hill, with a capacity of installed capacity of 16.5 MW [26]- [28]. See figure 1.

In addition, a project on Baltra Island with a capacity of 2.25 MW is under construction. Given the environmental relevance of the Galápagos Archipelago, the previous Ministry of Electricity and Renewable Energy established as its goal, to satisfy most of the electricity demand of the islands with renewable energies. The equivalent of the energy provided by these projects can supply the homes of 150 thousand Ecuadorians [3, 4].

Fig. 1.- Panoramic view of the Villonaco Wind Power Plant.

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## II. METHOD OF DISTRIBUTION OF WEIBULL

The Weibull distribution is constituted by two shape parameters and the scale parameter and is the most efficient for the evaluation of wind energy [2]. The Weibull distribution is represented by Figure 4 [5].

$$F(v) = \frac{k}{c} * \frac{v^{k-1}}{c} * e^{-(\frac{v}{c})^{k}} \tag{1}$$

Where $k$ is the shape parameter; $v$ is the average wind speed and $c$ is the scale parameter, where we can indicate that $k$ determines the shape of the distribution, whereas parameter $c$ shows how sharp the function is, or in any other case how flat it is [6 ].

Cumulative distribution: It is the property that the wind speed does not exceed a value x is represented by Figure 4 [7].

$$\int_0^v f(v)dv = \int_0^v \frac{k}{c} * \frac{v^{k-1}}{c} * e^{-(\frac{v}{c})^{k}}\, dv = 1 - e^{-(\frac{v}{c})^{k}} \tag{2}$$

Complementary cumulative distribution: It is the probability that the wind speed exceeds a value $x$ is given by Figure 5 [7].

$$-\int_0^v f(v)dv = 1 - \int_0^v \frac{k}{c} * \frac{v^{k-1}}{c} * e^{-(\frac{v}{c})^{k}}\, dv \tag{3}$$
$$= 1 - 1 + e^{-(\frac{v}{c})^{k}} = e^{-(\frac{v}{c})^{k}}$$

**Determination of the parameters by the method of least squares:** The method of least squares allows finding the values of form and scale, for this the double logarithmic transformation of the cumulative distribution function is used as shown in Figure 4 [6].

$$ln\left(ln\left(\frac{1}{1-f(v)}\right)\right) = k * ln(v) - k * ln(c) \tag{4}$$

Figure 3 represents a linear equation of the form [6].

$$y = kx + b$$

From which we can conclude that the parameter of form $k$, is the slope of the regression. Intercept $b$ can be obtained by using Figure 3 [8].

$$k = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2}$$

$$b = \bar{y} - k\bar{x} \tag{5}$$

Where $\bar{x}$ and $\bar{y}$ correspond to the mean of the values of $x$ and $y$ and also respectively. Now the scale parameter of Weibull $c$ is a function of the intercept $b$ of the regression line. See Figure 4 [6].

## III. DATA MANAGEMENT

The data was granted by CELEC EP business unit GENSUR who are those who manage the Villonaco Wind Power Plant, see table 2 where they were classified in such a way that an analysis period was established March 2017 to March 2018; obtaining as a result 51355 data in a measurement interval of 10 minutes at a height of 60m; therefore it was determined that the equipment did not register an equivalent to 1243 data, that is why the average speed was calculated (11m/s) and it was estimated that for this missing data this was the speed.

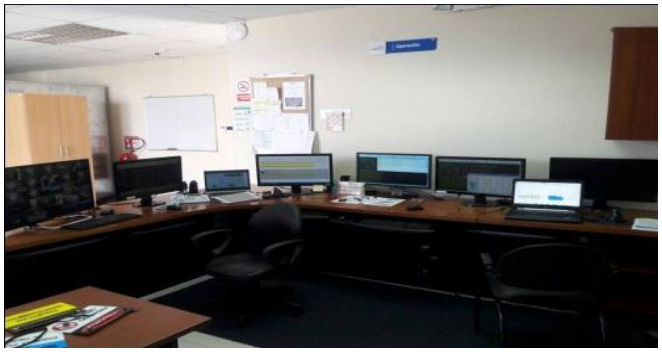

Fig 2. Monitoring Center for Villonaco Wind Power Plant. (Data management center).

The punctual and accumulated frequency is determined in the following equation:

$$Punctual\ frequency = \frac{data/year}{51355}$$

The number 51355 data corresponds total observations [5].

$$Accum\ freq\ \ n = \ Punctual\ freq\ n\ +\ punctual\ freq\ \ n - 1$$

The approximation for a linear equation taking the velocity values of the wind power station Villonaco in the period March 2017 to March 2018.

Through the equations already explained we obtained the following results of the parameters the results are indicated in the table 1.

TABLE 1. RESULTS OF THE PARAMETERS TO FIND THE WEIBULL DISTRIBUTION

| | |
|---|---|
| $\bar{x}$ | 2,57741 |
| $\bar{y}$ | 0,33585 |
| $K$ | 1,52017731 |
| $b$ | −3,58227211 |
| $C$ | 10,5537694 |

The results of these parameters allowed us to find the linear approximation of Weibull that is described in table 2 and is indicated graphically in figure 4. [29] - [31].

In Table 2 we indicate the wind speed in m/s and how many times they occur in the year, with the weibull density function that we obtained by finding the "*k*" and "*c*" scale parameters.

Figure 3 shows the Weibull distribution and in figure 5 the complementary cumulative distribution.

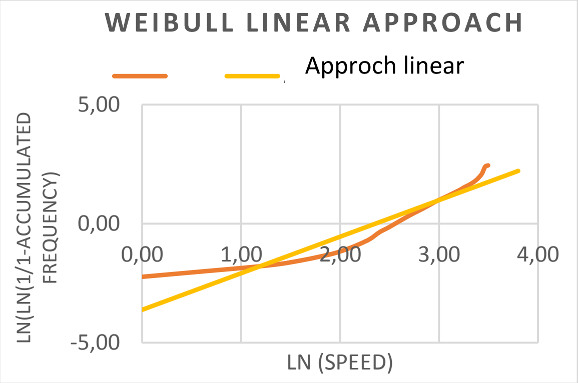

Fig 3. Weibull linear approximation.

TABLE 2. WEIBULL DENSITY FUNCTION

| Speeds m/s | WEIBULL Density function |
|---|---|
| 0,00 | 0,0000000 |
| 1,00 | 0,0400360 |
| 2,00 | 0,0551012 |
| 3,00 | 0,0639922 |
| 4,00 | 0,0688679 |
| 5,00 | 0,0707811 |
| 6,00 | 0,0704419 |
| 7,00 | 0,0684013 |
| 8,00 | 0,0651114 |
| 9,00 | 0,0609498 |
| 10,00 | 0,0562312 |
| 11,00 | 0,0512136 |
| 12,00 | 0,0461048 |
| 13,00 | 0,0410669 |
| 14,00 | 0,0362220 |
| 15,00 | 0,0316574 |
| 16,00 | 0,0274311 |
| 17,00 | 0,0235766 |
| 18,00 | 0,0201079 |
| 19,00 | 0,0170237 |
| 20,00 | 0,0143112 |
| 21,00 | 0,0119497 |
| 22,00 | 0,0099129 |
| 23,00 | 0,0081715 |
| 24,00 | 0,0066950 |
| 25,00 | 0,0054529 |
| 26,00 | 0,0044158 |
| 27,00 | 0,0035559 |
| 28,00 | 0,0028479 |
| 29,00 | 0,0022687 |
| 30,00 | 0,0017979 |
| 31,00 | 0,0014175 |
| 32,00 | 0,0011121 |
| 33,00 | 0,0008682 |

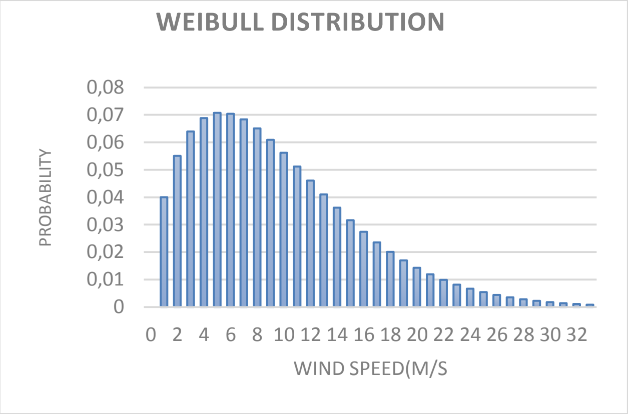

Fig 4. Weibull distribution.

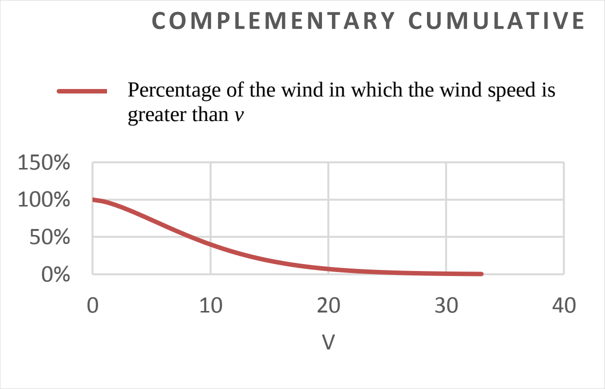

Fig 5. Complementary cumulative.

**Determination of power through mathematical analysis - Betz's Law:** According to the law of Betz, no more than 16/27 can be converted (59.3%) of the kinetic energy of wind into mechanical energy by means of a wind turbine [9, 33].

$$P = Cp\left(\frac{1}{2}\right)\rho A v1^3 = \frac{1}{2}Cp\rho\left(\frac{\pi D^2}{4}\right)v1^3(W) \qquad (7)$$

Where;
Cp = Power coefficient given by Betz's law.
ρ = air density.
D = rotor sweep diameter.
*v* = Average wind speed.

**Determination of Cp for the case study:** To find the mechanical power in a wind turbine, it is appropriate to extract the kinetic energy of the wind (7), it depends mainly on the cube of the wind speed, the diameter of the circle swept by the blades and the rotor coefficient *Cp* (which depends mainly on Its aerodynamic shape of its blade, which in its modern rotors its value is in a range of 0.4 to 0.5 In our case the Villonaco power plant has a three-bladed rotor, therefore its power coefficient is 0.5 it is indicated in Figure 6. [9, 15]

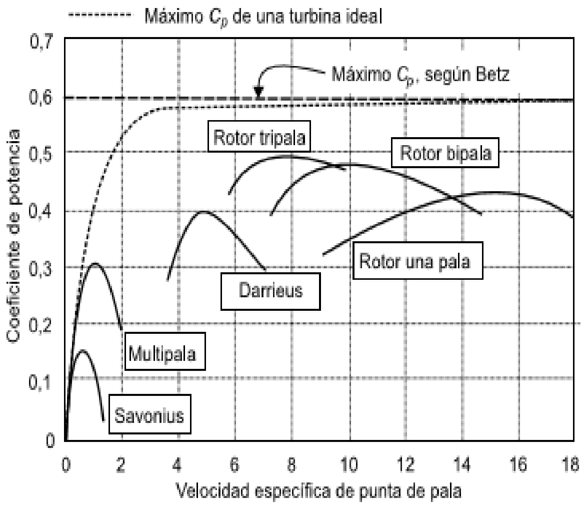

Fig 6. Power coefficients of different aeroturbines [9].

**Determination of air density for the case study:** Through equation 8 we can perform the calculation of air density for the case study, where z indicates the height where the density is desired, in this case the height of the wind turbines on average is 2716 meters above sea level and $T$ is the temperature is 12°C. [9, 32].

$$\rho = 1{,}225e^{\left(\frac{-z}{8435}-\frac{T-15}{288}\right)} \qquad (8)$$

$$\rho = 1{,}225e^{\left(\frac{-2716}{8435}-\frac{12-15}{288}\right)}$$

$$\rho = 0.897\ Kg/m^3$$

Determination of the average speed of Weibull: To determine the average Weibull velocity, we take Equation 9 as a reference [9].

$$v = c * \Gamma\left(1+\frac{1}{k}\right) \qquad (9)$$

Where;

$c$ = Weibull scale parameter
k = Weibull Shape Parameter
Γ = Range function, data taken from tables.

$$v = 10{,}52 * \Gamma\,(1{,}65)$$

$$\Gamma\,(1{,}65) = 0{,}90012$$

$$v = 10{,}52 * 0{,}90012$$

$$v = 9{,}52\ m/s$$

Table 3 shows the result of the calculation of the parameters needed to determine the power in the Villonaco Wind Power Plant.

TABLE 3. RESULT OF PARAMETERS NECESSARY FOR THE CALCULATION OF THE POWER.

| PARAMETER | RESULT |
|---|---|
| $\boldsymbol{Cp}$ | 0,5 |
| $\boldsymbol{\rho}$ | $0.897\ Kg/m^3$ |
| $\boldsymbol{v}$ | $9{,}52\ m/s$ |
| $\boldsymbol{D}$ | $70\ m$ |

Through the results shown in Table 1 the power (10) is determined [9]:

$$P = Cp\rho\left(\frac{\pi D^2}{4}\right)v1^3(W) \qquad (10)$$

$$P = 0{,}5 * 0.897\left(\frac{\pi * 70^2}{4}\right)9{,}52^3(W)$$

$$\boldsymbol{P = 744{,}61\ W}$$

**Determination of the power through the power curve of the wind turbine mounted at the Villonaco Wind Power Plant:** For this calculation it is necessary to obtain the power curve of the GW70/1500 wind turbine. This curve can be seen in Figure 7. Based on these data and the Weibull distribution shown in Figure 4, we can calculate the average power output and then to this, the cumulative power output that will be obtained as a result. The average output power and accumulated output mean is calculated through Equation 9 and 10, respectively [10, 11].

TABLE 4. GENERAL DATA OF THE STUDIO WATERTIGER.

| **MODEL** | **GW70/1500** |
|---|---|
| TYPE OF TECHNOLOGY | DIRECT -DRIVE (NO MULTIPLIER BOX) |
| HEIGHT OF THE TOWER | 65m |
| ROTOR DIAMETER | 70m |
| LENGTH OF THE BLADES | 34m |
| CERTIFICATION | IEC CLASS S (SPECIAL FOR THE CONDITIONS OF VILLONACO |
| MINIMUM STARTING SPEED | 4 m/s |
| MAX. SPEED STOP | 25m/s |
| TIPE OF GENERATOR | MULTIPOLO SYNCHRONO PERMANENTS MAGNETS |
| NOMINAL POWER | 1500KW |
| USEFUL LIFE | 20 YEARS |
| TYPE | Multipolous synchronous generator of permanent magnets |
| DESIGN | Direct drive |
| NOMINAL CURRENT | 660 A |
| NOMINAL ROTATION SPEED | 19 rpm |
| CLASS OF PROTECTION | IP23 |
| ISOLATION CATEGORY | F |

The equation of the average output power is described below:

$$Pmsn = \left(\frac{Pin{-}1{+}Pin}{2}\right) f(v) \qquad (11)$$

While the accumulated average output power is:

$$Pmsa_n = Pms_{n-1} + Pmsa_n \qquad (12)$$

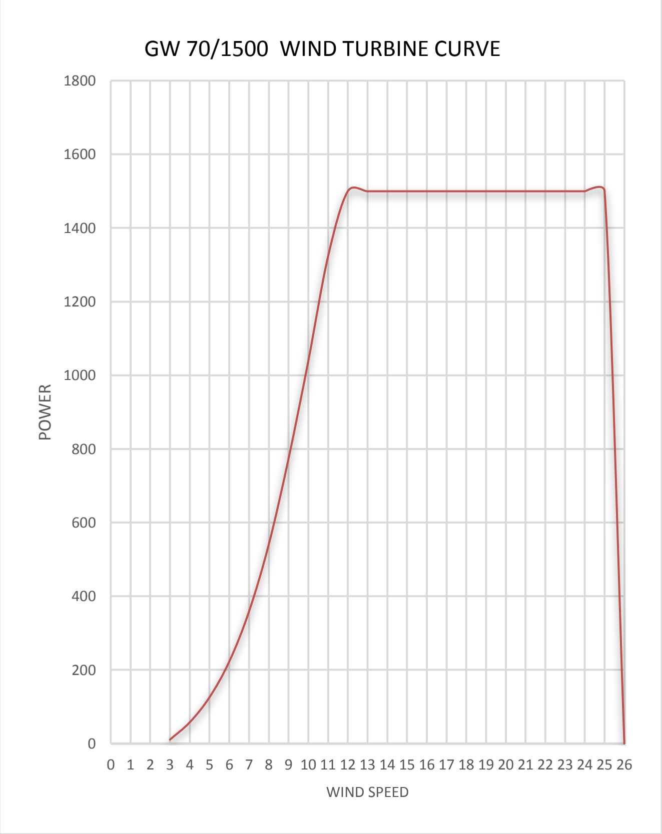

Fig 7. Wind Turbine Power GW 70/1500.

Table 5 shows the results where Pms is the average output power, Pi is the instantaneous power that corresponds to the powers of the different speeds of the wind turbine, f (v) is the probability density function of Weibull, and as Accumulated output power was obtained 671.03 KW.

As a complement to this analysis, the one-line diagram represented in figure 8, which has the Villonaco Wind Power Station, is shown. See first stage is the generation stage then proceed to the transformation stage to reach the interruption stage these mentioned for each generation unit. The output is connected to a three-way switch to reach the Villonaco substation of 34 KV. The power plant does not have an energy accumulation stage since it has preferential clearance, that is, what is generated is consumed.

TABLE 5. RESULTS OF POWER CALCULATION

| **Speeds m/s** | **F (v) Density function of WEIBULL** | **Pi Instant Power Wind turbine [KW]** | **Pms Average output power [KW]** | **Pmsa Average power of accumulated output [KW]** |
|---|---|---|---|---|
| 0,00 | 0,0000000 | 0,00 | 0,00 | 0,00 |
| 1,00 | 0,0400360 | 0,00 | 0,00 | 0,00 |
| 2,00 | 0,0551012 | 0,00 | 0,00 | 0,00 |
| 3,00 | 0,0639922 | 11,00 | 0,35 | 0,35 |
| 4,00 | 0,0688679 | 58,00 | 2,38 | 2,73 |
| 5,00 | 0,0707811 | 126,00 | 6,51 | 9,24 |
| 6,00 | 0,0704419 | 223,00 | 12,29 | 21,53 |
| 7,00 | 0,0684013 | 359,00 | 19,90 | 41,44 |
| 8,00 | 0,0651114 | 541,00 | 29,30 | 70,74 |
| 9,00 | 0,0609498 | 774,00 | 40,07 | 110,81 |
| 10,00 | 0,0562312 | 1039,00 | 50,97 | 161,78 |
| 11,00 | 0,0512136 | 1323,00 | 60,48 | 222,27 |
| 12,00 | 0,0461048 | 1500,00 | 65,08 | 287,35 |
| 13,00 | 0,0410669 | 1500,00 | 61,60 | 348,95 |
| 14,00 | 0,0362220 | 1500,00 | 54,33 | 403,28 |
| 15,00 | 0,0316574 | 1500,00 | 47,49 | 450,76 |
| 16,00 | 0,0274311 | 1500,00 | 41,15 | 491,91 |
| 17,00 | 0,0235766 | 1500,00 | 35,36 | 527,28 |
| 18,00 | 0,0201079 | 1500,00 | 30,16 | 557,44 |
| 19,00 | 0,0170237 | 1500,00 | 25,54 | 582,97 |
| 20,00 | 0,0143112 | 1500,00 | 21,47 | 604,44 |
| 21,00 | 0,0119497 | 1500,00 | 17,92 | 622,37 |
| 22,00 | 0,0099129 | 1500,00 | 14,87 | 637,23 |
| 23,00 | 0,0081715 | 1500,00 | 12,26 | 649,49 |
| 24,00 | 0,0066950 | 1500,00 | 10,04 | 659,53 |
| 25,00 | 0,0054529 | 1500,00 | 8,18 | 667,71 |
| 26,00 | 0,0044158 | 0,00 | 3,31 | 671,03 |
| 27,00 | 0,0035559 | 0,00 | 0,00 | 671,03 |
| 28,00 | 0,0028479 | 0,00 | 0,00 | 671,03 |
| 29,00 | 0,0022687 | 0,00 | 0,00 | 671,03 |
| 30,00 | 0,0017979 | 0,00 | 0,00 | 671,03 |
| 31,00 | 0,0014175 | 0,00 | 0,00 | 671,03 |
| 32,00 | 0,0011121 | 0,00 | 0,00 | 671,03 |
| 33,00 | 0,0008682 | 0,00 | 0,00 | 671,03 |

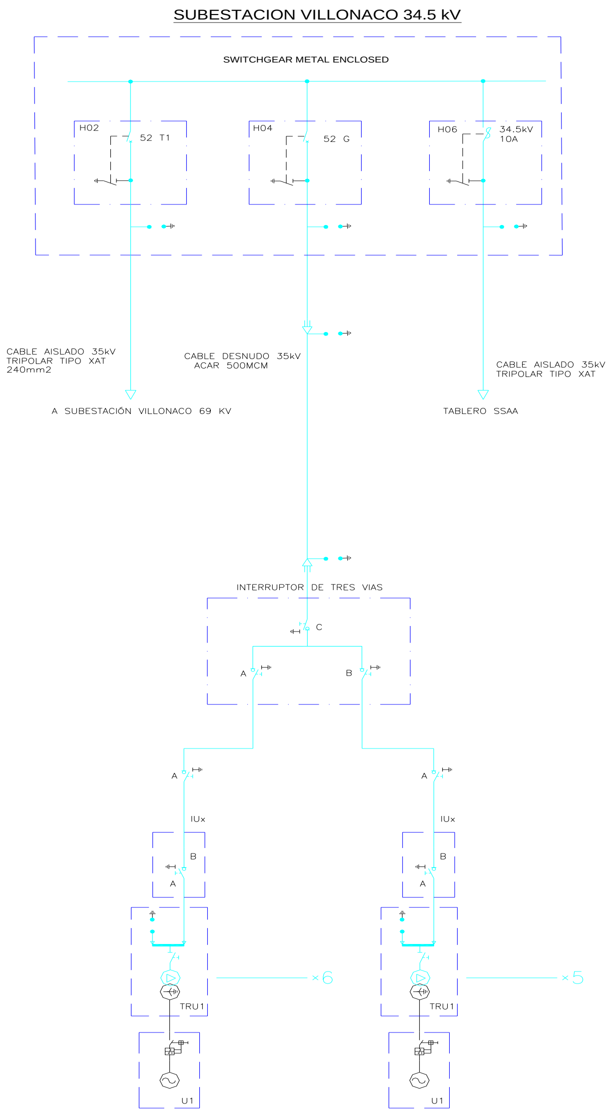

Fig 8. Simplified Uniform Diagram for Villonaco Wind Power Plant.

## IV. RESULTS AND DISCUSSION

For the calculation of energy in the analysis period, the Equation 13 is applied where values for losses due to unavailability, transportation and maintenance are shown, these values are 0.98 0.97 0.97 respectively, these are estimated [9].

$$E = P * 8760 * P_i * P_t * P_m * NA \qquad (13)$$

Where;

E = Generated Energy
P = Assigned Power
$P_i$ = Lost due to unavailability
$P_t$ = Lost by transport
$P_m$ = Losses for maintenance
NA = Number of wind turbines

TABLE 6. RESULTS OF ENERGY GENERATION IN VILLONACO

| ***ITEM*** | ***VALUE*** |
|---|---|
| Energy produced through mathematical analysis. Period Mar-2017 Mar-2018 | $E = 744,61 * 8760 * 0,98 * 0,97 * 0,97 * 11$<br>$\boldsymbol{E = 66.1599\ GWH\ año}$ |
| Energy produced through the power curve of the GW 70/1500 wind turbine. Period Mar-2017 Mar-2018 | $E = 671,03 * 8760 * 0,98 * 0,97 * 0,97 * 11$<br>$\boldsymbol{E = 59.6222\ GWH\ año}$ |
| Energy delivered to the interconnected national system: Report March 2017 - March 2018 | $\boldsymbol{E = 86,58\ \ GWH\ año}$ |

The Villonaco wind power plant is a work of great importance for the country since apart from providing a good part of energy to the country it is an important reference that has given rise to generate other projects such as in Galapagos and that will undoubtedly continue to be a benchmark for the realization of other important wind power generation projects.

## V. RESULTS

According to the monthly report of CELEC, it is delivered 86.58 GWH year in period March 2017 - March 2018, while according to the mathematical analysis the energy production is 66.16 GWH per year and per power curve is 59.22 GWH per year , that is why it can be concluded that the Weibull distribution method and the use of the Betz Law is acceptable for the determination of energy production, especially in places where new wind power plants are planned. In addition, it should be mentioned that the calculated energy production is reduced by loss parameters due to unavailability, transport, maintenance (0.98, 0.97, 0.97). For the present case study, these values are below those shown in the monthly report of CELEC E.P. Business Unit GENSUR.

To perform the mathematical analysis with respect to the determination of the power, it is necessary to use the real data of the site where the wind power plant is located, as a specific case we can mention the calculated air density (ρ = 0.897 Kg/m^3) which differs with the standard density (ρ = 1,225 Kg/m^3).

Before performing the analysis of the data, the criteria concerning height and periodicity of the taking of these should be established. In the present case study, the data collection is 60m and the periodicity of 10 minutes per data. In order to perform the power calculation by mathematical analysis, the mean Weibull velocity must be determined.

For the determination of the frequency of velocities in the period March 2017 - March 2018, it was necessary to interpret the periodicity of the data collection.

Projects of this type contribute to peace engineering, since the fact that there are functional and innovative projects such as Villonaco guarantee the stability of a nation in what has to do with production. They are avoided as in some occasions where there were large droughts and the river flows were under the nominal height, the wind exploited technically as is our case, generates confidence in the Ecuadorian society.

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