Research Article

Economic Analysis of Wind Turbine Installation in Taiwan

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The wind speed characteristics are analyzed statistically based on a long-term hourly data record to evaluate the proper wind energy potential. The annual average wind speed and wind power density are investigated and compared by some significant indices, wind energy output and capacity factor, to show the variations of proper wind turbine specifications of installation in different locations of Taiwan. The minimum cost of wind energy is used to assess the economical feasibility for turbine installation in Taiwan. Great variations occur in the simulation results in both of the cost of energy and capacity factor. The detailed statistical analysis should be conducted to ensure the successful operation after wind turbine installations.

1. Introduction

The demand for energy and particularly for electricity is growing rapidly in the country of rapid economic growth. Taiwan has no nature reserves, but electricity mainly relied on conventional fossil fuel. The development of electricity capacity from renewable energy in Taiwan is vital. In this aspect, wind power plays a major role in the enhancement of renewable energy before a sharp increasing in the photovoltaic energy after year 2020 [1]. With abundant wind resources along the west coast of Taiwan and some offshore islands, the Asian monsoon, tropical cyclones during the summer season and the northeast trade winds during the winter season, induces high winds speed in many regions. Taiwan has superior advantages to develop wind energy geographically.

Many studies related to the study of wind characteristics and wind power potentials have been conducted worldwide recently [2–6]. Belu and Koracin studied the wind characteristic in western Nevada, USA, in which the wind speed at different tower heights is estimated using the standard power extrapolation equation and consequently the power law exponent values are analyzed for different time periods and locations [7]. The empirical and graphical methods were used to analyze the wind power density at the heights of 10, 30, and 60 m, respectively [8]. Two statistical methods,

meteorological and Weibull, were presented to evaluate the wind speed characteristic and the wind power potential at an open area of 17 synoptic sites distributed throughout the territory of Tunisia [9].

Many researchers have proposed different economic methods to assess installation of wind turbine. Fingersh et al. presented a simple payback period method [10]. The simple payback period is the number of years which will be taken to recover the initial capital cost for installation of a new wind turbine generator (WTG). An important issue of this model is assumed by the fact that WTG will produce the same amount of electricity each year and attain constant revenue stream. However, the discount rate and the lifetime of the project are not considered. The cost model of wind energy is defined as the unit cost to produce energy from the WTG system. The numbers of lifetime of project and discount rate are included when annual cost is evaluated. Schmidt constructed expressions for computing component costs of wind turbine [11].

This paper proposes a procedure based on the detailed economical model including wind turbine components cost, the annual operation, and maintenance cost of wind turbine to get the minimum cost of wind energy. The minimum cost of wind energy was used to assess the feasibility of installed wind turbine at 24 locations in Taiwan. The wind energy output and capacity factor of twenty commercial wind

turbines in terms of different designed hub height were also investigated.

2. The Mathematical Models for Wind Energy

Using estimation of regional wind resources, one can estimate the electrical producing potential of wind energy. This wind energy resource atlas identifies the wind characteristics and distribution of the wind resource. An important parameter in the characterization of the wind resource is the variation of horizontal wind speed which is expected to be zero at the earth's surface and to increase with height in the atmospheric boundary layer. Wind speed is the most important aspect of the wind resource; in fact the year variation of long-term mean wind speed provides an understanding of the long-term pattern of wind speed and also gives confidence to an investor in the availability of wind power in coming years [12].

The wind speed measured at weather station differs from the height of WTG hub. If these heights do not match the hub height of a WTG, it is necessary to extrapolate the wind speeds to the hub height of the WTG. This variation of wind speed with elevation is called the vertical profile of the wind speed or vertical wind shear, and it can be implemented by the following [13]:

$$V_Z = V_{Z_0} \left(\frac{Z}{Z_0} \right)^\alpha, \quad (1)$$

where V_Z is wind speed at the hub height of WTG; V_{Z_0} is wind speed at the weather station; Z is hub height of WTG; Z_0 is sea level height of the weather station; α is wind speed power law coefficient.

The actual wind power output of WTG is determined by the turbine performance curve, which is well described by (2). The a_1 – a_4 coefficients of the power curve can be described by the specification of wind turbine manufacturer. The power curve with third-order equation is easily digitized into any discrete points dependent on the simulation accuracy. Consider

$$P_T(V) = \begin{cases} 0, & V \leq V_i \\ (a_1 V^3 + a_2 V^2 + a_3 V + a_4) P_r, & V_i \leq V < V_r \\ P_r, & V_r \leq V < V_f \\ 0, & V \geq V_f, \end{cases} \quad (2)$$

where a_1 , a_2 , a_3 , and a_4 are coefficients of the power curve of WTG; V_i is cut-in speed of WTG; V_r is rate speed of WTG; V_f is cut-off speed of WTG; P_r is rated power of WTG (kW); $P_T(V)$ is the electrical power output of WTG (kW).

After comparing the actual WTG energy output and the energy output with rated capacity, the capacity factor (CF) can be conducted. Consider

$$\text{CF} = \frac{E_{\text{TA}}}{E_{\text{TR}}} = \frac{\int_{V_i}^{V_r} (a_1 V^3 + a_2 V^2 + a_3 V + a_4) f(V) d(V)}{\int_{V_i}^{V_f} f(V) d(V)}. \quad (3)$$

The wind energy output from a wind turbine evaluated by the Weibull, Rayleigh, Lognormal, and Gamma probability models are denoted by the following:

$$\begin{aligned} E_{\text{TA}} &= T \int_{V_i}^{V_f} P(V) f(V) dV \\ &= TP_r \int_{V_i}^{V_r} (a_1 V^3 + a_2 V^2 + a_3 V + a_4) \left(\frac{k}{c} \right) \left(\frac{V}{c} \right)^{k-1} \\ &\quad \times \exp \left[- \left(\frac{V}{c} \right)^k \right] dV \\ &\quad + TP_r \int_{V_r}^{V_f} \left(\frac{k}{c} \right) \left(\frac{V}{c} \right)^{k-1} \exp \left[- \left(\frac{V}{c} \right)^k \right] dV \\ E_{\text{TA}} &= T \int_{V_i}^{V_f} P(V) f(V) dV \\ &= TP_r \int_{V_i}^{V_r} (a_1 V^3 + a_2 V^2 + a_3 V + a_4) \left(\frac{\pi}{2} \right) \left(\frac{V}{V_m} \right) \\ &\quad \times \exp \left[- \left(\frac{\pi}{4} \right) \left(\frac{V}{V_m} \right)^2 \right] dV \\ &\quad + TP_r \int_{V_r}^{V_f} \left(\frac{\pi}{2} \right) \left(\frac{V}{V_m} \right) \exp \left[- \left(\frac{\pi}{4} \right) \left(\frac{V}{V_m} \right)^2 \right] dV \\ E_{\text{TA}} &= T \int_{V_i}^{V_f} P(V) f(V) dV \\ &= TP_r \int_{V_i}^{V_r} (a_1 V^3 + a_2 V^2 + a_3 V + a_4) \frac{1}{\sigma \sqrt{2\pi}} \\ &\quad \times \exp \left[- \left(\frac{(V - V_m)^2}{2\sigma^2} \right) \right] dV \\ &\quad + TP_r \int_{V_r}^{V_f} \frac{1}{\sigma \sqrt{2\pi}} \exp \left[- \left(\frac{(V - V_m)^2}{2\sigma^2} \right) \right] dV \\ E_{\text{TA}} &= T \int_{V_i}^{V_f} P(V) f(V) dV \\ &= TP_r \int_{V_i}^{V_r} (a_1 V^3 + a_2 V^2 + a_3 V + a_4) \\ &\quad \times \left[V^{k-1} \frac{\exp(-V/c)}{\Gamma(k) c^k} \right] dV \\ &\quad + TP_r \int_{V_r}^{V_f} \left[V^{k-1} \frac{\exp(-V/c)}{\Gamma(k) c^k} \right] dV, \end{aligned} \quad (4)$$

where E_{TA} is the actual wind energy output of the WTG for the period T (kW/h), E_{TR} is the wind energy output operated with the full capacity for the period T (kW/h), $f(V)$ is the probability density function (Weibull, Rayleigh, Lognormal, and Gamma), and V_m is the mean winds speed (m/s).

FIGURE 1: Initial capital cost model.

3. Economic Analysis Methods

The unit cost of wind electricity power can be determined by knowing capital investment and operating costs. It is important for estimating the investment cost of each WTG type in each location before installation. However, the value of the wind electricity power is somewhat difficult to determine, but it must be evaluated before making investment decision. The significant cost of wind energy will be included and discussed in this study.

The cost of energy (COE, \$/kWh) can be defined by (5), where C_{TA} is the total annual cost (\$) and E_{AP} is the annual electrical energy output of WTG (kWh). Consider

$$COE = \frac{C_{TA}}{E_{AP}}. \quad (5)$$

The total annual cost of a WTG is the sum of its operation, maintenance expenses, and annual repayments on its capital. It can be determined by the following:

$$C_{TA} = (a + 0.025) \cdot C_{IT} \quad (6)$$

$$a = \frac{r}{1 - (1 + r)^{-t}},$$

where a is the discount factor; r is the discount rate (%) and often takes about 10%; t is the lifetime of project, often taken to be 20 years; C_{IT} is the initial capital cost of building WTG (\$).

The operation and maintenance cost yearly may be expressed as a proportion of the initial capital cost about 2.5% [14]. In this study, the initial capital cost of WTG is set based on references [10]. Using the model, the total annual cost

(C_{TA}) of the project can be estimated. The annual COE is a popular index to estimate the different amount of electricity for each WTG at each year. The component cost models needed to calculate the initial capital cost of wind turbine can be summarized in the following list of the components cost and in Figure 1 [11].

List of the Components Cost

$$Cost_{blade} = 0.5582(D_r/2)^2 + 3.8118(D_r/2)^{2.5025} - 955.24,$$

$$Mass_{blade} = 0.1452(D_r/2)^{2.9158},$$

$$Cost_{hub} = 4.05Mass_{blade} + 24141,$$

$$Cost_{total-pith-system} = 0.4802D_r^{2.6578},$$

$$Cost_{nosecone} = 103D_r - 2899,$$

$$Cost_{low-speed-shaft} = 0.1D_r^{2.887},$$

$$Cost_{bearing-system} = D_r^{2.5}(0.0043D_r - 0.011),$$

$$Cost_{gearbox} = 16.45P_r^{1.249},$$

$$Cost_{brake-coupling} = 1.9894P_r - 0.1144,$$

$$Cost_{generator} = 65P_r,$$

$$Cost_{electronics} = 79P_r,$$

$$Cost_{yaw-system} = 0.0678D_r^{2.964},$$

$$Cost_{main-frame} = 9.489D_r^{1.953},$$

$$Mass_{main-frame} = 2.233D_r^{1.953},$$

$$Cost_{platform-and-railing} = 1.09Mass_{main-frame},$$

$$Cost_{electrical-connection} = 40P_r,$$

$$Cost_{hydraulic-and-cooling} = 12P_r,$$

FIGURE 2: Geographical location of the meteorological stations used in the study.

$$\begin{aligned}
 \text{Cost}_{\text{nacelle-cover}} &= 11.537P_r + 3849.7, \\
 \text{Cost}_{\text{control-safely-monitoring}} &= \$35000, \\
 \text{Cost}_{\text{tower}} &= 0.596 \times A \times \text{Hub} - 2121, \\
 \text{Cost}_{\text{foundation}} &= 303.24 \times (A \times \text{Hub})^{0.4037}, \\
 \text{Cost}_{\text{transportation}} &= (1.58E - 5)P_r^3 - 0.0375P_r^2 + 54.7P_r, \\
 \text{Cost}_{\text{roads-civil-work}} &= (2.17E - 6)P_r^3 - 0.0145P_r^2 + 69.54P_r, \\
 \text{Cost}_{\text{assembly-and-installation}} &= 1.965(\text{Hub} \times D_r)^{1.1736}, \\
 \text{Cost}_{\text{electrical-interface}} &= (3.49E - 6)P_r^3 - 0.0221P_r^2 + 109.7P_r, \\
 \text{Cost}_{\text{engineering-permitting}} &= (9.94E - 4)P_r^2 + 20.31P_r.
 \end{aligned}$$

In the above list, D_r represents rotor radius (m), P_r is power nominal of wind turbine (kW), A is rotor swept area (m^2), and Hub is height of tower (m).

4. Simulation Results and Discussions

In this study, the wind speed data were measured hourly by Central Weather Bureau of Taiwan in these six years at the 24 locations. All measurements in the wind observation station are recorded using the cup anemometer at a height of 10 m above the ground level. The geographical and meteorological information of the 24 stations is given in Figure 2 [1] and Table 1, respectively.

4.1. Simulation Results of Capacity Factor. The average power output and capacity factor of a WTG are very important parameters to show the performance of WTG. The related specifications of 20 popular commercial WTGs for testing

are shown in Table 2 [13]. In general, the capacity factor decreases when the cut-in wind speed of a WTG reduces and its cut-off wind speed increases; another significant factor is the hub height of a WTG. The best and worst capacity factors at 24 tested sites evaluated by four different PDFs are listed in Table 3.

The highest CFs were operated by V90_1800 WTG at the 105 m hub height and E82 WTG at the height of 138 m. The lowest CF was operated by the E44 WTG at the height of 44 m. From the results of Table 3, three groups with different CF can be set.

(i) *The First Group with High CF Regions.* The CF varies from 0.482 to 0.6192 (with highest extreme status) and from 0.3111 to 0.4598 (with lowest extreme status); it includes the sites of Tungchitao, Lanyu, Yushan, and Pengchiayu. The highest CF occurs at Tungchitao with E82 WTG. The perfect CF operates at the sites of Lanyu and Pengchiayu by the V90_1800 WTG.

(ii) *The Second Group with Average CF Regions.* The CF varies from 0.045 to 2.587 (with highest extreme status) and from 0.0038 to 0.1336 (with lowest extreme status); it includes the sites of Wuchi, Hengchun, Penghu, Cheng Kung, Anpu, Keelung, Taipei, and Tainan. The average wind speed of this group varies in a range of 3 m/s~5 m/s, and the best CF in this group operated by E82 WTG with 138 m height occurs at Wuchi site. The worst CF calculated from whole probability density operated by E44 WTG with 45 m height occurs at Anpu site.

(iii) *The Third Group of Small CF Regions.* The remaining sites are Chutzehu, Tanshui, Hsinchu, Ilan, Taichung, Hualien, and so forth. The CF of WTG in this group is very low, while the lowest CF (with highest extreme status) occurs at Sun Moon Lake (0.0335) and Alishan (0.0243). The best capacity factor is operated by E82 WTG and the worst is operated by G80 WTG.

In general, the CF evaluated by the Weibull probability density in most of the sites is higher than that evaluated by other probability distributions, while the CF calculation by the lognormal model derived the lowest value.

4.2. Simulation Results of Wind Energy Cost. The capital cost of wind turbine depends on the size of wind turbine and its hub height. This study analyzes the sensitivity of minimizing cost of energy (COE) and specific rotor rating on various parameters and wind resource characteristics. The important decision is the choices of COE. As mentioned above, the wind energy resources of CF in Taiwan can be classified into three groups. The study of COE is focused on the first group with the higher wind energy potentials. Table 4 shows the evaluation of Pengchiayu site. In general, the wind speed at the first group, which includes Pengchiayu, Yushan, Tungchitao, and Lanyu, is very high; the wind speed at the weather stations' height is over 5.9 m/s. Therefore, the average capacity factors of wind turbines in this group are high. The maximum wind energy can be found in V90-3M wind turbine with 105 m hub height and the minimum can be found in E33 wind turbine with 36 m hub height.

TABLE 1: Details of the geographical information for the tested weather stations.

Number	Sites	Longitude (deg)	Latitude (deg)	Altitude (m)
1	Pengchiayu	122°04' E	25°37' N	12.5
2	Anpu	121°31' E	25°11' N	7.31
3	Chutzehu	121°32' E	25°09' N	11.03
4	Tanshui	121°26' E	25°09' N	12.2
5	Keelung	121°43' E	25°08' N	34.6
6	Taipei	121°30' E	25°02' N	34.9
7	Hsinchu	120°58' E	24°48' N	15.6
8	Ilan	121°44' E	24°45' N	26
9	Taichung	120°40' E	24°08' N	17.2
10	Wuchi	120°30' E	24°15' N	32.2
11	Hualien	121°36' E	23°58' N	12
12	Sun Moon Lake	120°53' E	23°52' N	8
13	Penghu	119°33' E	23°34' N	14.6
14	Alishan	120°48' E	23°30' N	15.1
15	Chiayi	120°25' E	23°29' N	14.5
16	Yushan	120°57' E	23°29' N	9.2
17	Tungchitao	119°39' E	23°15' N	9.1
18	Cheng Kung	121°21' E	23°05' N	12.8
19	Tainan	120°11' E	22°59' N	37.6
20	Taitung	121°08' E	22°45' N	11.4
21	Kaohsiung	120°18' E	22°34' N	14
22	Tawu	120°53' E	22°21' N	12.7
23	Lanyu	121°33' E	22°02' N	12.5
24	Hengchun	120°44' E	22°00' N	14.3

TABLE 2: Specifications of twenty different wind turbines.

Number	WTG type	Rated power (kW)	Cut-in speed (m/s)	Rated wind speed (m/s)	Cut-off speed (m/s)	Rotor diameter (m)	Hub height (m)
1	E33	330	3	17	28–34	33.4	36–50
2	E44	900	2	17	28–34	44	45–55
3	E48	800	2	14	28–35	48	50–76
4	E53	800	2	13	28–36	52.9	60/73
5	E71	2300	2	15	28–37	71	64–113
6	E82	2000	2	12	28–38	82	78–138
7	G52	850	4	16	25	52	45/55/65
8	G58	850	3	16	21	58	45/55/65
9	G80	2000	4	17	25	80	44–71
10	G87	2000	4	16	25	87	67–100
11	G90	2000	3	16	21	90	67–100
12	GE15xle	1500	3.5	12.5	20	82.5	80
13	GE15sle	1500	3.5	14	25	77	65/80
14	GE25	2500	3.5	12.5	25	100	75/85/100
15	V52	850	4	16	25	52	44/49/55/65/74
16	V80	2000	4	15	25	80	60/67/78/100
17	V82	1650	3.5	13	20	82	70/78/80
18	V90.1.8	1800	3.5	12	25	90	80/95/105
19	V90.2.0	2000	2.5	13	25/21	90	80/95/106
20	V90.3.0	3000	4	15	25	90	80/105

TABLE 3: Capacity factors of wind turbines extreme status at 24 sites during 6 years are computed from probability distributions.

Sites	Extreme status	Type WTG	Weibull Hub height	Capacity factor	Type WTG	Gamma Hub height	Capacity factor	Type WTG	Lognormal Hub height	Capacity factor	Type WTG	Rayleigh Hub height	Capacity factor
Pengchiayu	Highest	V90_1800	105	0.5772	V90_1800	105	0.5612	V90_1800	105	0.5245	V90_1800	105	0.5245
	Lowest	E44	45	0.3765	E44	45	0.3599	E44	45	0.3455	E44	45	0.3455
Anpu	Highest	V90_2M	105	0.1461	V90_2M	105	0.1477	V90_2M	105	0.1650	V90_2M	105	0.1433
	Lowest	E44	45	0.0734	E44	45	0.0734	E44	55	0.1027	E44	45	0.0661
Chutzehu	Highest	E82	138	0.1421	E82	138	0.1414	E82	138	0.1496	E82	138	0.1365
	Lowest	G80	44	0.0506	G80	44	0.0519	V52	44	0.0708	G80	44	0.0345
Tanshui	Highest	V90_2M	105	0.0541	E82	138	0.0607	E82	138	0.0878	V90_2M	105	0.0529
	Lowest	G80	44	0.0112	G80	44	0.0160	V52	44	0.0392	G80	44	0.0062
Keelung	Highest	E82	138	0.0451	E82	138	0.0512	E82	138	0.0812	V90_2M	105	0.0438
	Lowest	G80	44	0.0038	G80	44	0.0070	V52	44	0.0290	G80	44	0.0012
Taipei	Highest	E82	138	0.1037	E82	138	0.1137	E82	138	0.1418	E82	138	0.0905
	Lowest	G80	44	0.0257	G80	44	0.0336	V52	44	0.0627	G80	44	0.0163
Hsinchu	Highest	E82	138	0.0868	E82	78	0.0936	E82	78	0.1192	V90_2M	105	0.0772
	Lowest	G80	44	0.0246	G80	44	0.0246	V52	44	0.0538	G80	44	0.0162
Ilan	Highest	E82	138	0.0570	E82	138	0.0598	E82	138	0.0860	V90_2M	105	0.0547
	Lowest	G80	44	0.0151	G80	44	0.0171	V52	44	0.0406	G80	44	0.0071
Taichung	Highest	E82	138	0.0525	E82	138	0.0598	E82	138	0.0867	V90_2M	105	0.0500
	Lowest	G80	44	0.0056	G80	44	0.0093	G80	44	0.0291	G80	44	0.0025
Wuchi	Highest	E82	138	0.2587	E82	138	0.2587	E82	138	0.2533	E82	138	0.2675
	Lowest	E44	45	0.1336	E44	45	0.1395	E44	45	0.1605	E44	45	0.1287
Hualien	Highest	E82	138	0.1805	E82	138	0.1728	E82	138	0.1819	E82	138	0.1809
	Lowest	E44	45	0.0737	E44	45	0.0737	V52	44	0.0881	E44	45	0.0705
Sun Moon Lake	Highest	E82	138	0.0335	E82	138	0.0352	E82	138	0.0514	E82	138	0.0368
	Lowest	G80	44	0.0030	G80	44	0.0043	G80	44	0.0180	G80	44	0.0007
Penghu	Highest	E82	138	0.2505	E82	138	0.2515	E82	138	0.2532	E82	138	0.2533
	Lowest	E44	45	0.1186	E44	45	0.1310	V52	44	0.1566	E44	45	0.1130
Alishan	Highest	E82	138	0.0243	E82	138	0.0231	E82	138	0.0264	E82	138	0.0284
	Lowest	G80	44	0.0002	G80	44	0.0005	G80	44	0.0049	G80	44	0.0000
Chiayi	Highest	E82	138	0.0619	E82	138	0.0690	E82	138	0.1013	V90_2M	105	0.0572
	Lowest	G80	44	0.0154	G80	44	0.0205	V52	44	0.0492	G80	44	0.0077
Yushan	Highest	E82	138	0.4824	E82	138	0.4493	E82	138	0.3858	E82	138	0.5329
	Lowest	E44	45	0.3111	E44	45	0.2950	E44	45	0.2648	E44	45	0.3323
Tungchitao	Highest	E82	138	0.6192	E82	138	0.5805	E82	138	0.5069	E82	138	0.6546
	Lowest	E44	45	0.4598	E44	45	0.4299	E44	45	0.3779	E44	45	0.4823
Cheng Kung	Highest	E82	138	0.1867	E82	138	0.1853	E82	138	0.1991	E82	138	0.1859
	Lowest	E44	45	0.0841	E44	45	0.0885	V52	44	0.1109	E44	45	0.0798
Tainan	Highest	E82	138	0.1179	E82	138	0.1267	E82	138	0.1529	E82	138	0.1174
	Lowest	G80	44	0.0320	G80	44	0.0385	G80	44	0.0616	G80	44	0.0316
Taitung	Highest	V90_2M	105	0.0537	E82	138	0.0552	E82	138	0.0693	V90_2M	105	0.0537
	Lowest	G80	44	0.0111	G80	44	0.0118	G80	44	0.0118	G80	44	0.0118
Kaohsiung	Highest	V90_2M	105	0.0528	V90_2M	105	0.0560	E82	138	0.0749	V90_2M	105	0.0530
	Lowest	G80	44	0.0102	G80	44	0.0130	G80	44	0.0297	G80	44	0.0081
Tawu	Highest	E82	138	0.1369	E82	138	0.1408	E82	138	0.1588	E82	138	0.1335
	Lowest	G80	44	0.0378	G80	44	0.0378	G80	44	0.0427	G80	44	0.0344
Lanyu	Highest	V90_1800	105	0.5576	V90_1800	105	0.5457	V90_1800	105	0.5004	V90_1800	105	0.5870
	Lowest	E44	45	0.3898	E44	45	0.3710	E44	45	0.3442	E44	45	0.4051
Hengchun	Highest	E82	138	0.2534	E82	138	0.2502	E82	138	0.2400	E82	138	0.2706
	Lowest	E44	45	0.1176	E44	45	0.1245	V52	49	0.1427	E44	45	0.1072

TABLE 4: The average capacity factor of WTG and the average cost of wind energy at “Pengchiayu” site evaluated from four different probability distributions.

Type wind turbine	Height (m)	C_{IT} (\$)	C_{TA} (\$)	V_{Mean} (m/s)	σ (m/s)	Weibull			Gamma			Lognormal			Rayleigh		
						CF	E_{AP} (kW/h)	COE (\$)	CF	E_{AP} (kW/h)	COE (\$)	CF	E_{AP} (kW/h)	COE (\$)	CF	E_{AP} (kW/h)	COE (\$)
E33	36	351683.21	66735.922	8.17	3.91	0.4656407	1346074	0.051	0.448	1295884	0.053	0.427	1235276	0.055	0.449	1298155	0.053
E33	50	367008.95	69644.158	8.47	4.06	0.4902	1417073	0.0503	0.4731	1367527	0.0520	0.4493	1298957	0.0547	0.4720	1364516	0.0522
E44	45	758045.53	14384784	8.38	4.01	0.3765	2968249	0.0496	0.3599	2837622	0.0518	0.3455	2724304	0.0539	0.3659	2884902	0.0510
E44	55	774782.46	147023.86	8.56	4.10	0.3912	3084305	0.0488	0.3742	2950208	0.0510	0.3579	2821934	0.0532	0.3796	2993059	0.0503
E48	50	751905.43	142682.68	8.47	4.06	0.4601	3224316	0.0454	0.4416	3094976	0.0472	0.4194	2938985	0.0497	0.4441	3112572	0.0470
E48	76	801628.7	152118.24	8.87	4.25	0.4913	3443048	0.0453	0.4731	3315335	0.0470	0.4472	3133946	0.0496	0.4493	3316498	0.0470
E53	60	829915.6	157486	8.65	4.14	0.5148	3607771	0.0448	0.4971	3483821	0.0463	0.4702	3295026	0.0489	0.4953	3471394	0.0465
E53	73	859053.45	163015.25	8.83	4.23	0.5292	3708292	0.0451	0.5119	3587412	0.0465	0.4835	3388252	0.0492	0.5088	3565517	0.0468
E70	64	2008539.6	381143.44	8.71	4.17	0.4112	8283960	0.0471	0.3927	7911310	0.0493	0.3734	7522395	0.0518	0.3981	8020871	0.0487
E70	113	2188995.1	415386.94	9.27	4.44	0.4537	9140657	0.0466	0.4346	8756834	0.0486	0.4099	8257840	0.0514	0.4376	8816383	0.0482
E82	78	212179.1	402620.53	8.90	4.26	0.5291	9270084	0.0445	0.5111	8954247	0.0461	0.4815	8436746	0.0488	0.5084	8907754	0.0463
E82	138	2405766.6	456521.81	9.48	4.54	0.5701	9987912	0.0468	0.5539	9703543	0.0481	0.5203	9116219	0.0512	0.5468	9580310	0.0488
G52	55	834916.73	158435.03	8.56	4.10	0.4568	3400969	0.0477	0.4384	3264454	0.0497	0.4128	3074068	0.0527	0.4397	3274152	0.0495
G52	44	810736	153846.46	8.36	4.00	0.4400	3276224	0.0481	0.4219	3141445	0.0501	0.3985	2967149	0.0530	0.4242	3158578	0.0498
G58	44	939752.92	178328.9	8.72	4.18	0.5151	3835784	0.0476	0.4939	3677435	0.0496	0.4556	3392727	0.0537	0.4912	3657608	0.0499
G80	44	1916854.2	363745.08	8.36	4.00	0.4303	7539464	0.0494	0.4125	7226231	0.0515	0.3896	6825318	0.0544	0.4150	7271575	0.0512
G80	71	2039716.6	387059.62	8.81	4.22	0.4661	8166670	0.0485	0.4478	7844775	0.0505	0.4203	7363750	0.0537	0.4482	7852279	0.0504
G87	67	2197598.8	417019.58	8.75	4.19	0.5049	8845380	0.0483	0.4872	8536126	0.0500	0.4570	8007278	0.0532	0.4843	8485555	0.0503
G87	100	2370945.5	449914.11	9.15	4.38	0.5335	9347258	0.0492	0.5164	9047727	0.0508	0.4830	8461965	0.0543	0.5109	8950975	0.0514
G90	67	2279840.4	432625.86	8.75	4.19	0.5208	9123928	0.0485	0.5004	8766327	0.0505	0.4622	8097666	0.0545	0.4966	8698848	0.0508
G90	100	2463887.3	467550.87	9.15	4.38	0.5459	9564877	0.0500	0.5262	9219648	0.0518	0.4851	8498163	0.0561	0.5191	9095502	0.0525
GE15 xle	80	1848137.4	350705.28	8.92	4.27	0.4930	6477982	0.0553	0.4695	6168810	0.0580	0.4285	5630400	0.0634	0.4678	6147450	0.0582
GE15 sle	65	1648152.6	312755.86	8.72	4.18	0.4497	5909668	0.0541	0.4289	5635277	0.0566	0.4019	5281593	0.0603	0.4328	5687517	0.0561
GE15 sle	80	1711806.8	324834.97	8.92	4.27	0.4655	6116669	0.0542	0.4444	5839736	0.0567	0.4153	5457118	0.0606	0.4473	5877890	0.0564
GE25	75	2970201.4	563629.78	8.86	4.24	0.5048	11054583	0.0521	0.4856	10634667	0.0541	0.4541	9944176	0.0578	0.4840	10600468	0.0543
GE25	85	3037456.1	576392.13	8.98	4.30	0.5140	11256219	0.0523	0.4949	10839270	0.0544	0.4623	10124534	0.0580	0.4926	10786941	0.0546
GE25	100	3138342.2	595536.43	9.15	4.38	0.5258	11515020	0.0528	0.5070	11102857	0.0547	0.4729	10357531	0.0586	0.5056	11026052	0.0551
V52	44	810736	153846.46	8.36	4.00	0.3995	2974314	0.0529	0.3843	2861735	0.0549	0.3660	2725029	0.0576	0.3867	2879177	0.0546
V52	49	821752.85	155937.03	8.46	4.05	0.4071	3031211	0.0526	0.3917	2916877	0.0546	0.3724	2772684	0.0574	0.3938	2932120	0.0543
V52	55	834916.73	158435.03	8.56	4.10	0.4153	3092333	0.0524	0.3997	2976187	0.0544	0.3793	2823922	0.0572	0.4014	2988921	0.0541
V52	65	856758.16	162579.69	8.72	4.18	0.4272	3180733	0.0523	0.4112	3062106	0.0542	0.3892	2898128	0.0572	0.4124	3070931	0.0541
V52	74	876343.56	166296.24	8.85	4.24	0.4364	3249266	0.0523	0.4202	3128840	0.0543	0.3970	2955760	0.0574	0.4209	3134389	0.0542
V80	60	1989770.7	377581.82	8.65	4.14	0.4229	7409170	0.0521	0.4062	7116137	0.0542	0.3843	6733133	0.0572	0.4084	7155137	0.0539
V80	67	2021565.1	383615.17	8.75	4.19	0.4309	7549126	0.0519	0.4139	7252161	0.0540	0.3910	6850262	0.0571	0.4158	7284622	0.0538
V80	78	2071461.6	393083.6	8.90	4.26	0.4419	7741548	0.0519	0.4246	7439563	0.0540	0.4002	7011673	0.0572	0.4259	7462357	0.0538
V80	100	2171159.6	412002.44	9.15	4.38	0.4597	8054318	0.0523	0.4421	7745219	0.0543	0.4152	7275163	0.0577	0.4424	7750490	0.0543
V82	78	191790.3	362784.13	8.90	4.26	0.5314	7680907	0.0483	0.5114	7392389	0.0502	0.4702	6795652	0.0545	0.5047	7294478	0.0508
V82	70	1873908.6	355595.66	8.79	4.21	0.5249	7586920	0.0480	0.5047	7294960	0.0498	0.4642	6708857	0.0541	0.4989	7210721	0.0504
V82	80	1921256.9	364580.53	8.92	4.27	0.5329	7702552	0.0484	0.5130	7414938	0.0503	0.4716	6815803	0.0546	0.5060	7343749	0.0509
V90 1800	95	2230658.5	423293.03	8.92	4.27	0.5582	8802234	0.0492	0.5414	8536623	0.0507	0.5066	7987870	0.0541	0.5343	8424996	0.0514
V90 1800	105	2370064.8	449746.98	9.19	4.40	0.5772	9101759	0.0505	0.5612	8849141	0.0519	0.5245	8270478	0.0555	0.5520	8703766	0.0528
V90 2M	80	2352366.3	446388.48	8.92	4.27	0.5456	959137	0.0478	0.5266	9225238	0.0495	0.4926	8629990	0.0528	0.5235	9172330	0.0498
V90 2M	95	2436005.8	462260.05	9.09	4.35	0.5703	8992593	0.0499	0.5540	8734997	0.0514	0.5180	8167046	0.0549	0.5455	8602205	0.0522
V90 2M	105	2491772.6	472842.43	9.19	4.40	0.5678	9772264	0.0484	0.5391	9444581	0.0500	0.5037	8942293	0.0535	0.5348	9369516	0.0504
V90 3M	80	3067317	582058.58	8.92	4.27	0.4418	11609528	0.0513	0.4239	11141236	0.0534	0.3992	10489692	0.0566	0.4258	1118877	0.0531
V90 3M	105	3206723.3	608512.52	9.19	4.40	0.4614	12126387	0.0513	0.4432	11646236	0.0534	0.4157	10923987	0.0568	0.4438	11664188	0.0533

TABLE 5: The minimum COE at 24 sites within these six years.

Sites	$F(v)$	WTG	Hub height (m)	C_{IT} (\$)	C_{TA} (\$)	V_{mean} (m/s)	CF	E_{AP} (kWh)	COE (\$/kWh)
Pengchiayu	Weibull	E82	78	2121719.1	402620.5	8.898	0.529	9270084	0.0434
Anpu	Weibull	E82	138	2405766.6	456521.8	4.258	0.145	2553946	0.1788
Chutzehu	Weibull	E82	138	2405766.6	456521.8	3.937	0.142	2489782	0.1834
Tanshui	Weibull	E82	138	2405766.6	456521.8	2.796	0.053	940063	0.4856
Keelung	Weibull	E82	138	2405766.6	456521.8	2.525	0.045	789992	0.5779
Taipei	Reileigh	E82	138	2405766.6	456521.8	3.673	0.090	1585378	0.2880
Hsinchu	Weibull	E82	138	2405766.6	456521.8	3.390	0.086	1521036	0.3001
Ilan	Gamma	E82	138	2405766.6	456521.8	2.666	0.059	1047152	0.4360
Taichung	Weibull	E82	138	2405766.6	456521.8	2.780	0.052	920458	0.4960
Wuchi	Reileigh	E82	138	2405766.6	456521.8	5.726	0.267	468697	0.9740
Hualien	Gamma	E82	138	2405766.6	456521.8	4.868	0.172	3026950	0.1508
Sun Moon Lake	Gamma	E82	138	2405766.6	456521.8	2.067	0.035	616206	0.7409
Penghu	Reileigh	E82	138	2405766.6	456521.8	5.690	0.253	4438347	0.1029
Alishan	Gamma	E82	78	2121719.0	402620.5	1.475	0.021	367033	1.0970
Chiayi	Weibull	E82	138	2121719.0	456521.8	2.871	0.062	1083930	0.4212
Yushan	Reileigh	E82	78	2121719.0	402620.5	8.218	0.482	8443033	0.0477
Tungchitao	Weibull	E48	50	751905.40	142682.7	9.877	0.532	3728649	0.0383
Cheng Kung	Weibull	E82	138	2121719.0	456521.8	4.936	0.187	3270199	0.1396
Tainan	Gamma	E82	138	2121719.0	456521.8	4.270	0.127	2219498	0.2057
Taitung	Weibull	E82	138	2121719.0	456521.8	2.760	0.053	933972	0.4888
Kaohsiung	Gamma	V90	80	2352366.3	446388.5	2.677	0.050	878765	0.5080
Tawu	Weibull	E82	138	2405766.6	456521.8	4.375	0.137	2397660	0.1904
Lanyu	Reileigh	E82	78	2121719.1	402620.5	9.088	0.547	9579998	0.0420
Hengchun	Weibull	E82	138	2405766.6	456521.8	5.593	0.253	4439644	0.1028

The average wind speeds shown in Table 4 in six years vary from 8.17 m/s to 9.48 m/s. The minimum average wind speed can be found in E33 with a hub height of 36 m, while the maximum can be found in E82 with a hub height of 138 m. As a result, the CF of WTG and wind energy output is different when evaluated by different probability distributions. The maximum capacity factors computing from all probability functions can be found in V90-1800 at hub height of 105 m, but the maximum wind energy output results from the V90-3M WTG at the same hub height. The minimum cost of wind energy cannot be found neither in V90-1800 nor in V90-3M but can be found in E82 WTG at hub height of 78 m. From the simulation results, it can be concluded that the E82 WTG with 78 m hub height is the best option for installation at Pengchiayu site. It is noted that the average cost per kWh produced by all tested WTGs at Pengchiayu site during six years is below 0.06 \$/kWh.

Of course, the designer can choose a proper PDF at each site to evaluate the wind energy of WTG and its minimum COE. However, the general comment is similar after analysis of the results of all 24 tested sites. The minimum COE at 24 sites within these six years is shown in Table 5. The Enercon WTG type E82 with lower cut-in wind speed and higher cut-off wind speed can be achieved by the best operational performance among all tested WTG. Lower COE result

achieves smaller installation investment under the same wind energy output. The minimum COE (0.0477 \$/kWh) at Tungchitao site has the best performance, while Alishan site has the maximum COE (1.0970 \$/kWh).

5. Conclusion

In this study, the wind energy potential of 24 locations in Taiwan of six years was calculated. Great variations occur in the simulation results in both of the cost of energy (0.03936~1.105 \$/kWh) and capacity factor for different tested WTGs and 24 sites in Taiwan. Generally, capacity factor of the E82 GTW (at a height of 138 m) was evaluated to achieve the best choice of WTG in Taiwan, but at some sites, the capacity factor of V90_1800 (the hub height is 105 m) was second option. The capacity factor of WTG calculated from a Weibull probability distribution was higher than that calculated from other probability distributions, while the capacity factors of wind turbine computed by lognormal probability distribution was lower than those computed by other probability distributions. Any renewable energy system designer can benefit from the dedicated statistical analysis as investigated in this study to ensure the successful operation after WTG installations.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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