Energy and Exergy Analysis with Regression and Optimization of Wind Power Plant of Jamshoro Pakistan

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ABSTRACT

The study was conducted to investigate the wind power plant with the method of energy and exergy analysis as to determine the effectiveness of energy system. In order to precisely, quantitatively and qualitatively ascertain the system performance the comprehensive and combined energy (first law) and exergy (second law) technique was employed. It was found that neither energy nor exergy efficiency could go beyond 59.3% in the wind power plant and the rotor power is dependent on wind speed and that speed is limited in the form of cut-in speed of 3 m/s and cut-out speed of 25 m/s of wind power plant. The rated speed, rotor diameter and Swept Area of wind power plant is 13.07 m/s, 114 m and 10207 m sq respectively. Speed from 6 to 14 m/s is the optimal range for the efficiencies of both energy and exergy and through the optimization technique Quadratic Approximations Method it was found that at the speed of 7m/s the efficiencies of energy and exergy would be maximum. The regression analysis was also conducted to correlate the dependent variables like Energy efficiency, Exergy Efficiency and Rotor power with the independent variable to establish the relationship.

Key words: *Energy, Exergy, Speed, Wind, Optimization, Regression, Efficiency*

INTRODUCTION

Clean, green and environmentally friendly energy sources like Wind and Solar have ushered a sort of revolution in revitalizing the energy sector which was earlier heavily dependent on fossil fuels. Sustainable, clean, green and inexhaustible energy sources have become the vital for power production to re-place fossil fuels so in order to harness optimally green energy it is important to precisely and factually assess the system performance through the combined technique of energy and exergy analysis [1]. The integrated approach has become crucial in determining the exact magnitude and location of energy loss and exergy destruction which then helps in carrying out qualitative assessment of system performance and efficiency [2]. The majority of wind energy research focuses on maximizing energy harvesting [3]. Energy and energy efficiency of four distinct wind turbines, including the NACA 63 (2)-215 Airfoil, the FX 63-137 Airfoil, the Savvy VAWT, and the Zephyr VAWT, are measured both horizontally and vertically. Then, by comparing four distinct definitions of output velocity (V2), efficiency (energy and exergy) are calculated by the variation of entrance velocity (V1) versus four distinct V2 [4]. Exergy efficiency was shown to vary with wind speed, ranging from 0 to 48.7% [5]. Analysis revealed that when wind speeds range from 5 to 9 m/s, energy efficiency varies between 35 and 45% [6]. The 13th chapter of the book "Design and Performance Optimization of Renewable Energy Systems" has an energy analysis of wind turbines for the Tehran area [7]. Additionally, research was done on the energy efficiency of wind turbines at four distinct Nigerian locations [8]. Examined the energy analysis of renewable energy sources, such as wind turbines however wind speeds exceeding 9 m/s are taken to be zero, which is not realistic in the real world [9]. Using experimental data from wind fields, artificial neural networks were used to estimate and optimize wind turbine power [10].

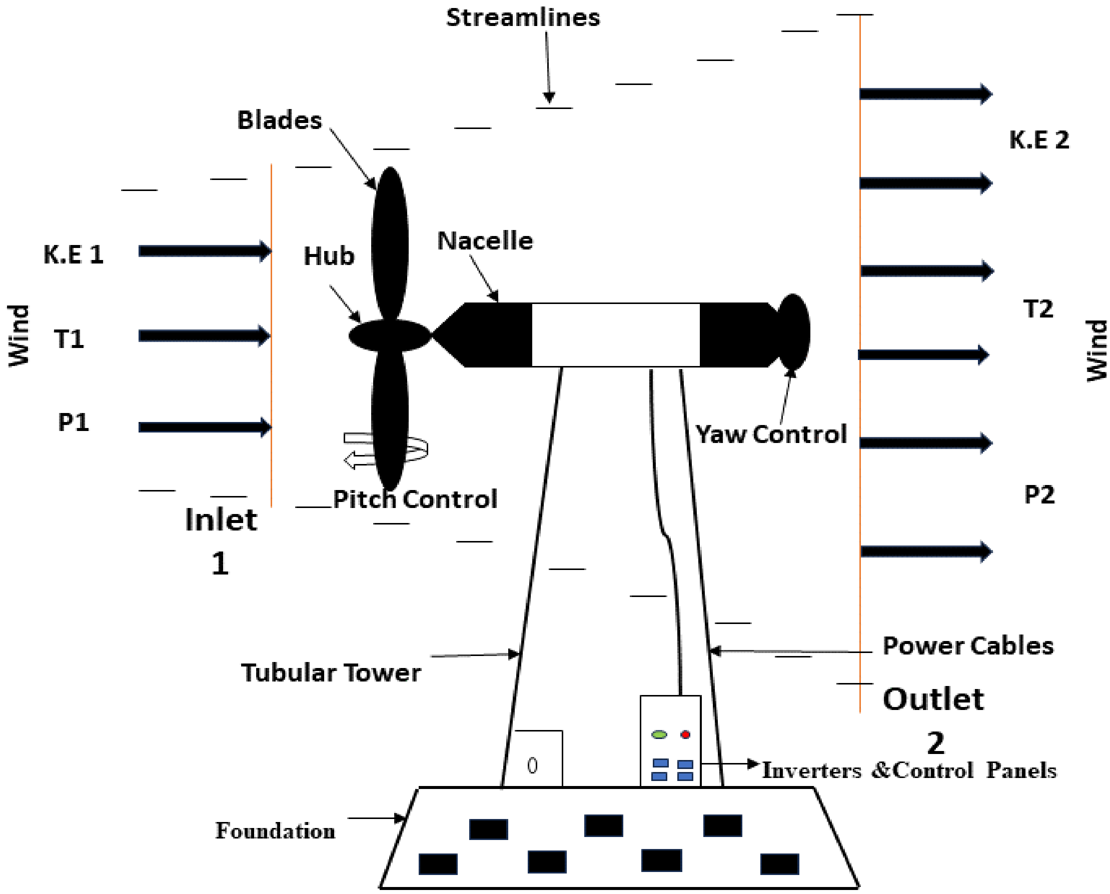

Figure1. The side view of horizontal axis three blade wind turbine in the Wind Farm

Table 1. Technical Specifications of Jamshoro Wind Farm

Installed Capacity of Wind Farm (MW)	50 MW
Number of Wind Turbine Units/Size of each unit	25×2.0 MW
Number of blades	3
Rotor Diameter	114 m
Swept Area	10207 m^2
Cut-in Wind Speed	3 m/s
Cut-out wind speed	25 m/s
Rated Wind speed	13.07 m/s
Survival Wind speed	59.5 m/s (max 3 sec)
Blade Length	56 m
Hub Height	93 m

CASE STUDY

The wind power plant of 50 MW is located in Jamshoro district as Sindh Province is very suitable for the installation of Wind Farms owing to long windy coastline of 290 Km. The primary shaft (low-speed shaft), gearbox, high-speed shaft, bearing, and generator are all located within the nacelle. Wind turbines often begin to rotate at a very slow pace, but this slow rotation is insufficient to produce power. In order to generate electricity, a high-speed shaft is connected to a generator at critical rpms, which are typically 1000–1800 rpms. This increases speed with the aid of a gearbox in the nacelle. On top of the nacelle are installed an anemometer and a wind vane to ascertain the direction and speed of the wind. For strong wind turbines, a steel tube tower with a conical shape, as seen in Figure 1, is favored over lattice towers. This illustration shows the principal parts of the investigated horizontal wind axis turbine. The capacity of horizontal axis turbines (shown in Figure 1) to cover a larger swept area makes them superior to vertical axis turbines. Cut-in (3 m/s) and cut-out (25 m/s) as shown in table 1 are the speeds at which wind turbines begin to generate power, and then shuts down respectively.

The following assumptions are assumed for the Wind Farm:

i) It is assumed that wind flow is stable, unidimensional, and incompressible.

ii) Heat transfer or phase shifts are not taken into consideration.

iii) Temperature and pressure differences at a wind turbine's inlet and exit are taken into account.

iv) The influence of humidity is neglected.

ENERGY AND EXERGY FORMULATIONS

$$K.E = \frac{I}{2} * m * v^2 \quad (1)$$

In the case of wind mass calculation can be expressed in terms of density and moreover the mass flow rate of air can be expressed as:

$$m = \rho * V \quad (2)$$

$$\check{m} = \rho * A * v \quad (3)$$

So the above K.E can be written as:

$$K.E = \frac{I}{2} * \rho * V * v^2 \quad (4)$$

Wind chill temperature can be found from the expression if we have velocity and air:

$$T_{windchill} = 35.74 + 0.6215 * T_{air} - 35.75(v^{0.16}) + 0.4274 * T_{air} * v^{0.16} \quad (5)$$

Momentum change expression is:

$$P_m = \check{m} * (v_1 - v_2) \quad (6)$$

The rate of extracted kinetic Energy (K.E) is:

$$W_{k.E} = \check{m} * (v_1 - v_2) * v_{avg} \quad (7)$$

Where $v_{avg} = \frac{v_1+v_2}{2}$ (8)

Change in K.E is expressed:

$K.E = m^{ˇ} * (v_1^2 - v_2^2)$ (9)

Rotor Power is expressed as:

$P = \boldsymbol{\rho} * \boldsymbol{A} * ((v_1 - v_2) * v_{avg}$ (10)

$P = \rho * A * v_1^3/4*(\alpha + 1)(1\text{-}\alpha^2)$ (11)

$\alpha = v_2/v_1$ (12)

$(\alpha + 1)(1\text{-}\alpha^2)$ is called Power Coefficient (C.P)

Power reaches maximum value when $\alpha = 1/3$ when the outlet wind velocity is equal to the one third of the inlet velocity. An ideal wind mill could extract 0.593 of the power by the wind when $\alpha = 1/3$. This is known as "Betz law".

Energy Efficiency $= \frac{Useful\ Work\ Output}{Energy\ input}$ (13)

The exergy of fluid that is wind is:

$\boldsymbol{\Psi}_f = \frac{1}{2} * \boldsymbol{\rho} * v^3$ (14)

$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_{destruction}$ (15)

$Ex_{phy} = (H - H_0) + T_0(S - S_0)$ (16)

$\Delta H = m^{ˇ}C_p(T_2 - T_1)$ (17)

$\Delta S = mT_0(C_p \ln\left(\frac{T_2}{T_1}\right) - Rln\left(\frac{P_2}{P_1}\right) - \frac{Q_{loss}}{T_0})$ (18)

$Q_{loss} = m^{ˇ}C_p(T_2 - T_{avg})$ (19)

$T_{avg} = \frac{T_1+T_2}{2}$ (20)

Exergy Efficiency $= \frac{Useful\ Work\ Output}{Exergy\ input}$ (21)

RESULTS & DISCUSSION

The effect of wind speed which is independent variable on the dependent variables like Exergy efficiency, Energy efficiency and Power of Rotor was witnessed and it was observed that high velocity is determinantal and ineffective and optimal range of speed which found to be 6 to 14 m/s is the suitable for the Wind Farm as shown in Figure 2,3, 4 &5. In the regression analysis the following below correlations were established between the independent variable like wind speed and dependent variables like Exergy efficiency, Energy efficiency & Power rotor. In the present study of the wind power plant for the Optimization method the Quadratic

Approximations Method an iterative method when there is one degree of freedom was used to get the optimal and the best value of wind speed that at 7 m/s all the dependent parameters are maximum and give maximum output so the wind power plant must operate on its optimized value of wind speed.

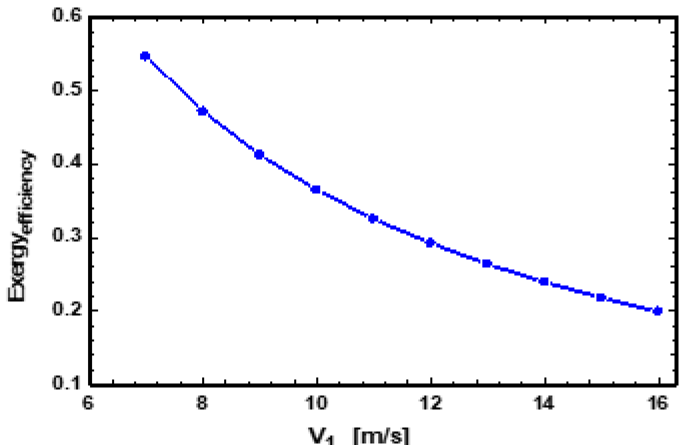

Figure 2. Wind speed effect on Exergy Efficiency

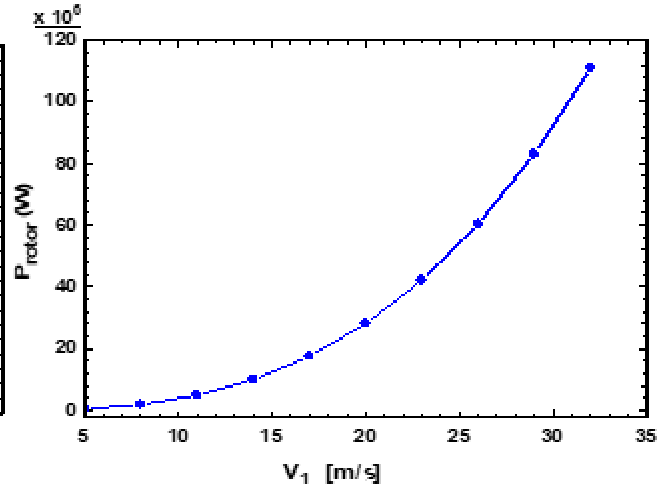

Figure 3. Wind speed effect on Protor

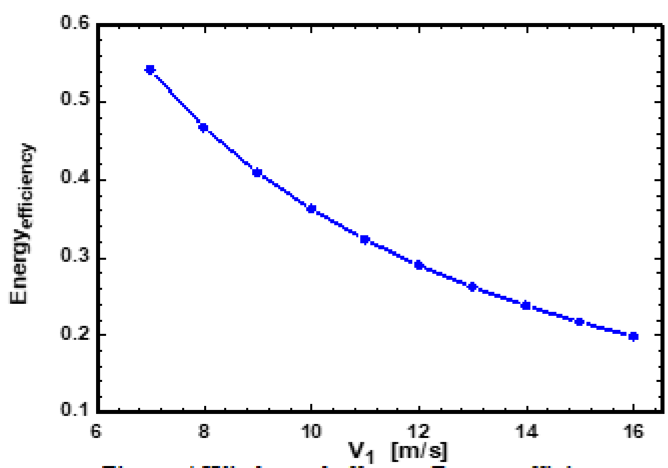

Figure 4.Wind speed effect on Energy efficiency

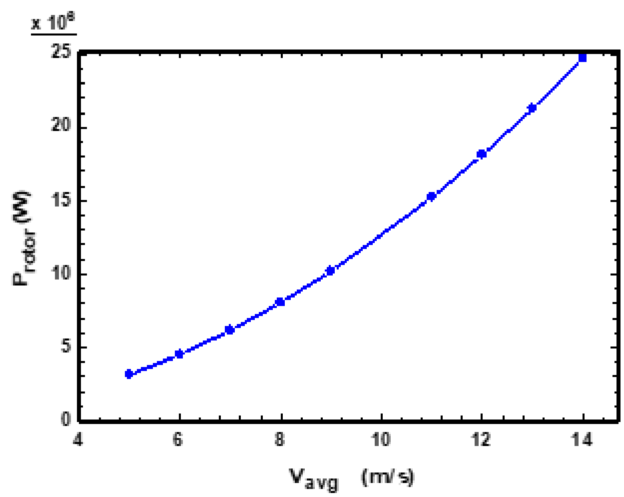

Figure 5. Average Wind speed effect on Protor

The following correlations were established by the regression analysis.

$$\text{Exergy}_{\text{efficiency}} = 2.65841126E+00 - 7.48392392E-01 * V_1 + 1.14163443E-01 * V_1^2 - 1.03566766E-02 * V_1^3 + 5.56590947E-04 * V_1^4 - 1.64001246E-05 * V_1^5 + 2.04471656E-07 * V_1^6$$

$$\text{Energy}_{\text{efficiency}} = 2.63479294E+00 - 7.41723273E-01 * V_1 + 1.13152931E-01 * V_1^2 - 1.02651532E-02 * V_1^3 + 5.51671451E-04 * V_1^4 - 1.62551211E-05 * V_1^5 + 2.02663465E-07 * V_1^6$$

$$P_{\text{rotor}} = -8.43991313E+04 - 2.81330437E+04 * V_1 + 9.37768125E+03 * V_1^2 + 3.12589375E+03 * V_1^3 - 3.47523619E-10 * V_1^4 + 7.72369126E-12 * V_1^5 - 6.78649548E-14 * V_1^6$$

$$P_{rotor} = 1.58935060E-04 - 1.13737801E-04 * V_{avg} + 1.25911000E+05 * V_{avg}^2 - 4.94646442E-06 * V_{avg}^3 + 4.06837492E-07 * V_{avg}^4 - 1.74064948E-08 * V_{avg}^5 + 3.03215789E-10 * V_{avg}^6$$

CONCLUSION

It was observed that the wind speed is the vital factor in the power generation through wind. It was also found that neither energy nor exergy efficiency could go beyond 59.3% in the wind power plant and the rotor power is dependent on wind speed and that speed is limited in the form of cut-in speed of 3 m/s and cut-out speed of 25 m/s of wind power plant. Increasing speed has adverse effect on the performance parameters and there is the optimal range of speed from 6 to 14 m/s and the optimization speed is 7 m/s where energy and exergy efficiencies are maximum whereas 13.07 m/s is the rated speed. In order to establish the proper correlation, the regression analysis was carried out to achieve that objective.

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