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Exergetic Analysis of La Rumorosa-I Wind Farm

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Abstract

Considering the produced power and the output wind velocity (V_2) for the year 2013 of five wind turbines in La Rumorosa I wind farm, located in the town of La Rumorosa, Baja California, Mexico; exergetic analysis was apply to determine relations between the efficiency variables, considering only the time the wind turbine is in use (worked hours H). Also, it was calculated the percentage of the entire year in which the turbines were producing energy. We found that relation between exergetic efficiency (ε) and power coefficient (C_p) is inversely proportional in all cases for the twelve months of the year 2013. In addition, we propose a new relation which shows the exergetic efficiency as a function of input wind velocity (V_1) and the power coefficient, for the mentioned period.

Keywords: Exergy; Wind energy; Efficiency; Power coefficient

Introduction

World scenario

Wind power is the world's fastest growing electricity generation technology. The year 2014 represented a record with the global installation of more than 50 GW, which added to the ones already operating make approximately a total of 369 GW. Nowadays, wind energy represents the 3% of the energy generated in the entire world. Some projections indicate that for 2019 the worldwide installed capacity will be over 660 GW. Wind turbine technology is moving fast, yet, there is the need to evaluate behavior of wind accurately [1].

National scenario

Mexico has a great wind potential. Although, this resource has just started to be utilized in the recently, this sector shows high dynamism and competitiveness. Proof of this is the fact that more than 1,900 MW are in operation in both, independent production and self-supply as well as more than 5,000 MW are at different levels of development. Mexico has the commitment to decrease the fossil fuel electric generation from the actual 80% to a 65% for the year 2024, which implies installing more than 25,000 MW of clean technology in the next 10 years. Wind technology plays a fundamental role to achieve this goal, since wind power has been responsible of about two-thirds of the total objective in most countries with similar goals. The goal for 2020-2022 is to attain an installed capacity of at least 12,000 MW in the country, which is going to represent about the 40% of the national renewables target. This goal would have a cumulative impact on GDP of about 170,000 million pesos (approximately 9.5B USD) besides of the creation of more than 45,000 jobs [2].

Exergy

Technically, exergy is defined as the maximum amount of work that can be produced by a system in non-equilibrium with its environment [3-5]. Exergy is a measure of the systems potential or flow to cause a change, as a consequence of not being completely in relative balance to a reference environment. Unlike energy, exergy is not linked to a conservation law. The exergy consumed during a process is proportional to the entropy created due to the irreversibility associated with that same process [6,7].

Exergetic analysis is a methodology based on the conservation of energy principle (first law of thermodynamics) along with the non-conservation of entropy one (second law of thermodynamics) for the analysis, design and improvement of energy and other systems. This analysis is useful to identify the causes, locations and magnitudes of inefficiencies in the processes. It recognizes that, although energy cannot be created or destroyed, it can be degraded in quality and eventually reached to a state in which it is in complete balance with its environment and therefore, without the ability to perform tasks [6]. This former process is currently used in innumerable fields involving energy transformation and optimization, such as the aforementioned sources of renewable energies (wind [8-12], geothermal [13], solar [14], biomass [15]), conventional sources (oil [16] and gas [17]), nuclear power [18], waste- water treatment [19] and even biology [20].

Regarding to energy efficiency of a wind turbine performance, the main factor to measure is the power coefficient C_p. Similarly, the main factor to be considered in performing the exergetic analysis is the exergetic efficiency ε. There are studies analyzing these relationships with interesting results [9,12]. In the present work, this type of analysis is carried out for the first time for five wind turbines at La Rumorosa I wind farm, pondering air density as a function of atmospheric pressure, relative humidity and temperature. Contrary to previous researches, this study only included data from the wind turbine (the output wind velocity V_2 and the electric power produced W_{out}), so it is necessary to represent the input wind velocity V_1, as a function of V_2 for the exergetic analysis.

Overview of the Object of Study

La Rumorosa I wind farm

La Rumorosa I wind farm is located within the town of its same name in the State of Baja California, Mexico; and it's operated under

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control of the State Energy Commission of Baja California (CEE BC). This area is the site, where wind resource is largely being exploited, in part, due to its excellent wind potential, to an acceptable transmission network of the Electricity Federal Commission (CFE for its acronym in Spanish) and to the fact of being border with the State of California, in the United States, which serves as the main customer. The park consists of five Gamesa G87-2.0 MW wind turbines with the following characteristics.

- Diameter: 87 m.
- Sweep area: 5945 m^2.
- Number of blades: 3 (Fiberglass pre-impregnated with epoxy resin).
- Cut-in speed: 4 m/s, cut-out speed: 25 m/s, rated speed: 16 m/s.
- Rotational speed 9.0-19.0 rpm.
- η_{mec}=0.98, η_{el}=0.95, η=0.93.

Figure 1 represents the power curve of the manufacturer; these results were obtained under the following conditions:

- Air density: 1,225 kg/m^3 (at sea level)
- Intensity of turbulence: 10
- Rotor speed between 9.0-19.0 rpm

La Rumorosas anemometric station (property of CONAGUA)

The meteorological data used for the exergetic analysis were provided by the National Water Commissions (CONAGUA for its acronym in Spanish) anemometric station located in the region of Agua Hechicera in the town of La Rumorosa, which is situated at approximately 27 km from the wind farm. The anemometer is positioned at a height of 10 meters above ground level and the altitude of the site is 1260 meters above sea level (Figure 2).

Data

Data of a ten-minute measurement, for both generated electric power and wind output velocity, emitted by the five wind turbines were obtained during the 12 months of the year 2013. The monthly averages are presented in Tables 1-5. Here, V_2 is the wind output speed (in m/s), *H* is the worked hours by the wind turbine, W_{out} is the electric power produced (in kW), *E* is the total electric energy produced in the month) and ρ is the average monthly air density (in kg/m^3). It is important to emphasize that the worked hours (*H*) represent the total number of hours the wind turbine was producing energy (that is, in operation and that the wind speed V_1 was higher than the cut-in speed); all average speed and output power take into account only the worked hours.

The behavior of the monthly electric power average and the total energy produced every month are presented in Figures 4 and 5, respectively.

Theoretical Framework

Energetic analysis

The kinetic energy of the wind can be written as

$$E = \frac{1}{2}\rho A t V^3 \quad (1)$$

Therefore, the available power is,

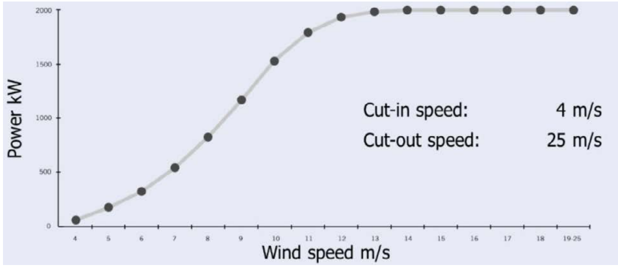

Figure 1: Gamesa G87-2.0MW power curve.

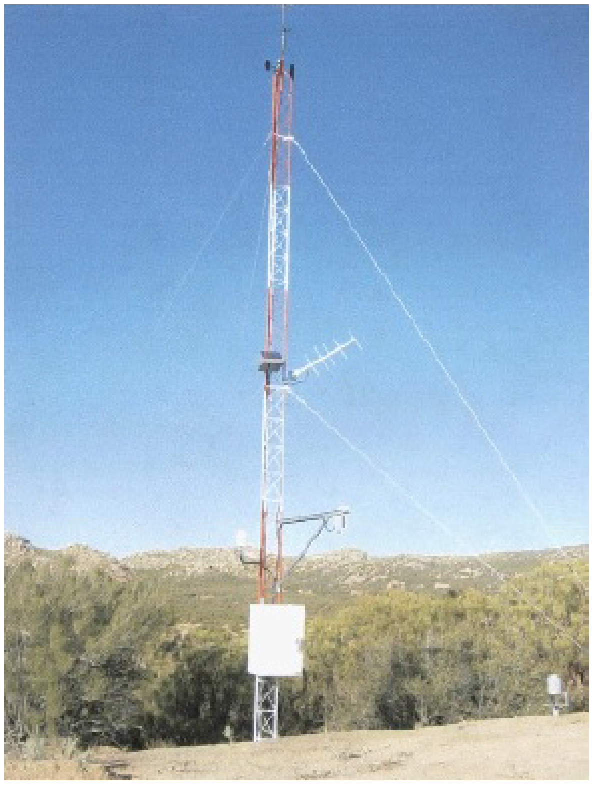

Figure 2: Anemometric tower in Agua Hechicera.

$$P = \frac{1}{2}\rho A V^3 \quad (2)$$

The power that absorbs the disk

$$P = m\,(V_1 - V_2)\,\overline{V} \quad (3)$$

Where,

$$\overline{V} = \frac{V_1 + V_2}{2} \text{ or}$$

$$P = \rho A\,(V_1 - V_2)\,\overline{V}^2 \quad (4)$$

Making $\alpha = \frac{V_2}{V_1}$ we have

$$P = \frac{1}{4}\rho A\,(1-\alpha^2)\,(1+\alpha)\;V_1^3 \quad (5)$$

The maximum power will be for $\alpha = \frac{1}{3}$.

Month	V_2 (m/s)	H (h)	W_{out} (kW)	E (MWh)	ρ (kg/m³)
January	8.17	633.83	821.13	520.46	1.0941
February	8.29	529.00	825.20	436.53	1.0940
March	8.17	536.00	801.79	389.38	1.0729
April	8.78	587.00	936.52	549.74	1.1028
May	9.00	627.67	995.61	612.77	1.0536
June	7.73	637.33	669.82	426.90	1.0335
July	6.61	515.00	447.77	220.07	1.0250
August	6.39	526.83	417.68	220.05	1.0287
September	7.10	430.33	576.91	248.26	1.0325
October	8.29	533.50	790.63	421.80	1.0557
November	7.32	523.00	643.81	336.71	1.0739
December	8.75	641.33	891.78	571.93	1.0850

Table 1: Turbine 1.

Month	V_2 (m/s)	H (h)	W_{out} (kW)	E (MWh)	ρ (kg/m³)
January	8.01	634.17	779.32	494.22	1.094
February	8.13	538.17	793.30	426.93	1.094
March	7.91	557.83	742.79	375.31	1.073
April	8.53	581.00	889.22	516.63	1.103
May	8.68	627.83	936.10	576.56	1.054
June	7.42	636.50	617.11	392.79	1.034
July	6.48	501.83	442.66	213.18	1.025
August	6.34	396.17	405.94	160.82	1.029
September	7.26	338.83	608.03	206.02	1.033
October	8.00	532.67	737.38	392.78	1.056
November	6.99	522.17	602.75	314.74	1.074
December	8.56	627.83	817.17	513.05	1.085

Table 2: Turbine 2.

The energy efficiency of a wind turbine is characterized by its power coefficient [9].

$$C_p = \frac{W_{out}}{\frac{1}{2} \cdot \eta_{el} \cdot \eta_{mec} \cdot \rho \cdot \pi \cdot \mathrm{R}^2 \cdot \mathrm{V}_R^3} \quad (6)$$

Where,

W_{out} is the electric power obtained, η_{el} and η_{mec} are the electrical and mechanical efficiencies of the turbine respectively; ρ is the density of air, R is the radius of the wind turbine and V_r is the speed at the boundary of the disk.

Then

Month	V_2 (m/s)	H (h)	W_{out} (kW)	E (MWh)	ρ (kg/m³)
January	8.38	549.33	815.85	448.17	1.094
February	8.48	543.17	852.35	462.97	1.094
March	8.23	570.17	794.11	413.58	1.073
April	8.93	586.67	948.60	556.51	1.103
May	9.05	628.33	990.96	610.41	1.054
June	7.98	467.00	703.61	328.59	1.034
July	6.82	505.67	495.84	243.18	1.025
August	6.52	518.67	424.88	220.37	1.029
September	7.25	428.17	578.69	247.77	1.033
October	8.34	540.67	787.13	425.57	1.056
November	7.37	508.00	624.71	317.35	1.074
December	8.97	593.67	918.52	545.29	1.085

Table 3: Turbine 3.

Month	V_2 (m/s)	H (h)	W_{out} (kW)	E (MWh)	ρ (kg/m³)
January	8.48	635.83	841.27	534.91	1.094
February	8.54	535.67	860.23	460.79	1.094
March	8.22	568.83	781.57	406.47	1.073
April	8.89	586.33	940.29	551.32	1.103
May	9.07	611.83	985.58	591.38	1.054
June	7.83	624.67	670.98	419.14	1.034
July	6.71	503.17	477.14	229.02	1.025
August	6.43	520.50	408.93	212.85	1.029
September	6.64	381.67	457.99	174.80	1.033
October	8.63	538.67	792.79	427.05	1.056
November	7.82	516.17	656.19	338.70	1.074
December	9.05	647.50	912.47	590.83	1.085

Table 4: Turbine 4.

$$V_r = \frac{V_1 + V_2}{2} = \overline{V} \quad (7)$$

The kinetic exergy of the air.

$$ke_1 = \frac{V_r^2}{2} \quad (8)$$

The mass flow is the amount of matter per second that passes through the turbine (in units of kg/s):

$$\dot{m} = \rho \cdot A \cdot V_r = \rho \cdot \pi \cdot R^2 \cdot \mathrm{V}_r \quad (9)$$

It can be obtained the input velocity of the mass flow (V_1) by means of the law of energy conservation.

$$\dot{m}ke_1 = C_p \cdot \dot{m}ke_1 + \dot{m}ke_2 \quad (10)$$

Substituting (8) and (9) into (10), leads to

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Month	V_2 (m/s)	H (h)	W_{out} (kW)	E (MWh)	ρ (kg/m³)
January	8.63	597.50	861.65	514.68	1.094
February	8.72	559.67	869.73	486.76	1.094
March	8.45	564.00	772.37	396.71	1.073
April	8.86	530.5	865.64	459.22	1.103
May	9.28	571.17	972.30	543.64	1.054
June	7.99	638.00	669.32	427.03	1.034
July	6.86	506.00	476.74	230.69	1.025
August	6.62	512.83	415.90	213.29	1.029
September	7.34	431.33	572.23	246.82	1.033
October	8.42	549.83	779.90	428.81	1.056
November	7.47	448.00	608.26	272.50	1.074
December	8.82	632.67	873.44	552.60	1.085

Table 5: Turbine 5.

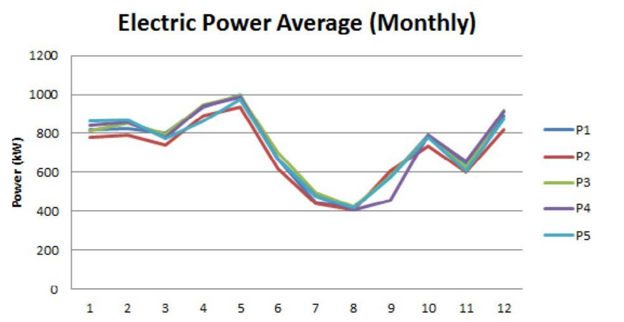

Figure 3: Monthly electric power average for 5 wind turbines.

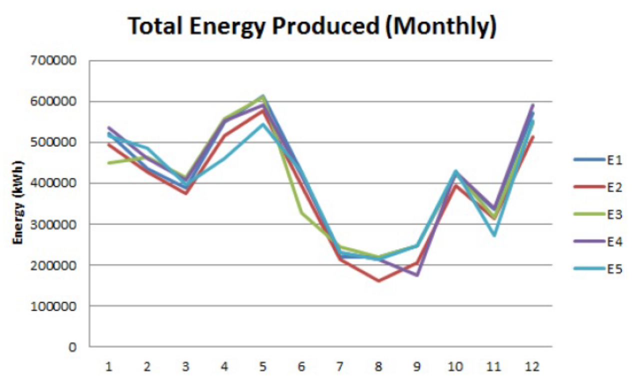

Figure 4: Total energy produced each month for the 5 wind turbines.

$$V_1 = \frac{V_2}{\sqrt{1-C_P}} \tag{11}$$

Energy efficiency is defined as

$$\eta = \frac{W_{out}}{W_{wind}} \tag{12}$$

Combining Equations (12) and (6) and then

$$\eta = \eta_{el} \cdot \eta_{mec} \cdot C_p \tag{13}$$

The total efficiency of the turbine is a function of both the rotor power coefficient and the mechanical and electrical efficiencies [21].

Exergetic analysis

Exergetic efficiency is defined as

$$\varepsilon = \frac{W_{out}}{W_u} \tag{14}$$

Where,

W_u is the useful power.

Neglecting the change in temperature of the mass flow when transferring the rotor, the useful power depends only on the change of pressure:

$$W_u = (p_1 - p_2)\frac{\dot{m}}{\rho} \tag{15}$$

Similarly, the loss of exergy (I) is defined as

$$I = W_u - W_{out} \tag{16}$$

Substituting the expression for the useful work (Equation 15) into exergetic efficiency (Equation 14), in addition to the equation for pressure as a function of velocity,

$$p_{1,2} = p_{at} + \frac{\rho}{2}V_{1,2}^2 \tag{17}$$

Is obtained then

$$\varepsilon = \frac{W_{out}}{W_u} = \frac{W_{out}}{\frac{\rho}{2}(V_1^2 - V_2^2)AV_r} \tag{18}$$

Replacing now the expressions for V_r (Equation 7) and V_1 (Equation 11):

$$\varepsilon = \frac{W_{out}}{\frac{\rho}{2}\left(\frac{V_2^2}{(1-C_p)} - V_2^2\right)A\frac{V_2}{2}\left(\frac{1}{\sqrt{1-C_p}}+1\right)} = \frac{4W_{out}}{\rho A\left(\frac{1}{\sqrt{1-C_p}}-1\right)\left(\frac{1}{\sqrt{1-C_p}}+1\right)^2 V_2^3} \tag{19}$$

Equation 19 relates the exergetic efficiency directly to the power coefficient for fixed values of V_2 and W_{out}.

Likewise, it can be find an expression for the loss of exergy:

$$I = W_u - W_{out} = \frac{\rho A}{4}\left(\frac{1}{\sqrt{1-C_p}}-1\right)\left(\frac{1}{\sqrt{1-C_p}}+1\right)^2 V_2^3 - W_{out} \tag{20}$$

Results and Discussions

Using Equation [19] for monthly average values of V_2 and W_{out} (Table 1), it can be found the relation between the efficiency variables ε and C_p. Figure 5 shows that as the power coefficient increased, the exergy efficiency decreased. The curve with the lowest values for the power coefficient in the allowed range {0<ε<1 and 0<C_p<0.59} were presented in the month of May, when the average speeds are higher, (alike the W_{out} output power, as shown in Figure 3). In the extreme case, the curve that shows the maximum values of power coefficient is the one that represents the month of August, which, conversely, refers to the lowest speeds and average output power. Figures 6-10 represent the relationship between the exergetic efficiency and the power coefficient for the months of May (blue) and August (red) for the five wind turbines.

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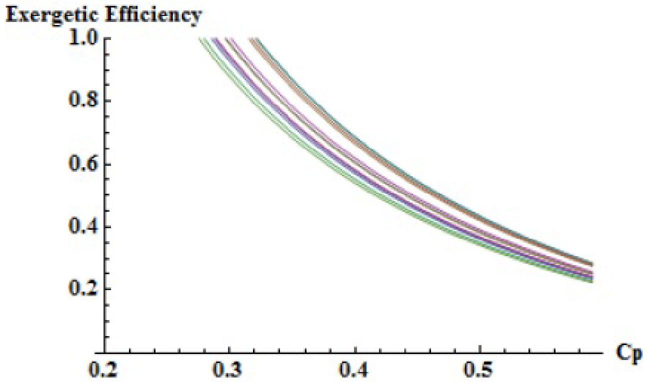

Figure 5: Relation between the power coefficient and exergetic efficiency for the 12 months of 2013 (Turbine 1).

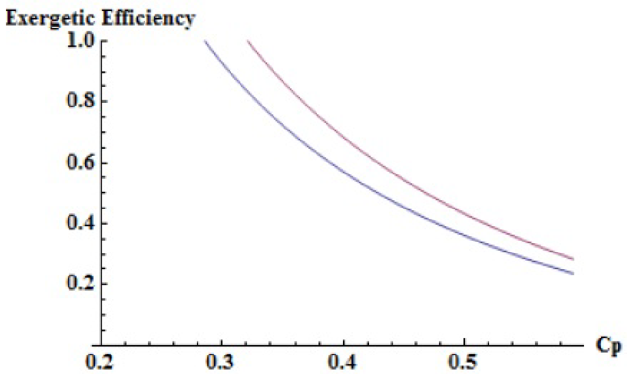

Figure 6: Relation between the power coefficient and exergetic efficiency for May (blue) and August (red) 2013 (Turbine 1).

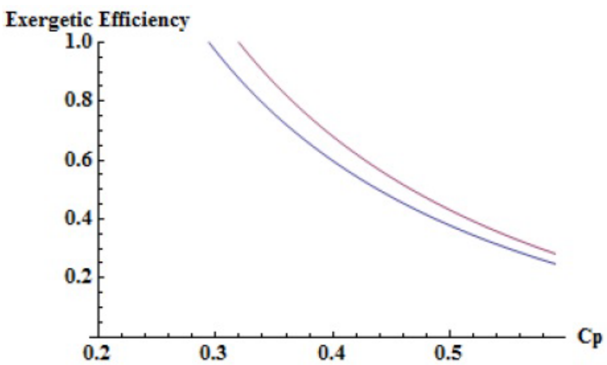

Figure 7: Relation between the power coefficient and exergetic efficiency for May (blue) and August (red) 2013 (Turbine 2).

In Figure 11 the curves for the month of May of the five wind turbines are compared.

Figure 12 is obtained using Equation 20 and shows the relationship between the loss of exergy and the power coefficient for the five turbines in the month of May 2013. Expectedly, the turbine 5, when showing the lowest effciency between 5, presents the greatest exergetic loss.

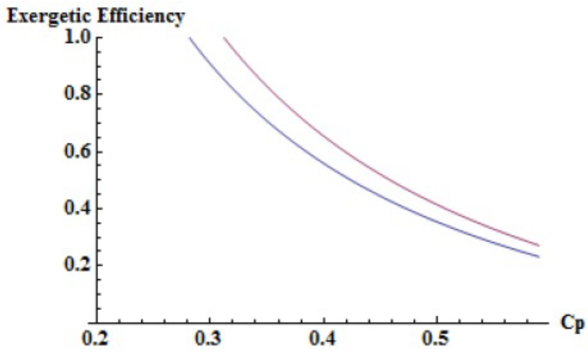

Figure 8: Relation between the power coefficient and exergetic efficiency for May (blue) and August (red) 2013 (Turbine 3).

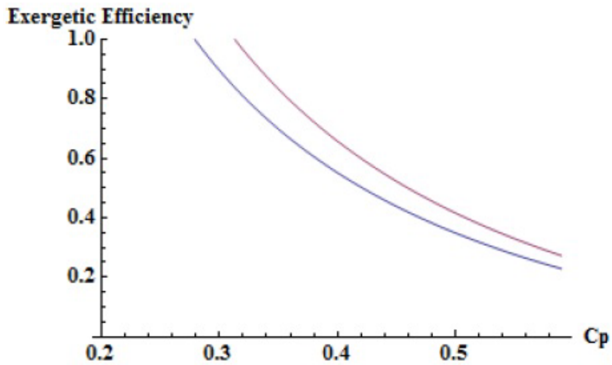

Figure 9: Relation between the power coefficient and exergetic efficiency for May (blue) and August (red) 2013 (Turbine 4).

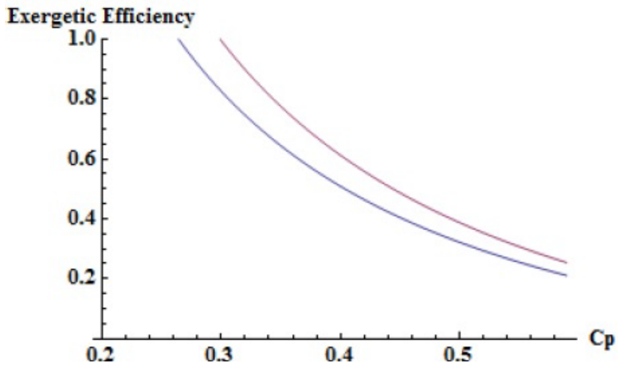

Figure 10: Relation between the power coefficient and exergetic efficiency for May (blue) and August (red) 2013 (Turbine 5).

Using Equation 18

$$\varepsilon = \frac{W_{out}}{W_u} = \frac{W_{out}}{\frac{\rho}{2}(V_1^2 - V_2^2)AV_r}$$

It can be directly replace $V_1 = \frac{V_2}{\sqrt{1-C_p}}$ and $V_r = \frac{V_1 + V_2}{2}$ to get to

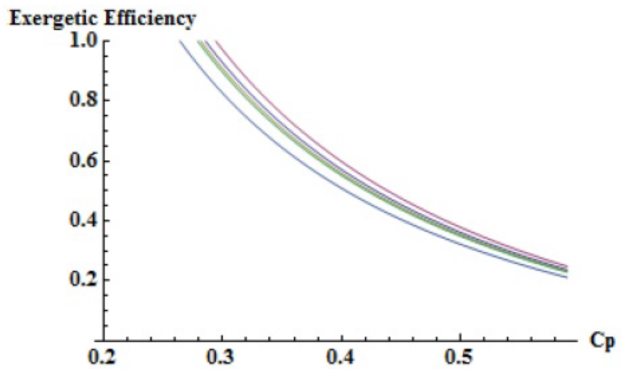

Figure 11: Relation between power coefficient and exergetic efficiency for the 5 turbines in May 2013.

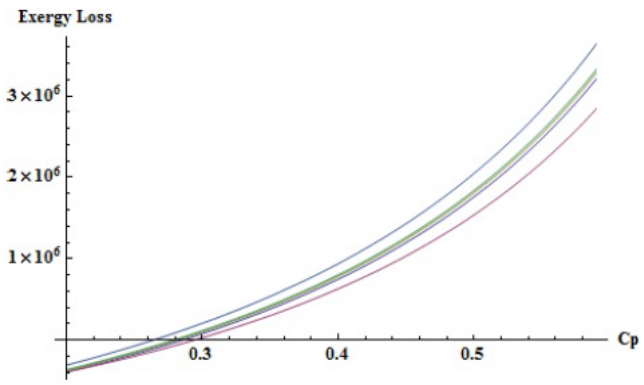

Figure 12: Relation between the power coefficient and exergy loss (in W) for the 5 turbines in May 2013.

$$\varepsilon = \frac{4\ .\ W_{out}}{\rho\ .\ A\ .\ \left(\frac{1}{1-C_p}-1\right)\left(V_1+V_2\right)\ .\ V_2^2} \tag{21}$$

This equation was plotted for turbine 1 in May 2013, the validity intervals of the variables are {0<ε<1}, {0<C_p<0.59} and {4<V_1<25}. Analyzing equation 19, it could be find a relation between the exergetic efficiency and the power coefficient. The equation became characteristic for each turbine (defining the relationship between the two important performance variables in this analysis), by setting the values of V_2 and W_{out} with measured data.

The relationship given in Equation 21 shows how exergy efficiency, power coefficient and input velocity V_1 varied each another. Figure 13 ensures (when reviewing the slopes) that exergetic efficiency decreases to a greater extent with respect to the power coefficient than with regard to the velocity in the bounded intervals of definition.

Conclusion

In the present study, the behavior of five wind turbines of the same model in the La Rumorosa I wind farm was analyzed. Even though, they are the same kind of turbine, when comparing their individual performance, it can be found that there are notable differences in both, their exergetic efficiency and the power coefficient. Differing the way exergy studies have previously been performed on wind turbines. This method was only based on using parameters obtained from the wind

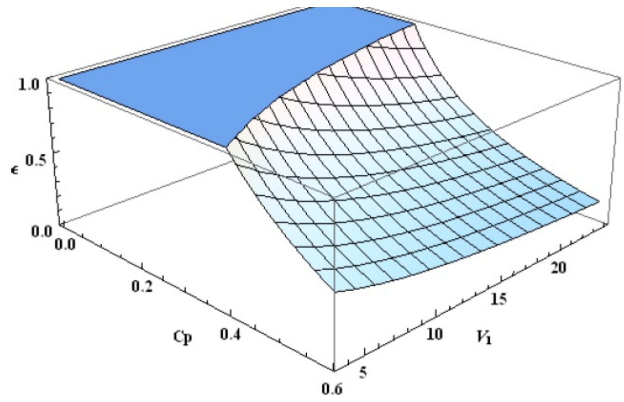

Figure 13: Relation between the power coefficient, exergetic efficiency and input velocity V_1, for turbine 1 in May 2013.

turbine (V_2, W_{out}). In addition, it only measured the time the wind turbine was producing energy (worked hours *H*).

The percentages of the annual time (2013) that the wind turbines produced energy (worked hours) were of 76.72%, 74.14%, 73.51%, 76.15% and 74.67%, for turbines 1 to 5 respectively.

Equation 19 demonstrate the characteristic exergy performance of the wind turbine by exposing all the parameters (V_1, V_2, ρ, W_{out} and C_p) that are involved in the conversion of wind energy to electric energy.

The graphs demonstrate that the exergetic efficiency decreased as the power coefficient increased, contrary to previous studies results, in which a linear relationship between the parameters has been reported. On the other hand, when we consider the value of C_p constant, we confirmed that the exergetic efficiency is greater for months with average V_2 approximately 6-7 m/s, like July and August. Furthermore, for months with an average V_2 of about 8-9 m/s the exergetic efficiency is smaller, as in April and May. This corresponds to the normal behavior of the wind speed (V_1) in the region, being lower in the summer and higher in spring and autumn [22,23].

According to the axial induction factor, the aforementioned data is an indication that the Cp has a maximum corresponding to wind speeds (V_1) between 9 and 11 m/s for the wind turbine analyzed.

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