Minimization of the Cost of Energy of Wind Turbine through Various Power Models

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Abstract: - Wind energy is the world's free form of energy, besides that it has expenses, because of the wind turbine construction and maintenance. The Cost of Energy (CoE) of the wind turbine is used to estimate the amount of time it takes to recover the cost of an investment by the wind farm owners. Hence optimization of the wind turbine CoE will make wind a very competent source of energy. In this article, the wind speed is modified using three alternative distributions in order to reduce the wind turbine CoE, and the turbine Annual Energy Production (AEP) is evaluated. Mathematical functions such as linear, quadratic and cubic have been used to model the wind power. This study enables us to figure out the minimum turbine CoE among the mathematical distributions, along with the optimum mathematical function for wind power modelling and to optimize the rotor radius of turbine.

Key-Words: - Annual Energy Production, Cost of Energy, Dagum distribution, rated wind power, rated wind speed**.**

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1 Introduction

The entire cost of wind energy is primarily determined by wind turbine choices depending on wind parameters. In [3], author has briefly explained the various types of wind turbines and also the elements that most affect the cost. In [13], author has offered an analysis of the wind power strategies in several nations. Appropriate power strategies may improve the installations of the wind turbine. The protection expenses of offshore wind turbines through various methods have been investigated [4]. The cost of turbine in the offshore is extremely correlated to the volume & the nacelle weight. It is more noteworthy and useful to reduce the turbine CoE [12]. Quite a lot of investigations have been made to reduce the turbine CoE. In [2], a method for multidisciplinary plan enhancement for offshore wind turbines deliberated. They explored the tower design and the rotor effects on the turbine CoE. In [11] the best possible wind turbine for a particular station to catch the most extreme power or else to decrease turbine CoE with the utilization of self-sorting out maps were chosen. An unhindered wind farm design optimization technique was suggested to concurrently enhance the turbines organization and assortment [6]. A model have established depending on plentiful evolutionary computing procedures and blade component motion theory for the assortment of wind turbine [15]. A method for calculating the impact of changes in the climate on wind energy prices suggested and familiarized a new Weibull transfer feature for characterizing the environment indicator [7]. The selection of a cost-effective wind turbine for a wind project is one of the most critical tasks. In order to overcome that, a system have been developed for measuring wind turbines based on energy costs [1]. In [8], the CoE of a turbine is demonstrated by the use of eight variables: turbine rotor diameter, blade number, hub height H, rotor speed, rated wind speed V_r, rated wind power P_r, regulation type and generator type. The method of optimization has become a complicated one, because it has several variables. In [14], the CoE model of a turbine is simplified to four variables: R, P_r, tip-speed ratio (TSR) and H. The TSR is an operational parameter, while the other three are physical properties of the turbine. The S-type curve, a widely used method for representing the output power of the turbine is being modified [9]. In this approach, the CoE of a turbine is simplified to a function of three variables: rotor diameter, turbine capacity and H. A mathematical model is developed to minimize the CoE using only two variables: V_r and P_r. As a result, CoE minimization is progressively decreased from eight variables to only two [5].

2 Types and Operating regions of Wind Turbines

There are various wind turbine models in use these days. The rotation of the rotor shaft, the mode of operation, and the power rating of wind turbines are used to rate them. Based on the rotation, there are two types of wind turbines, namely vertical-axis and horizontal-axis wind turbines. According to the operation of the turbine it is classified as fixed and variable-speed wind turbines. Based on its power level, it is categorized as a small turbine with less than 100 kW of power, moderate turbine with power between 100 kW – 1 MW and a massive turbine of power above 1 MW.

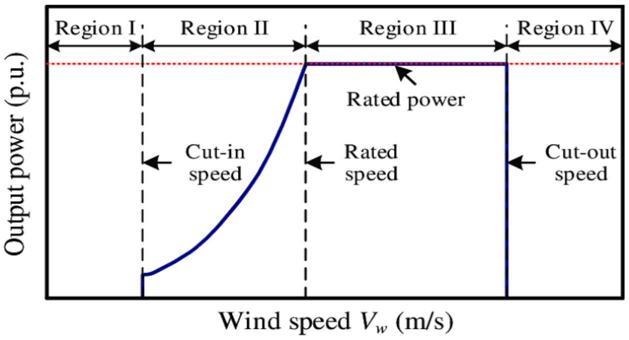


Fig.1 A wind turbine's operational zones

A current wind turbine's four significant operating parts are shown in Fig.1. There will be little power in area I since the wind speed is less than the cut-in speed (V_c), and the turbine will be in backup mode. Wind speed in region II will be higher than V_c but lower than the rated speed (Vr), causing the turbine in this region to produce extreme power. Whereas the wind speed in the region III is above V_r and below the cut-out speed (V_f) and thus the turbine's output power is limited to the rated power (P_r). In region IV, the wind speed will be greater than V_f, so the turbine will be shut down to avoid damage. By optimizing turbine output in area II, we can achieve maximum turbine yield power. Thus, the power (P) of the wind turbine in various operating regions is:

$$P=\begin{cases} 0, & V \le V_c \\ P(V), & V_c < V \le V_r \\ P_r, & V_r < V \le V_f \\ 0 & V > V_f \end{cases} \qquad (1)$$

where V is the wind speed.

3 Cost Minimization Methodology

The purpose of this research is to provide a scientific technique for restricting a turbine's CoE by utilizing several probability distributions and determining the best distribution to reduce the CoE for a given location. The ratio of the overall turbine cost to the turbine's annual energy production (AEP) is known as the turbine CoE. It has been simplified and reduced to an element of two variables, P_r and V_r [5]. Hence in the process of cost minimization, the P_r varies from 1 – 3 MW with the increment of 0.1 MW and the V_r varies from 8 – 16 m/s with the increment of 0.5 m/s.

The NREL cost model [10] is used to calculate the overall cost of a wind turbine.

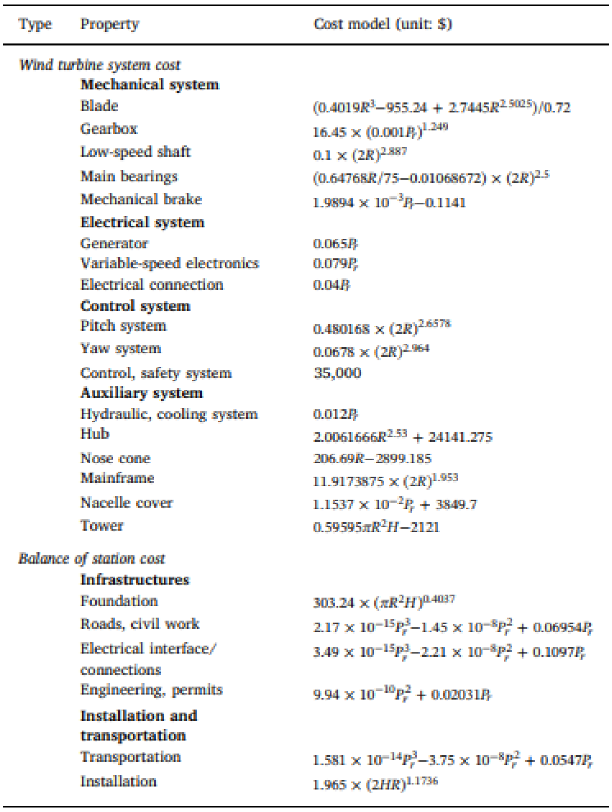
$$\text{Cost} = \text{ICC} \times \text{FCR} + \text{AOE} \qquad (2)$$

where ICC - Initial Capital Cost,
FCR - Fixed Charge Rate of the turbine
AOE - Annual Operating Expense of the turbine.

All these values are obtained from NREL. It must be clarified that the cost of the wind turbine is the average annual cost over the intended lifetime of the wind turbine.

The ICC is the total of the Balance-of-Station (BoS) and wind turbine system cost, which is comprised of numerous subsystems, containing electronic, electrical, and mechanical control systems, as well as some supplementary systems. The BoS cost contains infrastructure costs such as framework, roads, licenses, electrical wiring, installation and transportation costs. Table 1 illustrates the detailed initial capital cost of the turbine. The cost of each element or infrastructure depends on the rotor radius of the turbine (R), the rated power (Pr) of the turbine and the height of the hub (H).

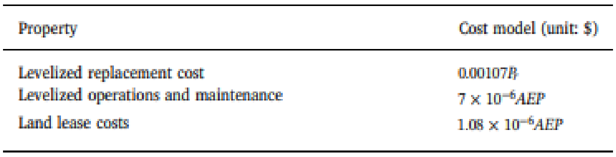
Table 1. ICC of a wind turbine [10]



Type	Property	Cost model (unit: \$)
Wind turbine system cost		
	Mechanical system	
	Blade	$(0.4019R^3-955.24+2.7445R^{2.5025})/0.72$
	Gearbox	$16.45\times(0.001P_r)^{1.249}$
	Low-speed shaft	$0.1\times(2R)^{2.887}$
	Main bearings	$(0.64768R/75-0.01068672)\times(2R)^{2.5}$
	Mechanical brake	$1.9894\times10^{-3}P_r-0.1141$
	Electrical system	
	Generator	$0.065P_r$
	Variable-speed electronics	$0.079P_r$
	Electrical connection	$0.04P_r$
	Control system	
	Pitch system	$0.480168\times(2R)^{2.6578}$
	Yaw system	$0.0678\times(2R)^{2.964}$
	Control, safety system	35,000
	Auxiliary system	
	Hydraulic, cooling system	$0.012P_r$
	Hub	$2.0061666R^{2.53}+24141.275$
	Nose cone	$206.69R-2899.185$
	Mainframe	$11.9173875\times(2R)^{1.953}$
	Nacelle cover	$1.1537\times10^{-2}P_r+3849.7$
	Tower	$0.59595\pi R^2H-2121$
Balance of station cost		
	Infrastructures	
	Foundation	$303.24\times(\pi R^2H)^{0.4037}$
	Roads, civil work	$2.17\times10^{-15}P_r^3-1.45\times10^{-8}P_r^2+0.06954P_r$
	Electrical interface/ connections	$3.49\times10^{-15}P_r^3-2.21\times10^{-8}P_r^2+0.1097P_r$
	Engineering, permits	$9.94\times10^{-10}P_r^2+0.02031P_r$
	Installation and transportation	
	Transportation	$1.581\times10^{-14}P_r^3-3.75\times10^{-8}P_r^2+0.0547P_r$
	Installation	$1.965\times(2HR)^{1.1736}$

The turbine's AOE includes land-buying costs, construction, maintenance and replacement costs. These costs are determined by the rated turbine power or the turbine's AEP. The overall turbine cost is calculated using the following factors: R, H, P_r, and annual turbine energy production. Table 2 shows the specifics of each expenses.

Table 2. AOE of a wind turbine [10]



Property	Cost model (unit: \$)
Levelized replacement cost	$0.00107P_r$
Levelized operations and maintenance	$7\times10^{-6}AEP$
Land lease costs	$1.08\times10^{-6}AEP$

The AEP for a turbine is calculated as follows:

$$AEP = 8760\times P_{ave}\times(1-\mu) \tag{3}$$

where μ - total turbine losses represented by a constant 0.17 and the mean turbine output power $P_{ave,}$ is calculated as

$$P_{ave}=\int_0^{\infty} Pf(V)dV \tag{4}$$

From the equation (1)

$$P_{ave}=\int_{V_c}^{V_r} P(V)f(V)dV+\int_{V_r}^{V_f} P_r f(V)dV \tag{5}$$

3.1 Operating Procedure of Proposed Methodology

The operating procedure of minimization of turbine cost of energy is explained in the stepwise algorithm as given below:

Step 1: Input the Scale and Shape parameter values of the data.

Step 2: Set the variable range for rated wind power P_r and rated wind speed V_r as $\left[P_r,P_{r_{\max}}\right]$, $\left[V_{r_{\min}},V_{r_{\max}}\right]$.

Step 3: Set the incremental step (m, n) for P_r, V_r.

Step 4: Initialize P_r=m(i)+$P_{r_{\min}}$ with i=0

Step 5: Initialize V_r=n(j)+$V_{r_{\min}}$ with j=0

Step 6: If $P_r<P_{r_{\max}}\,\&\,V_r<V_{r_{\max}}$, evaluate the Cost, AEP, and CoE else go to Step 5 with the increment j=j+1

Step 7: If $V_r>V_{r_{\max}}$, then go to Step 4 with the increment i=i+1.

Step 8: If $P_r>P_{r_{\max}}$, then print the minimum CoE and optimal P_r and V_r.

3.2 Rotor Radius of a Turbine

The turbine's rotor radius R is a function rated wind power and rated wind speed.

$$R=\sqrt{\frac{2P_r}{\rho\pi C_{pr}\eta_{mf}\eta_{gf}V_r^{\,3}}} \tag{6}$$

where ρ - Density of the air (1.225 kg/m3)

C_{pr} - The blade's aerodynamic efficiency (0.45)

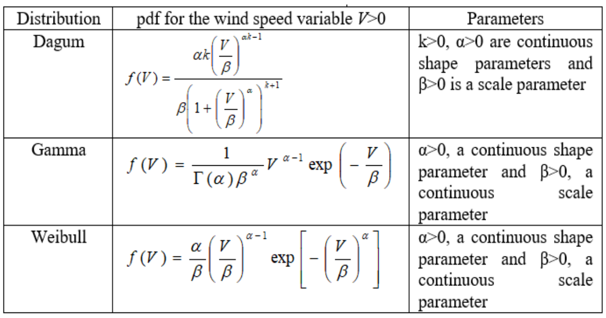
η_{mf} - Efficiency of the gearbox (0.96)

η_{gf} - Efficiency of the generator (0.97)

3.3 Wind Speed Models

The P_{ave} has a significant part in reducing turbine CoE. In this article, the Dagum, Gamma, and Weibull distributions were used to simulate wind speed data from six distinct sites.

Table 3. Probability density functions (pdf) and parameters of the examined distributions



Distribution	pdf for the wind speed variable V>0	Parameters
Dagum	$f(V)=\dfrac{\alpha k\left(\frac{V}{\beta}\right)^{\alpha k-1}}{\beta\left(1+\left(\frac{V}{\beta}\right)^{\alpha}\right)^{k+1}}$	k>0, α>0 are continuous shape parameters and β>0 is a scale parameter
Gamma	$f(V)=\dfrac{1}{\Gamma(\alpha)\beta^{\alpha}}V^{\alpha-1}\exp\left(-\dfrac{V}{\beta}\right)$	α>0, a continuous shape parameter and β>0, a continuous scale parameter
Weibull	$f(V)=\dfrac{\alpha}{\beta}\left(\dfrac{V}{\beta}\right)^{\alpha-1}\exp\left[-\left(\dfrac{V}{\beta}\right)^{\alpha}\right]$	α>0, a continuous shape parameter and β>0, a continuous scale parameter

In the equation (5), replacing the pdf listed in Table 3 we get P_{ave} for the Dagum, Gamma, and Weibull distributions respectively.

3.4. Wind Power Models

The turbine yield power between the regions V_c and V_r is characterized by a mathematical equation of a polynomial function, a logistic four-parameter function, or a logistic five-parameter function in cost minimization analysis. The output power of the turbine is defined in this work using polynomial equations of linear, quadratic, and cubic models.

Linear model. The linear model is fairly straightforward, requiring only the variables V_c, V_r, and P_r. In region II, the turbine yield power will increase linearly as the wind speed increases. The linear power model formulation is provided in equation (7).

$$P(V)=\frac{V-V_c}{V_r-V_c}P_r \tag{7}$$

By putting the wind power of linear model (7) in equation (5), we get the linearly modelled mean turbine output power.

$$P_{ave}=\int_{V_c}^{V_r}\frac{V-V_c}{V_r-V_c}P_r\,f(V)dV+\int_{V_r}^{V_f}P_r\,f(V)dV$$

$$=\frac{P_r}{V_r-V_c}\int_{V_c}^{V_r}(V-V_c)f(V)dV+\int_{V_r}^{V_f}P_r\,f(V)dV$$

(8)

Quadratic model. The wind turbine yield power in quadratic function is presumed to be proportionate to square of the wind speed in the region II. To describe the power using quadratic model, the values needed are the V_c, V_r and P_r.

$$P(V)=\frac{V^2-V_c^{\,2}}{V_r^{\,2}-V_c^{\,2}}P_r \tag{9}$$

By replacing the wind power from quadratic model (9) into (5), we get the mean turbine output power, which is quadratically modelled as

$$P_{ave}=\int_{V_c}^{V_r}\frac{V^2-V_c^{\,2}}{V_r^{\,2}-V_c^{\,2}}P_r\,f(V)dV+\int_{V_r}^{V_f}P_r\,f(V)dV$$

$$=\frac{P_r}{V_r^{\,2}-V_c^{\,2}}\int_{V_c}^{V_r}(V^2-V_c^{\,2})f(V)dV+\int_{V_r}^{V_f}P_r\,f(V)dV$$

(10)

Cubic model. The turbine yield power in cubic expression, is expected to be proportionate to cube of the wind speed, which indicates the turbine proficiency is presumed to be a constant. The cubic power model is given as

$$P(V)=\frac{V^3-V_c^{\,3}}{V_r^{\,3}-V_c^{\,3}}P_r \tag{11}$$

Substituting the cubic power model (11) in equation (5), yields the cubically modelled mean turbine output power.

$$P_{ave}=\int_{V_c}^{V_r}\frac{V^3-V_c^{\,3}}{V_r^{\,3}-V_c^{\,3}}P_r\,f(V)dV+\int_{V_r}^{V_f}P_r\,f(V)dV$$

$$=\frac{P_r}{V_r^{\,3}-V_c^{\,3}}\int_{V_c}^{V_r}(V^3-V_c^{\,3})f(V)dV+\int_{V_r}^{V_f}P_r\,f(V)dV \tag{12}$$

3. Results and Discussion

The findings of this study are deliberated further down.

4.1 Data description

To offer a concrete presentation concerning the above conferred approaches, real time data sets have been considered from the U.S. National Renewable Energy Laboratory and evaluated in this paper. October – December 2006 hourly data were used from six separate wind farms. The descriptive statistics of the tested data are given in the Table 4.

In the process of turbine CoE minimization, the shape and scale parameters for every distribution at a given station are provided as inputs. As a result, the parameters are calculated using the Maximum Likelihood Estimate (see Table 5).

Table 4. Descriptive statistics of the wind speed data in various stations

Data	Sample size	Max Speed (m/s)	Mean	Variance	Std. Deviation	Std. Error	Skewness	Kurtosis
1	2208	17.065	6.8626	7.9181	2.8139	0.05988	0.0112	-0.111
2	5000	16.574	8.9792	11.605	3.4066	0.04818	-0.1507	-0.596
3	5000	17.768	9.1766	14.133	3.7594	0.05317	0.05971	-0.642
4	5000	17.191	8.9384	13.046	3.612	0.05108	-0.0186	-0.746
5	5000	19.483	9.3576	15.716	3.9644	0.05606	0.08845	-0.383
6	5000	19.924	9.0505	14.308	3.7826	0.05349	-0.0398	-0.626

Table 5. Parameters of six data

Data	Dagum Distribution			Gamma Distribution		Weibull Distribution	
	k	α	β	α	β	α	β
Data 1	0.1892	10.27	9.9515	5.9494	1.1536	2.3435	7.8114
Data 2	0.1537	12.775	13.321	6.9478	1.2924	2.5738	10.183
Data 3	0.2041	9.2986	13.509	5.9584	1.5401	2.4472	10.4
Data 4	0.1277	13.83	13.954	6.1239	1.4596	2.4848	10.119
Data 5	0.2127	8.7206	13.697	5.5717	1.6795	2.2435	10.685
Data 6	0.1442	12.221	13.922	5.7247	1.5809	2.331	10.283

The minimum CoE has been identified, as well as the optimized P_r and V_r, by using the scale and shape parameters as inputs and altering the V_r and P_r. Table 6 shows the minimum CoE for the six stations that were modelled using the Dagum, Gamma, and Weibull distributions with three different methodologies.

Table 6. Minimum Cost of Energy

Data	Minimum Cost of Energy (CoE) $								
	Dagum Distribution			Gamma Distribution			Weibull Distribution		
	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic
1	31.70	37.12	41.69	33.13	39.86	45.67	31.88	37.63	42.65
2	20.74	23.23	25.23	21.85	25.13	27.82	21.61	24.58	27.02
3	20.58	23.11	25.12	21.58	24.76	27.42	21.28	24.19	26.54
4	20.74	23.21	25.19	22.23	25.63	28.40	21.92	24.98	27.48
5	20.45	22.94	24.98	21.23	24.31	26.84	21.05	23.85	26.16
6	20.77	23.27	25.28	22.04	25.35	28.11	21.78	24.81	27.27

The best turbine rotor radius R is found by combining the P_r and V_r to optimize the individual data. For each data, the best P_r and V_r are found, lowering the CoE. The turbine rotor radius for every data set is calculated using these P_r and V_r, as shown in Table 7. As a result, the proposed method is useful for determining the appropriate size of wind turbine for each station.

Table 7. Rotor Radius of the Turbine

Data	Optimized P_r and V_r		Rotor Radius R (m)
	P_r (MW)	V_r (m/s)	
1	1	11	30.52
2	1.3	12.5	28.72
3	1.4	13	28.11
4	1.4	13	28.11
5	1.4	13	28.11
6	1.4	13	28.11

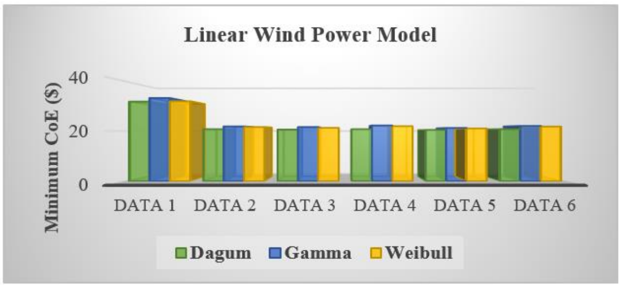


Fig. 2. Comparison of minimum CoE using linear wind power model

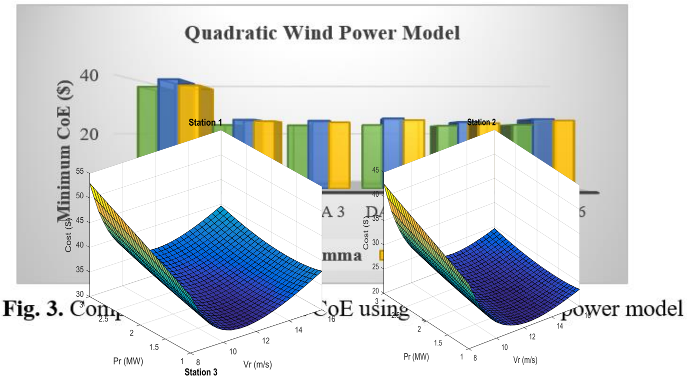


Fig. 3. Com CoE using power model

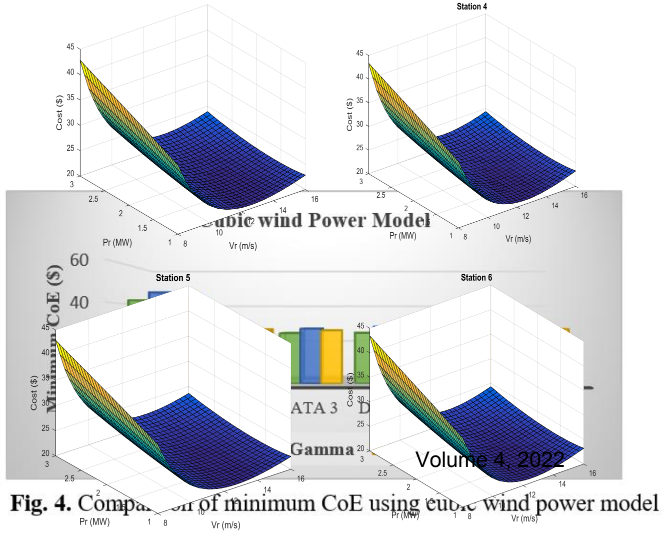


Fig. 4. Compa on of minimum CoE using cubic wind power model

Fig. 1. Results of minimized Turbine CoE for six stations by modelling the wind speed with Dagum distribution & wind power with linear function

From the Table 6, it is observed that among the three linear, quadratic and cubic wind power models, the minimum CoE occurred when using linear model. Also among the three distributions, the least CoE attained by modelling the wind speed through Dagum distribution. The minimum CoE comparison for the different wind power models have been presented in the Figures 2, 3 and 4. From the Table 6 and Figures 2, 3 and 4, it is observed that for all the discussed wind power models, the minimum CoE occurred while modelling the wind speed with the Dagum distribution. Figure 5 depicts a three dimensional (3D) map of the minimum turbine CoE for all of the data discussed.

4. Conclusion

A mathematical approach for minimizing the CoE of wind turbine is presented in this article. To minimize the CoE, the observed wind speed data was modelled using the Dagum, Gamma, and Weibull distributions, and the wind power was modelled using linear, quadratic, and cubic functions. The research is being conducted on data collected from six different stations. The minimum CoE estimation was performed in a comparative study using the three statistical distributions. The Dagum distribution produces the lowest turbine CoE, according to the results of statistical distributions used to model wind speed. Correspondingly, with respect to the mathematical functions, the minimum CoE ensued when the power is modelled using the linear function. Overall, this research shows that the turbine CoE can be reduced by using the Dagum distribution to model wind speed and a linear function to model wind power. The proposed method also determines the optimal radius of the turbine rotor for each station. As a result, the best turbine size for producing maximum energy at the lowest cost is determined.

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