

EVALUATION OF HYDROELECTRIC, WIND AND SOLAR POTENTIAL: A CASE STUDY OF EXISTING PLANTS

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ABSTRACT

The current scenario of electricity generation in Brazil shows a matrix strongly supported by hydroelectricity. Despite being considered a clean source, strong dependence on power from a single source reduces the security of supply and reliability of a system. This was evident in the middle of 2014, when a serious water crisis was installed in the country, which affected drastically the level of reservoirs, requiring the activation of thermal plants to meet demand, causing economic losses to society given the more onerous character of this last type of generation. In this way, this article points to the insertion of renewable sources, namely, solar and wind, as an alternative for the diversification of the national energy matrix and consequent increase of the reliability of the current generation model. A case study was carried out to evaluate the wind and solar potential in two localities where there are

hydroelectric plants already functioning, the Emborcação power plant and the small hydroelectric plant of Cachoeira do Brumado, located in the State of Minas Gerais, Brazil, in order to evaluate the potential of combined use of these sources, verifying their gains in terms of seasonal stability of generation. The study was based on the analysis of historical wind speed and solar radiation data recorded in the regions that were the object of study. The achieved results show significant gains in terms of increased energy availability and stabilization of the annual generation. Therefore, it is considered feasible for the state of Minas Gerais to adopt complementary generation models based on the analyzed sources, which may reduce the use of thermal plants during the drought season, which may result in a decrease of carbon emissions rates, given the cleaner generation characteristics of the analyzed sources.

1. INTRODUCTION

In the modern world, several human activities have been causing damage to the environment and natural resources. In this sense, segments linked, among others, to the civil society and the academia have sought to draw attention to the urgent need for changes in existing productive models. One of these models is the generation of energy based on fossil sources, which is at the base of the development of the current society [1] and also characterizes one of the main causes of the high emission rates of Greenhouse Gases (GHG) in the terrestrial atmosphere, one of the main damages that civilization has implied to the planet. In this way, we have sought alternatives that can meet the current needs of society by observing the conservation of resources and care for the environment. In this context, renewable energy sources appear, which may play a relevant role in meeting the demands for electricity and have GHG emission levels along their production chain, much lower than those found in sources of fossil origin [2]. According to the National Electric Energy Agency [3], the Brazilian energy matrix is represented by hydroelectricity (64.87%), thermoelectricity (26.97%), thermonuclear generation (1.31%), wind generation (8%) and solar (0.02%). It is observed, therefore, that the generation of national electricity is strongly supported in hydroelectricity. This guarantees the country less GHG emission indices when compared to other countries that have their generation based on fossil sources, however, hydroelectricity is a resource linked to the country's rainfall regime, which has a stochastic character and seasonal variability. In this way, meeting the demand has always faced the challenge of stabilizing generation during the dry period of the year. This situation becomes even more

difficult in times of rainfall. As a coping strategy, there is a need to diversify the energy supply, where, within the context of environmental concern previously mentioned, the use of renewable sources becomes an increasingly interesting alternative.

It is known that Brazil is a country with ample availability of renewable resources. In terms of wind energy, according to the "Atlas of Brazilian Wind Potential" [4], the wind potential in Brazil reaches 143,000 MW, not including in this calculation offshore potential, and considering only heights up to 50 m. In Brazil, The Wind Atlas of Minas Gerais, completed in May 2010 by Energy Company of Minas Gerais (CEMIG), estimated the seasonal wind potential in the state, in three different dimensions, and the results indicate a potential of 10.6 GW, 24.7 GW and 39.0 GW, at heights of 50 m, 75 m and 100 m, respectively [5]. In Brazil, the wind regime tends to reach higher velocities in periods that coincide with low rainfall, which opens space for wind operation in a complementary way to hydroelectric dams, that contributes to preserving reservoir water in drought periods [4]. In the case of solar energy, despite the different climatic characteristics observed in Brazil, it can be noticed that the annual average of global irradiation shows good uniformity, with annual averages relatively high in all of the country, varying from 4.25 kWh/m².day to 6.5 kWh/m².day. The values of global solar irradiation in any region of the brazilian territory (1500-2500 kWh/m²) are higher than in most European Union countries, such as Germany (900-1250 kWh/m²), France (900-1650 kWh/m²) and Spain (1200-1850 kWh/m²), where projects using solar resources, some with strong government incentives, are widely disseminated [6].

In this sense, the present work shows and evaluates the complementarity of hydraulic generation with wind and solar sources as a strategy for the seasonal stabilization of energy supply. Wind and solar resources were evaluated from two localities where two hydroelectric plants are located in operation in the State of Minas Gerais, Brazil, in order to determine the annual generation profile obtained through the joint use of these three sources. The plants analyzed were the Emborcação Hydroelectric Plant and the Small Hydroelectric Plant of Cachoeira do Brumado. The wind and solar generation were evaluated by means of the theoretical power plant design, carried out through historical series of wind velocities and values of solar radiation recorded in the regions of interest. The results allowed relevant discussions about the characteristics of each source and the strategic role that each one can play in meeting the demands for electricity.

2 - MATERIALS AND METHODS

2.1 Characterization of study areas

The plants analyzed are located in the State of Minas Geras, Brazil. The Emborcação plant is located in the Paranaíba river basin, on the river of the same name, between the States of Minas Gerais and Goiás, more specific in the cities of Catalão (Goiás) and Araguari (Minas Gerais) at the coordinates 47°59'13" W and 18°27'05" S. It has a reservoir with an area of approximately 476 km² and an installed capacity of 1.192 MW. The Cachoeira do Brumado plant is located in the Paraíba do Sul river basin, on the Peixe river, in the city of Lima Duarte (MG), at the coordinates 43°53'19" W and 21°51'10" S. It has a reservoir with an area of approximately 0,0075 km² and an installed capacity of 2,340 MW. Figure 1 illustrates the location of the power plants and Figure 2 shows their satellite images.

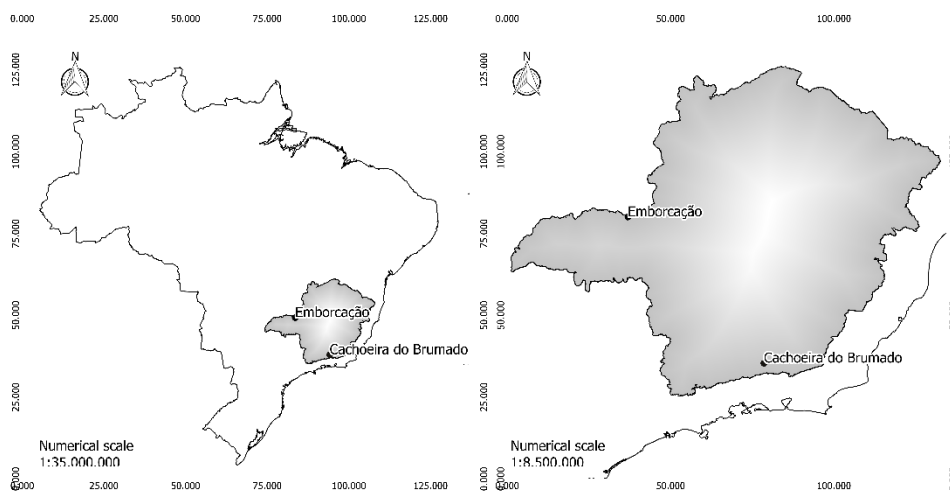


Figure 1: Location of the plants analyzed in relation to Brazil (left) And Minas Gerais (right).



Figure 2: Satellite image of the Emborcação (left) and Cachoeira do Brumado (right) plants.

2.2 Stages of the methodology

The methodology used was characterized by the collection of data related to the plants analyzed and the determination of an annual generation curve for the hydraulic, wind and solar sources for each of the plants. The determination of the hydraulic generation was carried out by means of the survey of the historical series of generation of the plants in question, through contact with the responsible owners or organizations. The seasonal water potential was considered as the monthly average of the historical generation raised. The solar generation was determined through the design of a theoretical plant using solar radiation data recorded for the latitude and longitude values of the plants and made available by the Reference Center for Solar and Wind Energy Sérgio Brito (CRESESB) [7]. Wind generation was determined through the design of a theoretical plant, using historical series of wind speeds recorded and made available by the National Institute of Meteorology (INMET) [8].

For sizing of wind and solar generation it was considered that each of the theoretical plants would have 100% of the installed power of the hydroelectric plant. It should be emphasized that this consideration does not take into account the economic viability of wind and solar power plants of the aforementioned size, since this is not the scope of this work. It is only a premise used for the seasonal evaluation of resources. Figure 3 presents the steps of the methodology used, that is described in detail in the next section.

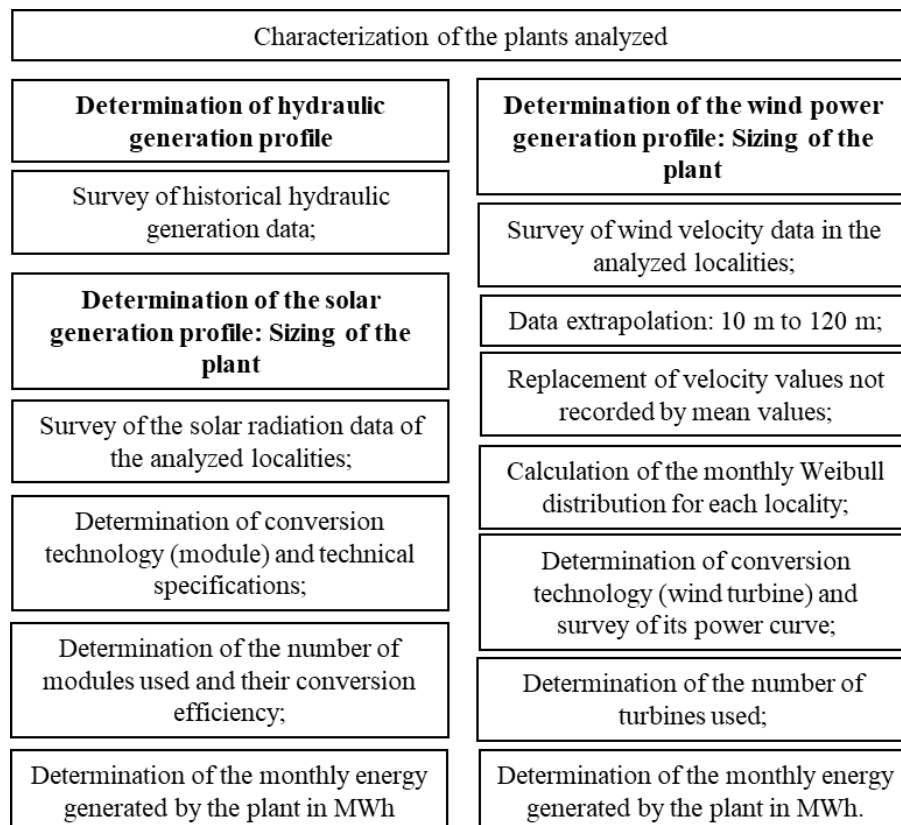


Figure 3: Methodological flowchart.

3 - THEORIES / CALCULATIONS

3.1 Calculations of seasonal energy generation

The wind potential was calculated from historical measurement series recorded by the INMET measuring stations located in the vicinity of the hydroelectric plants analyzed. With the latitude and longitude data of the plants, it was identified, through Google Earth, the closest station to each hydroelectric plant and, consequently, of the wind power plants. For the Cachoeira do Brumado plant, the Juiz de Fora station was used, and, in the case of the Emborcação plant, the Uberlândia station.

The data provided by INMET are wind velocity values in m/s recorded hour per hour during the day, from 2008 to 2013. The figures provided presented, however, two inconsistencies for the purpose used here:

- The occurrence of unmeasured values;
- The fact that the measurements were carried out at 10m, inadequate height to the energy use.

In this way, it was first determined that the last year of measurements would be used for the sizing, and the values of speeds not recorded in that year were replaced by the average values recorded on the same day and hour of previous years.

For the calculation of the wind speed for a height of 120 meters, suitable for the energy use, was used the Hellmann Law, given by Equation 1 [9-11]:

$$V_z = V_r \cdot \left(\frac{z}{z_r}\right)^n$$

Eq 1

Where V_z is the velocity for height z ; z is the height to be extrapolated; V_r is the velocity measured at the reference height; Z_r is the reference height; n is the soil roughness coefficient [4]. A soil roughness coefficient of 0,19 (mean roughness class) was used, since it was considered that the characteristics of the areas where the hydroelectric plants are located are close to forests, live fences and shrubs.

Land Type	Coefficient
Lake, ocean and smooth soil	0,10
Florests	0,15
Fences and shrubs	0,20
Small towns with few trees and shrubs	0,25
Large cities with high buildings	0,30

Table 1: Roughness coefficients [12].

Wind speeds and directions show well-defined seasonal trends within their stochastic character. Therefore, in order to determine the annual energy production, a probabilistic distribution must be analyzed that can represent, as accurately as possible, the behavior of the wind regime in a region. The Weibull distribution, (v), given by Equation 2, is classified as the most adequate to describe the wind regime of a place and represent the monthly frequencies of its velocity [12].

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad \begin{cases} k > 0 \\ c > 1 \end{cases}$$

Eq. 2

Where v is the wind speed recorded in m/s; c is the scaling factor in m/s and k is the (dimensionless) form factor. The scale factor "c" is related to the average local wind speed.

On the other hand, the form factor "k" is related to the wind velocity variance around the mean velocity. The scale factor can be estimated by means of Equation 3:

$$c = \frac{v}{\left[\frac{\Gamma}{\left(1 + \frac{1}{k}\right)} \right]}$$

Eq. 3

According to Freitas and Volpato [13] many mathematical methods can be used to estimate the parameters of the Weibull distribution, including least squares analysis for an observed distribution, methods of average wind speeds and quartiles, correlation method of "k" with the mean velocity. Still in accordance with these authors, the present work used the least squares analysis to determine the parameter "k". This method makes an adjustment of this by minimizing the square sum of the differences between the estimated value for the probability distribution and the observed data. The observed values and the monthly probability distributions found for each plant are presented in Appendices A and B.

The next step is characterized by the specification of the equipment considered in the design. The chosen wind turbine was the Enercon E-126 EP4 with rotor diameter of 127 m and power of 4,200 kW. Figure 4 shows the power curve of this wind turbine [14].

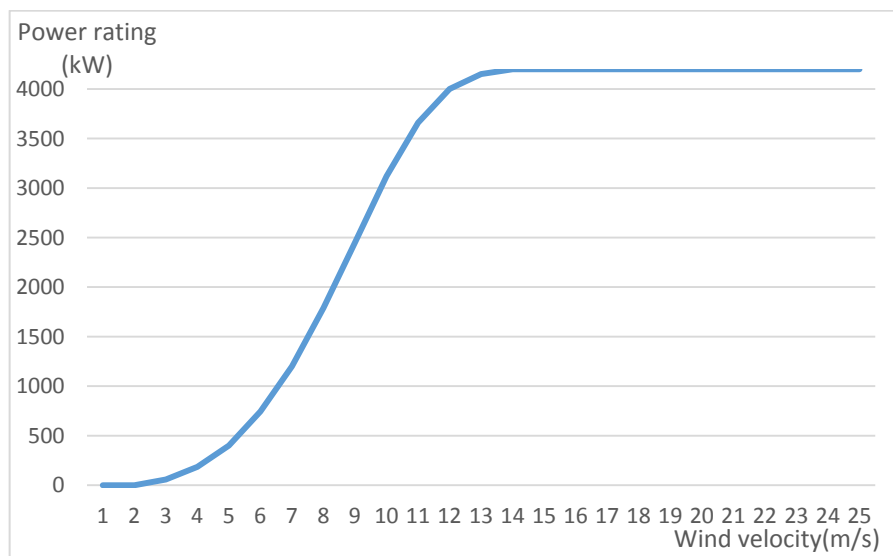


Figure 4: Power curve of the wind turbine.

The number of turbines used by the plant is characterized by the ratio of turbine power to installed power at the plant. Finally, the monthly generation can be determined by means of Equation 4:

$$G_{MEE} = \left[\sum (W(v) \cdot P(v)) \right] \times 720 \times n \quad \text{Eq 4}$$

Where G_{MEE} is the average monthly generation of wind energy; v is the wind speed in m/s; $W(v)$ is the Weibull distribution for each wind speed; $P(v)$ is the power generated by the turbine for each wind speed; 720 is the number of hours considered in the month; n is the number of turbines [15].

The potential of solar generation was obtained from information provided by CRESESB, which allows the consulting of data of average monthly solar radiation in kWh /m².day from the geographical coordinates (latitude and longitude) of the desired places. For the sizing of the solar generation the data of solar radiation in the horizontal plane for the latitudes of the analyzed plants were considered. Note that the radiation values for the horizontal plane are lower than those observed for the radiation in the inclined plane (whose inclination angle can be considered equal to the latitude of the place, in order to optimize the performance of the systems), however, it was decided to use them, adopting a scenario of pessimistic design. In terms of conversion technology, the Canadian MAXPOWER CS6X of 325 W [16] photovoltaic module was adopted. The total number of modules used is characterized by the ratio between the installed power of the plant and the nominal power of the module used. The estimated generation curve was obtained by means of Equation 5.

$$G_{MES} = RS \times AM \times \eta \times d \quad \text{Eq 5}$$

Where G_{MES} is the average monthly generation of solar energy; RS are the average daily solar radiation values in the analyzed locations (in kWh/m².day); AM is the estimated total area of modules, obtained by multiplying the number of modules of the plant with the area of each module; η is the conversion efficiency of solar energy into electric energy obtained by the technology, in this case, 17% [15].

4 - RESULTS

Figure 5 and Figure 6 show the results obtained in terms of the evaluations of the renewable resources in the locations of the plants under study. The wind velocity data were obtained

from the Uberlândia (MG) measuring station for the Emborcação plant and the Juiz de Fora (MG) station for the Cachoeira do Brumado plant and are related to the years 2008 to 2013. It can be seen that, in the case of Emborcação, the wind velocity values range from 2 to 4,5 m/s. The values of solar radiation vary between 4,22 to 5,44 kWh/m².day (horizontal plane) and 4,81 to 6,02 kWh/m².day (angle equal to latitude). In the case of Cachoeira do Brumado, wind velocity values range from 3,5 to 6 m/s. The values of solar radiation vary between 3,11 to 5,03 kWh/m².day (horizontal plane) and 3,86 to 4,82 kWh/m².day (angle equal to latitude).

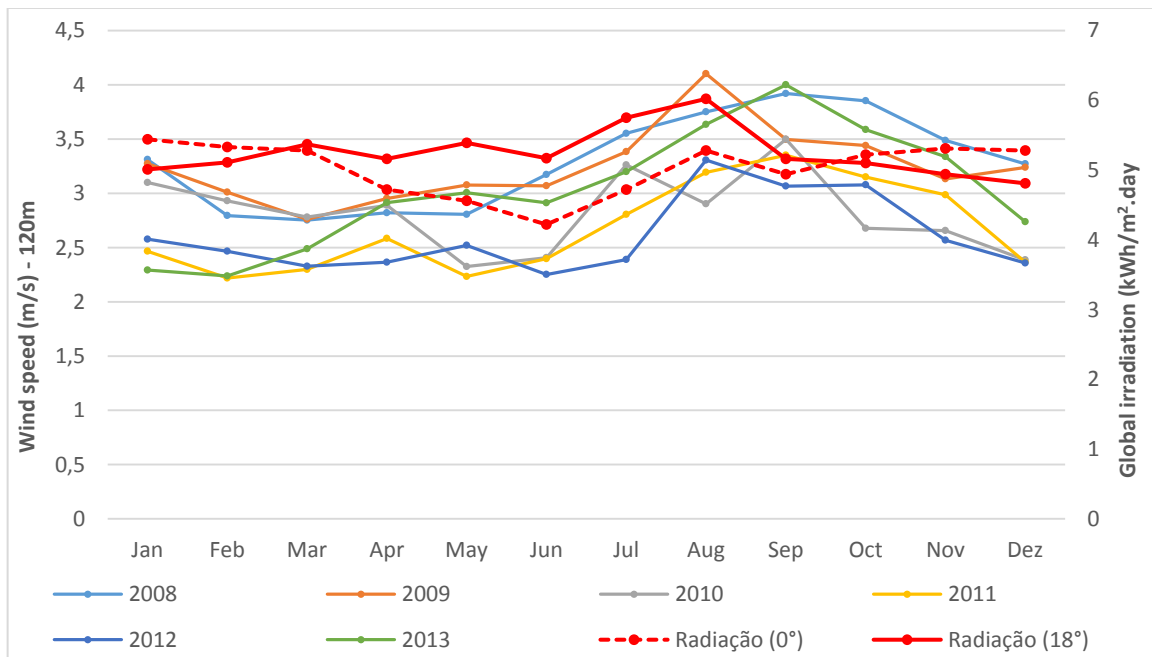


Figure 5: Evaluation of resources for the Emborcação plant.

Source: INMET (2014) and CRESESB (2017)

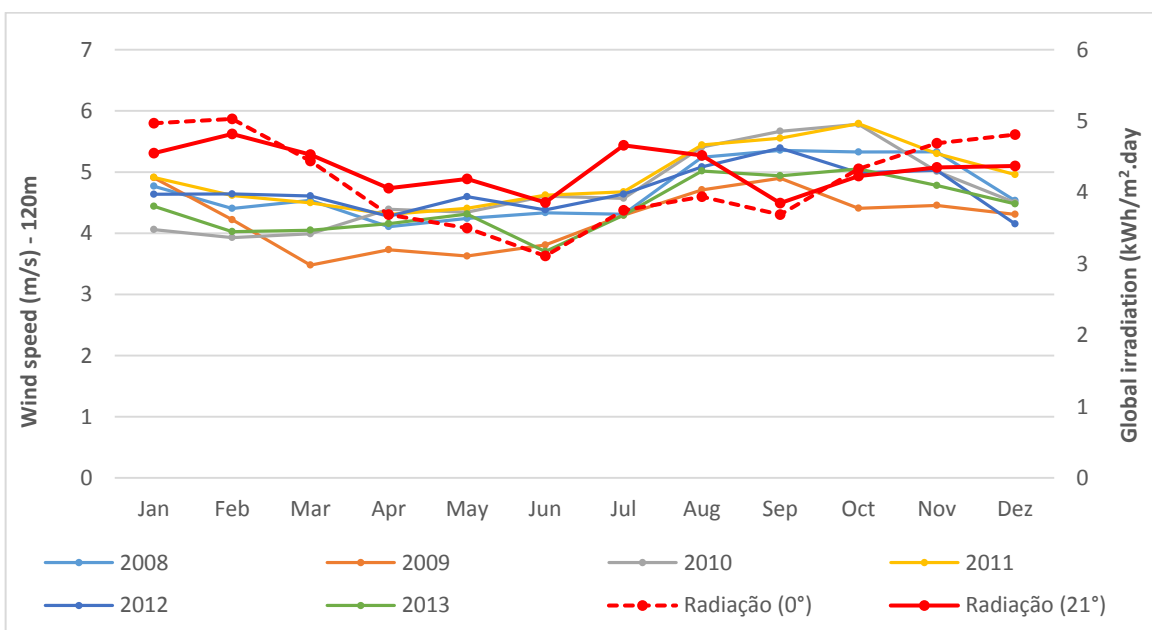


Figure 6: Evaluation of the resources for the Cachoeira do Brumado plant.

Source: INMET (2014) and CRESESB (2017)

Figure 7 and Figure 8 present the estimated generation profiles for the two plants under analysis. In the case of the Emborcação plant, the dimensioned solar generation is able to supply, annually, about 54% of the hydraulic energy produced. Wind power is capable of supplying about 10% of this value. For the Cachoeira do Brumado plant, solar generation is able to respond annually to 37% of the hydropower, and the wind power source accounts for 40% of that value.

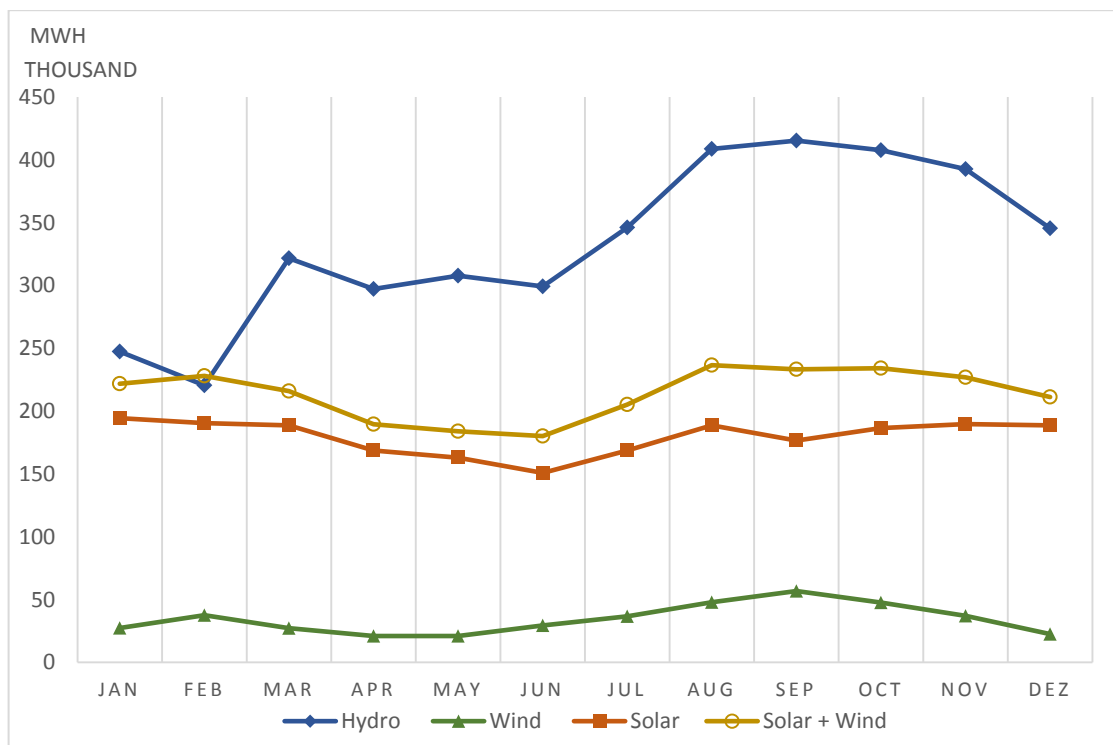


Figure 7: Estimated generation profiles for the Emborcação plant.

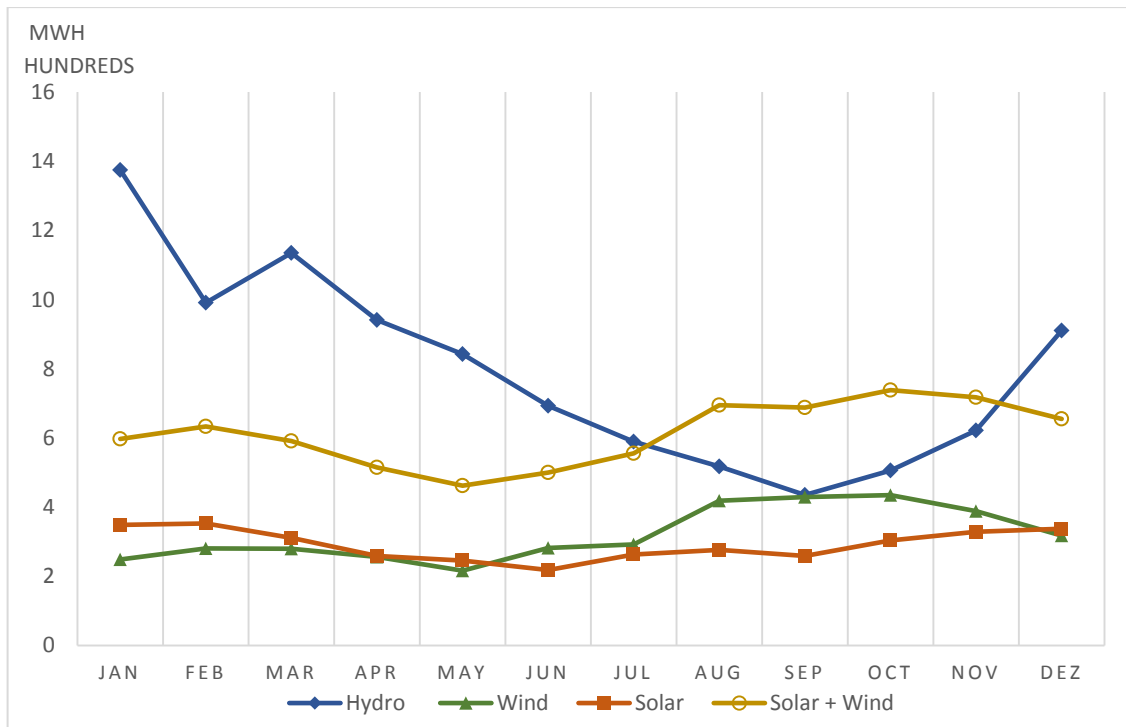


Figure 8: Estimated generation profiles for the Cachoeira do Brumado plant.

Other important results to be presented are the Capacity Factor of the plants and the area occupied by each one, as shown in Figure 9 and Figure 10. The estimation of the area occupied by the wind turbines was performed as proposed by Garbe, Mello and Tomaselli [17], where the authors point out that, in general, a safe distance for the installation of turbines is of the order of 10 times the diameter "D", if installed downstream, and 5 times "D" if installed next to in relation to the prevailing wind.

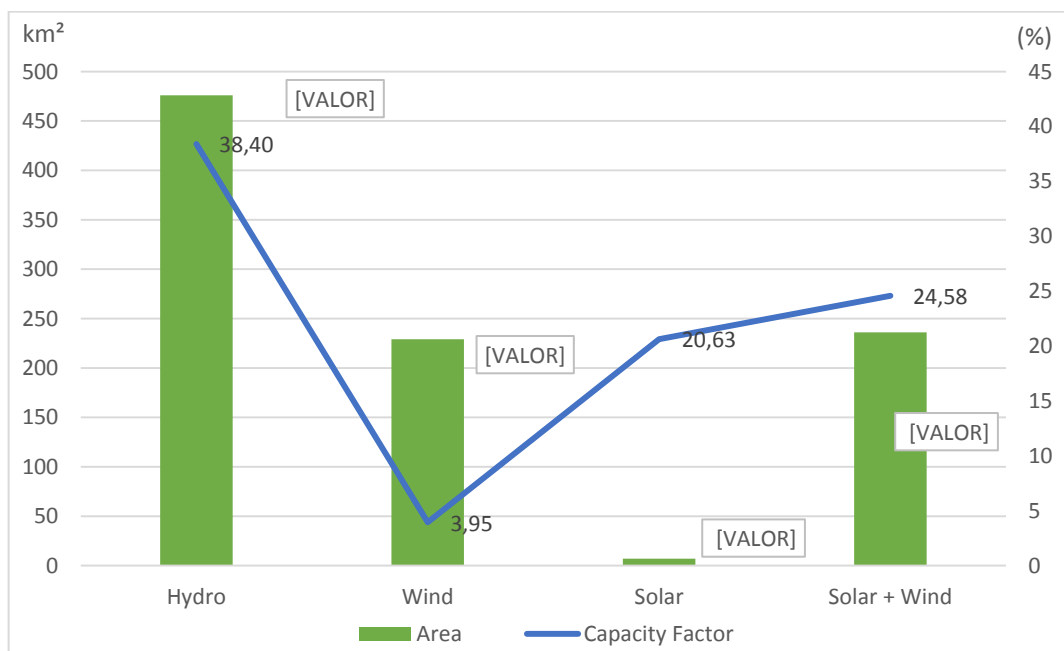


Figure 9: FC and estimated occupied areas for the Emborcação plant.

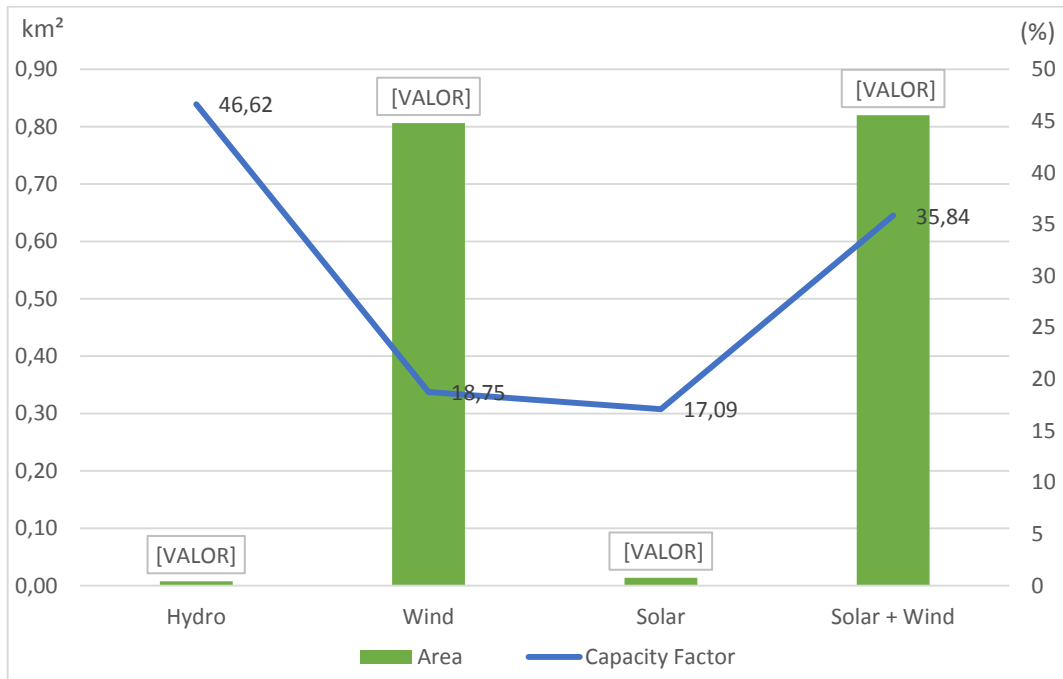


Figure 10: FC and estimated occupied areas for the Cachoeira do Brumado plant.

6 – CONCLUSIONS

The present work carried out a case study of two existing plants in Minas Gerais, Brazil – Emborcação e Cachoeira do Brumado – evaluating based on their generation profiles, their seasoned complementarity with wind and solar sources. It was observed that the availability of the hydraulic and wind resources has inverse behaviors throughout the year, characterizing a final profile with complementary characteristics. The generation based on the solar source has lower values of variability, however, presented significant values of generation. In the strategic assessment of the use of energy sources, there are no good, bad or any impediment classification for their uses. Each source has its own characteristics and a strategic role that it can play in the national system. In this sense, the knowledge of these characteristics can play a very important role in meeting the demands, which will be met in an increasingly reliable way through the diversification of the matrices.

7 – BIBLIOGRAPHY

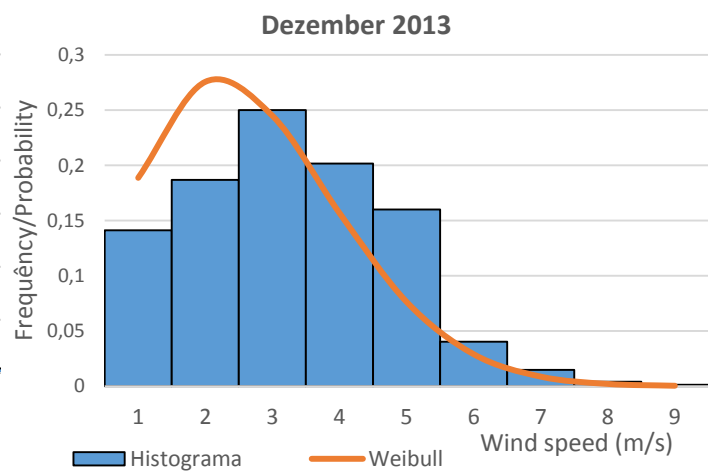
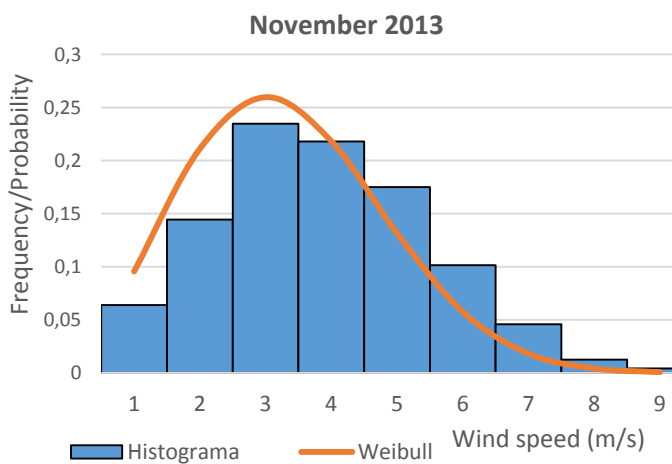
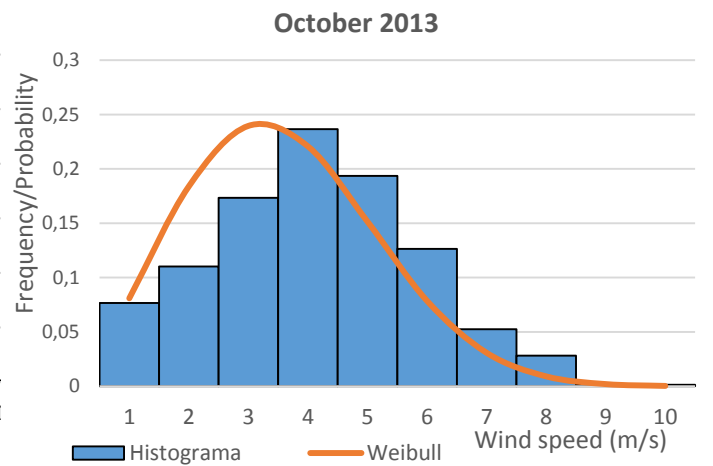
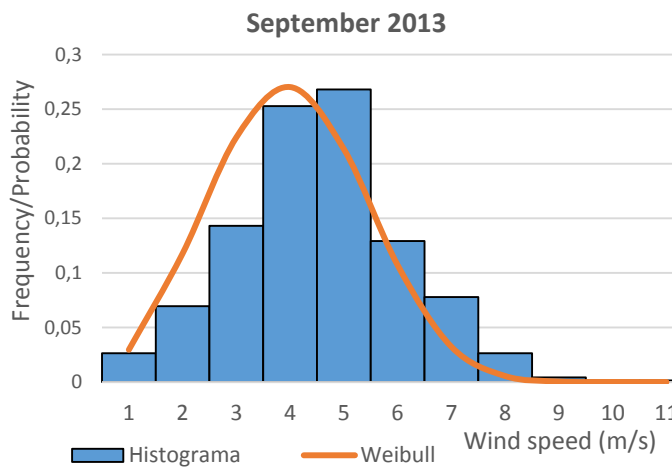
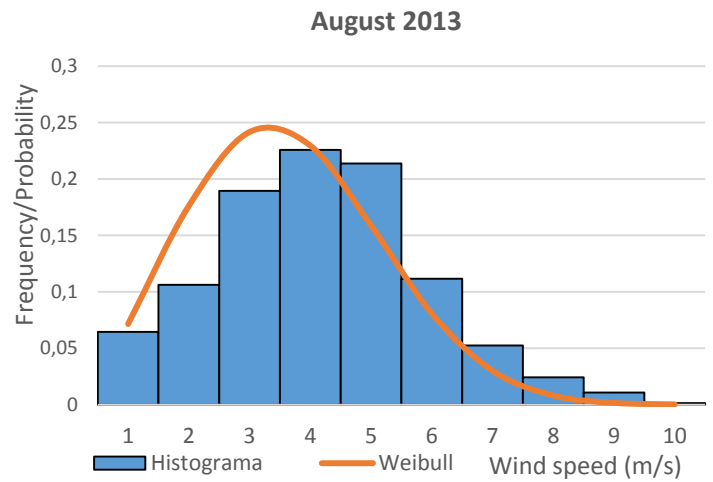
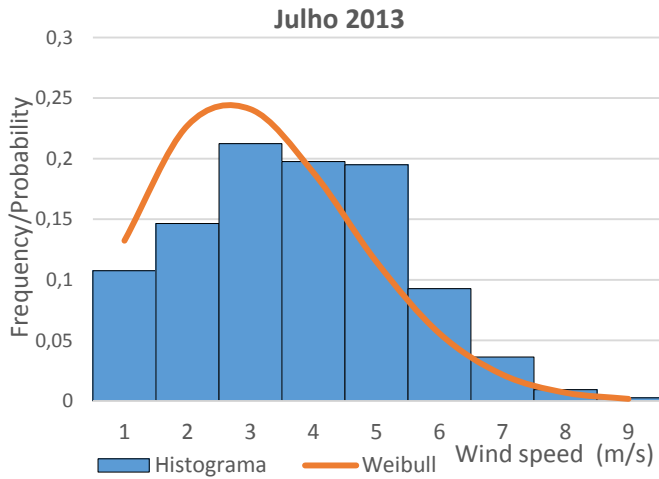
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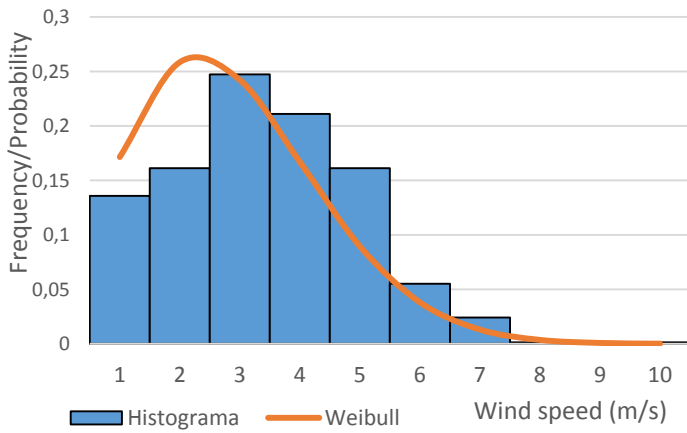
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APPENDICES

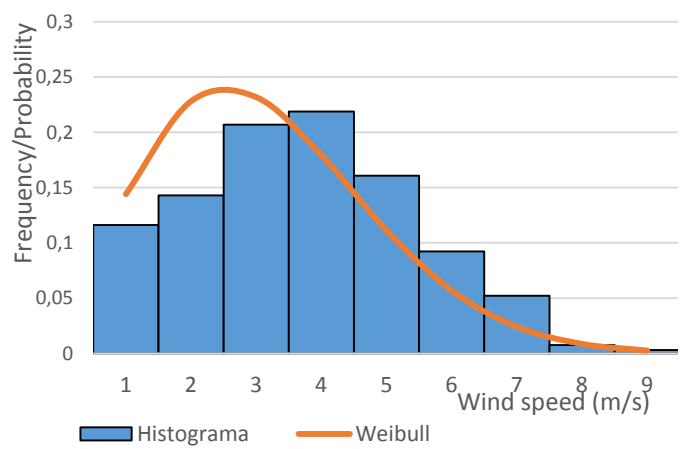
A. Monthly histograms and distributions of Weibull elaborated for the Emborcação power plant.



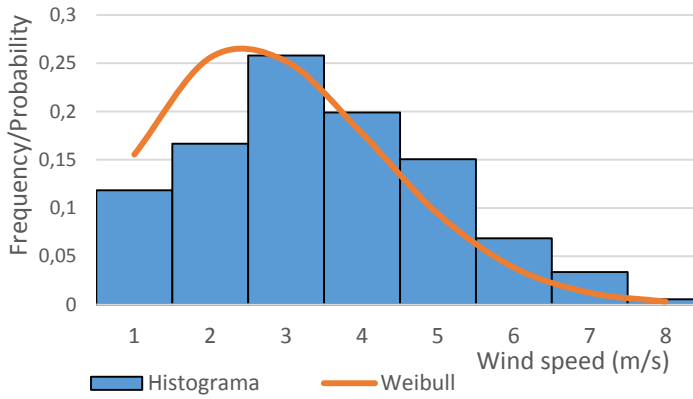
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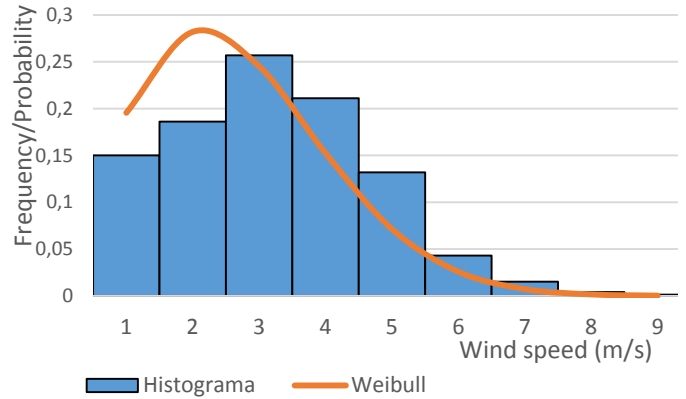
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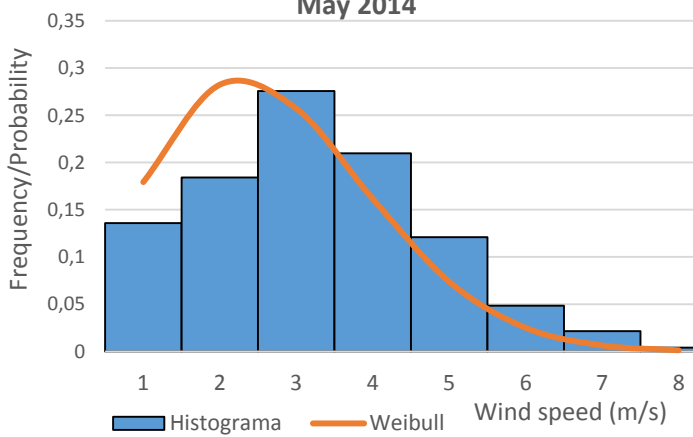
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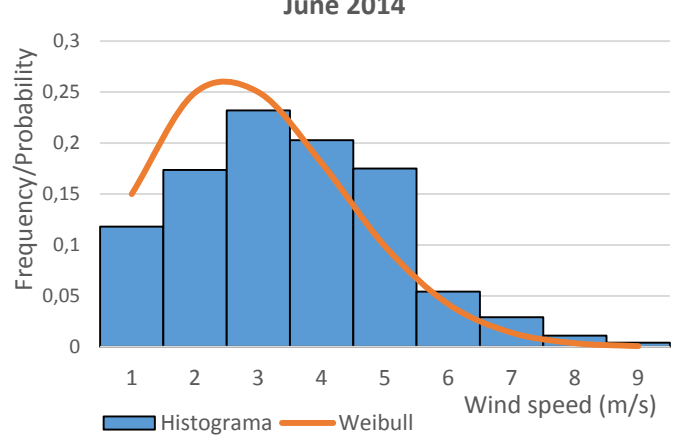
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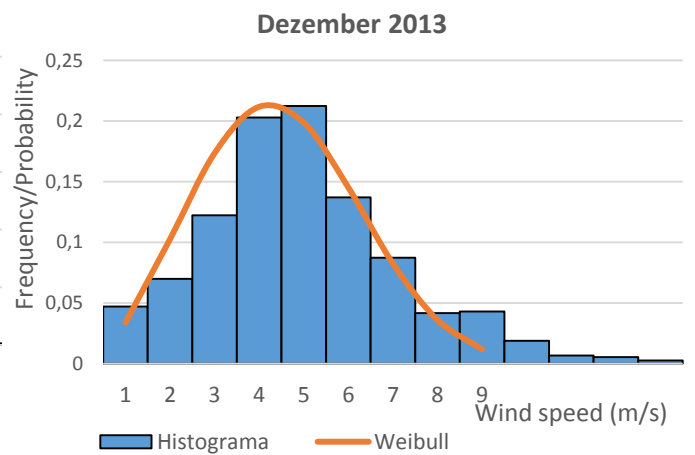
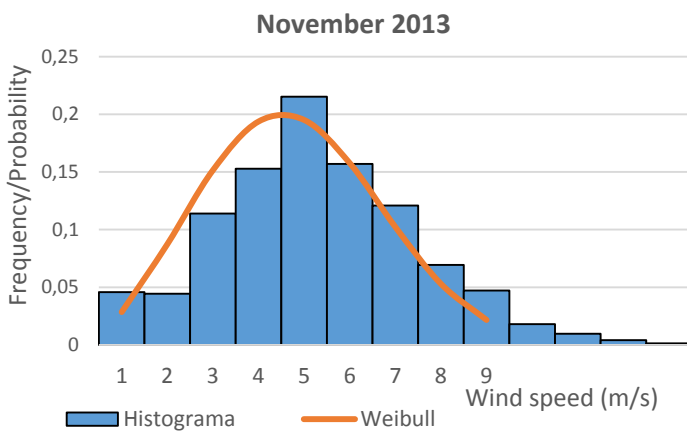
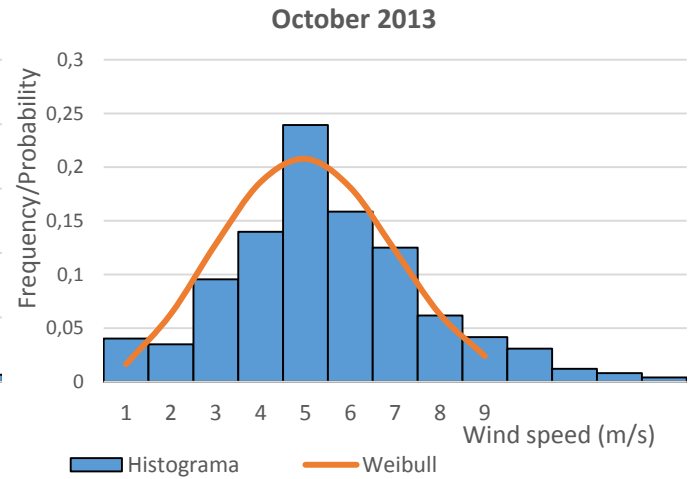
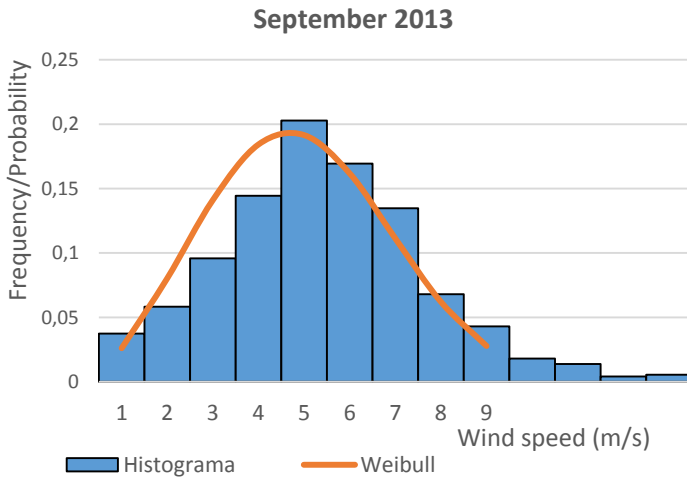
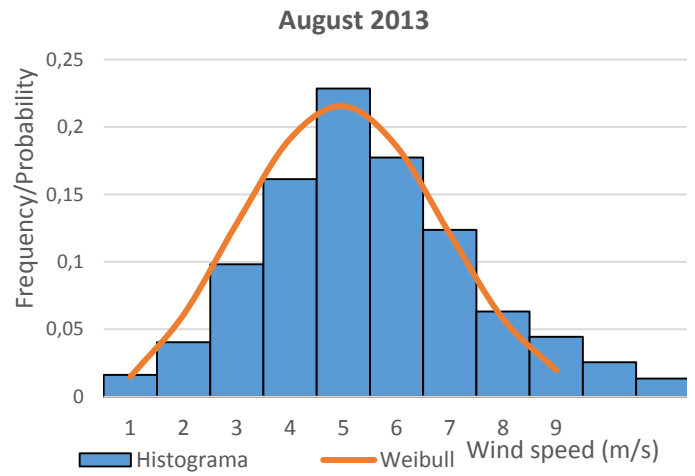
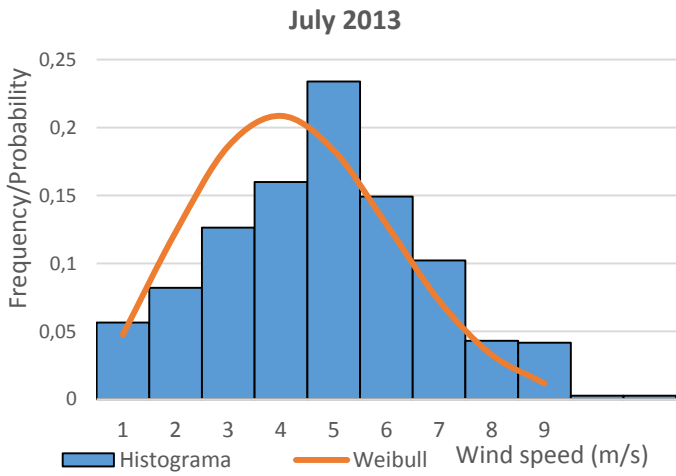
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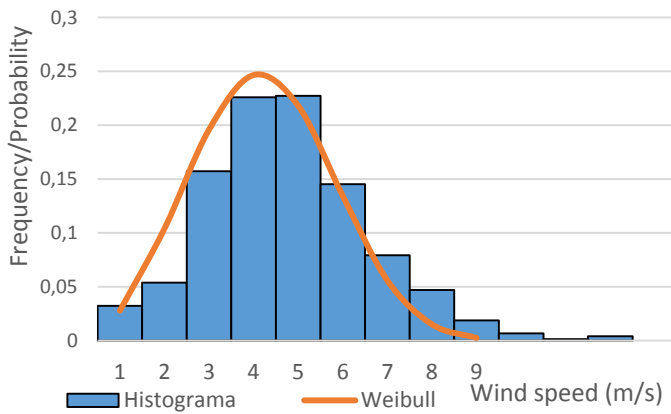
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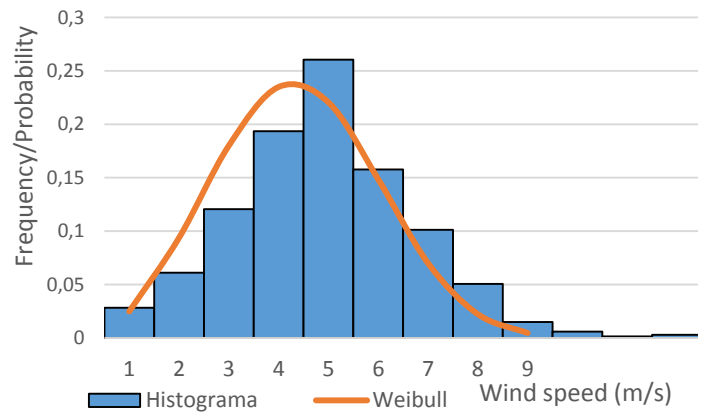
B. Monthly histograms and distributions of Weibull elaborated for the Cachoeira do Brumado power plant



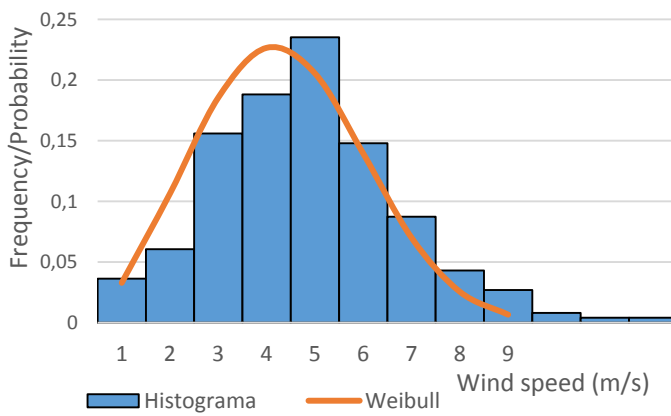
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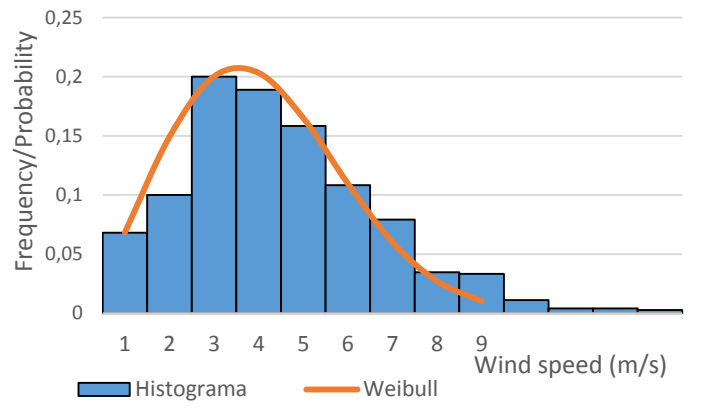
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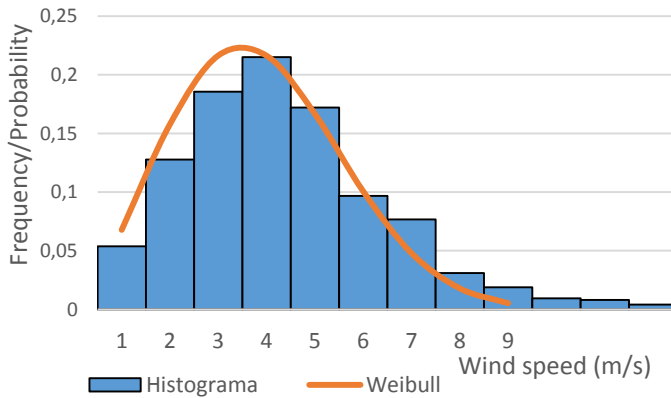
March 2014



April 2014



May 2014



June 2014

