# Wind Turbine Energy Cost Optimisation Using Various Power Models

DIVYA.P. S[1], VIJILA MOSES[2], MANOJ G*[3], LYDIA. M[4]
[1,2]Department of Mathematics, Karunya Institute of Technology and Sciences, Karunya Nagar, Coimbatore, Tamil Nadu, INDIA
[3]Department of ECE, Karunya Institute of Technology and Sciences, Karunya Nagar, Coimbatore, Tamil Nadu, INDIA
[4]Department of Mechatronics, Sri Krishna College of Engineering and Technology, Coimbatore, Tamil Nadu, INDIA

*Abstract:* - In modern times, the worldwide wind turbine installations have developed swiftly resulting in the decrease of green gas emissions. Though wind is a free gift of nature, it is expensive to harness this energy for useful applications like electricity generation. The cost of installation of the wind turbine at a particular station does not depend only on the wind resource, but also on the structure of the turbine and the energy conversion technology. The wind turbine Cost of Energy (CoE) is used to estimate the payback time for the return on the investment made by the wind farm owners for the turbine. Meticulous research is required to optimize the turbine CoE which will make wind a very competent source of energy. In this article, in order to minimize the wind turbine CoE, the wind speed is modelled using three different distributions namely, Dagum, Gamma and Weibull and the evaluation of the turbine Annual Energy Production (AEP) is carried out. Mathematical functions such as linear, quadratic and cubic have been used to model the wind power. For the cost analysis of the turbine, the price model which was established by United States, National Renewable Energy Laboratory (NREL) is employed. The comparative study of the proposed methodology have been done for six different stations. The turbine CoE model is an element of two factors, the rated power $P_r$ of a turbine and the rated wind speed $V_r$ of a turbine. Based on the results obtained, a broad recommendation to reduce the turbine CoE is presented. This study enables us to figure out the minimum turbine CoE among the three discussed mathematical distributions, the finest distribution for wind speed modelling and the optimum mathematical function for wind power modelling. The suitable size of the wind turbine also can be found by optimizing the rotor radius R of the turbine for each data.

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

Received: June 15, 2021. Revised: June 11, 2022. Accepted: July 21, 2022. Published: September 9, 2022.

## 1. Introduction

The selection of wind turbines based on wind parameters determines the majority of the cost of wind energy. 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

The capacity of the Wind Turbine (WT) to serve loads dependably and economically in the context of the inherent uncertainty associated with wind as a resource presents a problem for power engineers. Modelling the reaction of WTs to changes in wind speed and network frequency is a crucial first step in overcoming this obstacle. The power curve of a wind turbine, which shows the relationship between power output and observed wind speed, is the traditional method of evaluating a wind turbine's performance. A wind turbine is made up of five main components and numerous auxiliary ones. The tower, rotor, nacelle, generator, and base or foundation make up the key components. A wind turbine cannot operate without all of these, as depicted in Fig.1. The electrical network whose frequency impacts the machine's slip is directly connected to fixed-speed WTs using squirrel cage induction generators. Fixed-speed WTs therefore respond to grid frequency disruptions in a way that lessens the disturbance. WTs with variable speeds are easier to control. For instance, maximum power point tracking (MPPT) used to maximize the amount of wind energy captured causes higher variability in WTG active power output due to changes in wind speed at low wind speeds.

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.

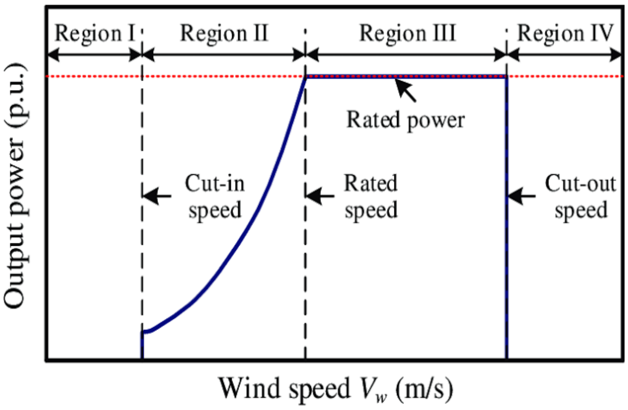


**Fig1**. A wind turbine's operational zones

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 objective of this study is to give a scientific way to limit the CoE of a turbine with the use of various probability distributions and to find the appropriate distribution to minimize the CoE for the particular region. The turbine CoE is the ratio of the total turbine cost and the turbine Annual Energy Production (AEP). Six variables namely $R$, $P_r$, H, $V_c$, $V_r$ and $V_f$ were there in the turbine CoE function.

$$CoE = \frac{Cost(R, P_r, H, V_c, V_r, V_f)}{AEP(P_r, H, V_c, V_r, V_f)} \qquad (2)$$

This was simplified and reduced to an element of two variables, $P_r$ and $V_r$ by Chen et al. (2018). 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.

Thus $CoE = f(P_r, V_r)$

$$= \frac{Cost(P_r, V_r)}{AEP(P_r, V_r)}$$

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

Cost = ICC x FCR + AOE (3)

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 ($P_r$) 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 | $1.9894 \times 10^{-3}P_r - 0.1141$ |
| | **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 | $1.1537 \times 10^{-2}P_r + 3849.7$ |
| | Tower | $0.59595\pi R^2H - 2121$ |
| *Balance of station cost* | | |
| | **Infrastructures** | |
| | Foundation | $303.24 \times (\pi R^2H)^{0.4037}$ |
| | Roads, civil work | $2.17 \times 10^{-15}P_r^3 - 1.45 \times 10^{-8}P_r^2 + 0.06954P_r$ |
| | Electrical interface/ connections | $3.49 \times 10^{-15}P_r^3 - 2.21 \times 10^{-8}P_r^2 + 0.1097P_r$ |
| | Engineering, permits | $9.94 \times 10^{-10}P_r^2 + 0.02031P_r$ |
| | **Installation and transportation** | |
| | Transportation | $1.581 \times 10^{-14}P_r^3 - 3.75 \times 10^{-8}P_r^2 + 0.0547P_r$ |
| | 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 | $7 \times 10^{-6}AEP$ |
| Land lease costs | $1.08 \times 10^{-6}AEP$ |

The AEP for a turbine is calculated as follows:

$$AEP = 8760 \times P_{ave} \times (1-\mu) \qquad (4)$$

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

$$P_{ave} = \int_0^\infty P f(V) dV \qquad (5)$$

From the equation (1)

$$P_{ave} = \int_{V_c}^{V_r} P(V) f(V) dV + \int_{V_r}^{V_f} P_r f(V) dV \qquad (6)$$

### 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.

$$R = \sqrt{\frac{2P_r}{\rho \pi C_{pr} \eta_{mf} \eta_{gf} V_r^{\,3}}} \qquad (7)$$

where $\rho$ - Density of the air (1.225 kg/m3)

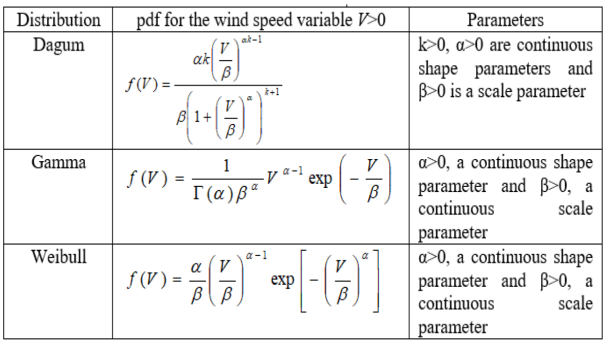
$C_{pr}$ - The blade's aerodynamic efficiency (0.45)

$\eta_{mf}$ - Efficiency of the gearbox (0.96)

$\eta_{gf}$ - 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.



| 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 |

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

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 (8).

$$P(V) = \frac{V - V_c}{V_r - V_c} P_r \tag{8}$$

By putting the wind power of linear model (8) in equation (6), we get the linearly modelled mean turbine output power.

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

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

(9)

**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 $P_r$.

$$P(V) = \frac{V^2 - V_c^{\ 2}}{V_r^{\ 2} - V_c^{\ 2}} P_r \tag{10}$$

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

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

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

(11)

**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

$$P(V) = \frac{V^3 - V_c^{\ 3}}{V_r^{\ 3} - V_c^{\ 3}} P_r \tag{12}$$

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

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

$$= \frac{P_r}{V_r^{\ 3} - V_c^{\ 3}} \int_{v_c}^{v_r} (V^3 - V_c^{\ 3}) f(V) dV + \int_{V_r}^{V_f} P_r\, f(V) dV \tag{13}$$

# 4. 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.

**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 |

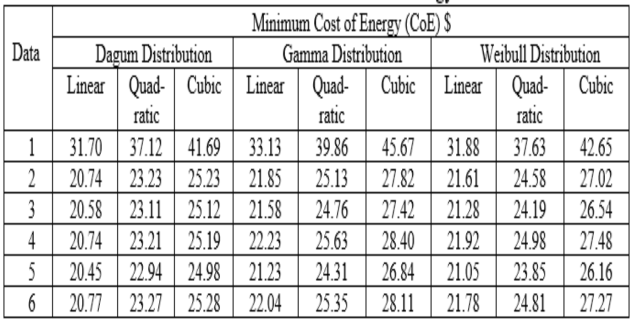
In the process of turbine CoE minimization, the shape and scale parameters for every distribution at a given station are provided as inputs. As a result, the parameters are calculated using the Maximum Likelihood Estimate (see Table 5).

**Table 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 | Quad-ratic | Cubic | Linear | Quad-ratic | Cubic | Linear | Quad-ratic | 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 |

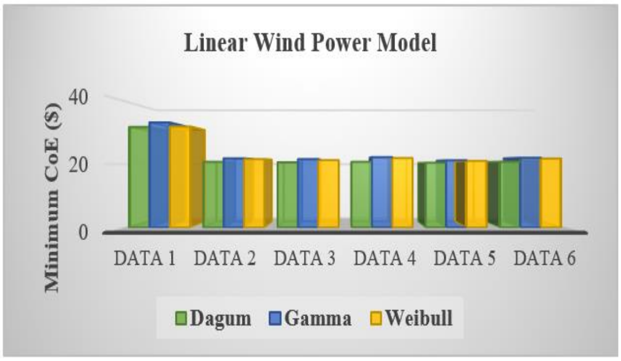


**Fig. 2.** Comparison of minimum CoE using linear wind power model

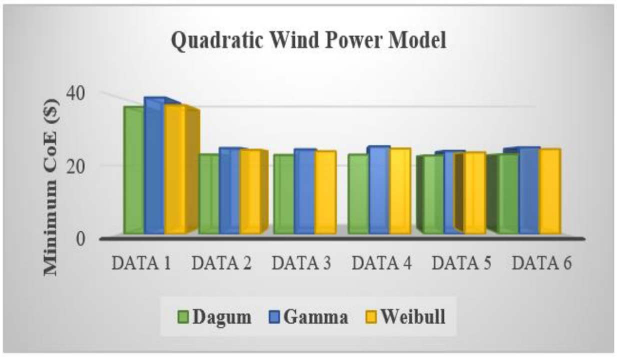


**Fig. 3.** Comparison of minimum CoE using quadratic wind power model

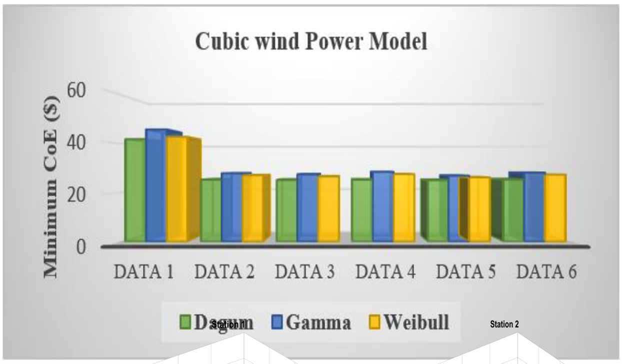


**Fig. 4.** Con E usin model

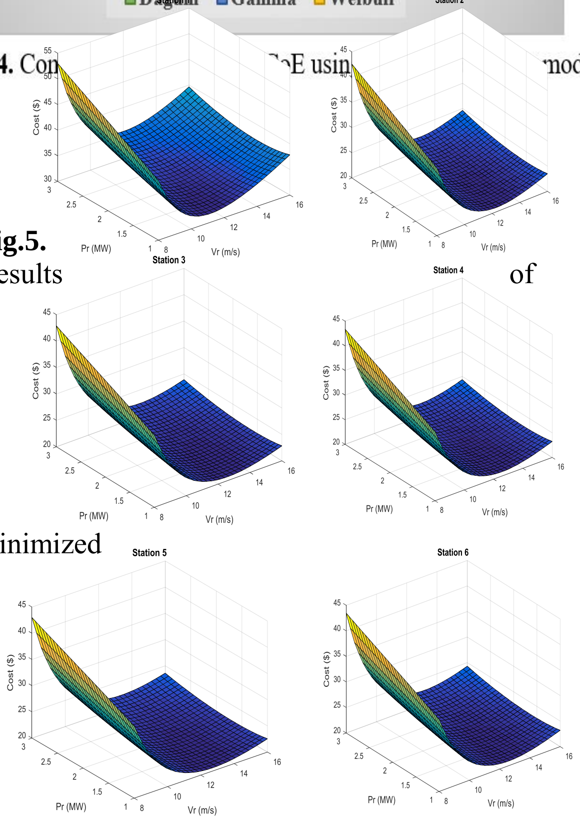


**Fig.5.** Results of minimized Turbine CoE for six stations by modelling the wind speed with Dagum distribution & wind power with linear function

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.

## 5. Conclusion

This article presents a mathematical strategy for reducing the CoE of wind turbines. The Dagum, Gamma, and Weibull distributions were used to model the observed wind speed data in order to minimise the CoE, while the linear, quadratic, and cubic functions were used to represent the wind power. The study is based on information gathered from six separate stations. Utilizing the three statistical distributions, comparative research was conducted to estimate the minimum CoE. The results of statistical distributions used to simulate wind speed give the lowest turbine CoE for the Dagum distribution. In accordance with the mathematical calculations, the smallest CoE resulted from modelling the power using a linear function. Overall, this study demonstrates that by modelling wind speed with the Dagum distribution and wind power with a linear function, the turbine CoE can be decreased. The suggested method also establishes the best turbine rotor radius for each station. The optimal turbine size for generating the most energy at the lowest cost is thus identified.

*References:*

[1] Andres A.S and Gilberto O.G., Wind turbine selection method based on the statistical analysis of nominal specifications for estimating the cost of energy, *Applied Energy,* Vol. 228, 2018, pp. 980–998.

[2] Ashuri T, Zaaijer MB, Martins JRRA, Bussel GJW and Kuik GAM, Multidisciplinary design optimization of offshore wind turbines for minimum levelized cost of energy, *Renewal Energy*, Vol. 68, 2014, pp.893–905.

[3] Blanco MI., The economics of wind energy, *Renewable and Sustainable Energy Review,* Vol.13, 2009, pp.1372–1382.

[4] Carroll J, McDonald A, Dinwoodie I, McMillan D, Revie M and Lazakis I., Availability, operation and maintenance costs of offshore wind turbines with different drive train configurations, *Wind Energy*, Vol. 20, 2017, pp.361–378.

[5] Chen J, Feng Wang and Kim A Stelson, A mathematical approach to minimizing the cost of energy for large utility wind turbines, *Applied Energy,* Vol. 228, 2018, pp.1413–1422.

[6] Chowdhury S, Zhang J, Messac A and Castillo L., Optimizing the arrangement and the selection of turbines for wind farms subject to varying wind conditions, *Renewable Energy,* Vol. 52, 2013, pp.273–282.

[7] Daniel Hdidouan and Iain Staffell, The impact of climate change on the levelised cost of wind energy, *Renewable Energy,* Vol.101, 2017, pp.575–592.

[8] Diveux T, Sebastian P, Bernard D and Puiggali JR., Horizontal axis wind turbine systems: optimization using genetic algorithms, *Wind Energy,* 2001, Vol. 4, pp.151–171.

[9] Eminoglu U and Ayasun S., Modeling and design optimization of variable-speed wind turbine systems, *Energies*, Vol.7, 2014, pp.402–419.

[10] Fingersh L, Hand M and Laxson A.,Wind turbine design cost and scaling model. Tech.Rep.Golden, Colorado: National Renewable Energy Laboratory; NREL/TP 500-40566, 2006.

[11] Gualtieri G., Improving investigation of wind turbine optimal site matching through the self-organizing maps, *Energy Conversion and Management,* Vol.143, 2017, pp.295–311.

[12] Islam MR., Guo YG and Zhu JG., A review of offshore wind turbine nacelle: technical challenges, and research and developmental trends, *Renewable and Sustainable Energy Reviews,* Vol.33, 2014, pp.161–176.

[13] Kaplan YA., Overview of wind energy in the world and assessment of current wind energy policies in Turkey, *Renewable and Sustainable Energy Review,* Vol.43, 2015 pp.562–568.

[14] Mirghaed MR and Roshandel R. ‘Site specific optimization of wind turbines energy cost: iterative approach’, *Energy Conversion and Management,* Vol.73, pp.167–175.

[15] Perkin S, Garrett D and Jensson P., Optimal wind turbine selection methodology: a case study for Búrfell, Iceland, *Renewable Energy,* Vol.75, 2015, pp.165–172.