Benefit Analysis of Wind Turbine Generators Using Different Economic-Cost Methods

Tai-Her Yeh and Li Wang, *Senior Member, IEEE*

Abstract--**Since petroleum's price increases in recent years, the employment of renewable energy has become one of the most important tasks for government's energy policy. To fully use wind power, different wind farms should have appropriate capacity for wind turbine generators (WTG) to get the most wind power and maximum economic benefit. Currently, there are various values for capacity and hub height of commercial WTG. This paper uses three different economical methods to analyze economical outcomes for different wind farms with different parameters for WTG sets prior to the installation of WTG. According to the comparative analyzed results, the influence of Weibull parameters proposed can quickly choose proper capacity for WTG.**

***Index Terms*--wind turbine generator (WTG), wind farms, capacity factor, Weibull distribution, economic benefit.**

I. Introduction

DUE to the higher petroleum price of the whole world, it severely influences the living quality and economic-growth condition of various countries. In addition, Kyoto Protocal was effective on Feb. 16, 2005 and most industrialized countries have had to obey and endeavor to reduce their overall emissions of gases at least 5% below the 1990 level in the commitment period from 2008 to 2012. Today, most electrical energy is generated by burning a huge amount of fossil fuels and it results in acid rain and snow, climate change, urban smog, regional haze, etc. It is now clear that installations of many wind turbine generators (WTG) can effectively reduce environmental pollution, fossil fuel consumption, and the costs of overall electricity generation. Some organizations have completed a research report recently and the conclusion is that the number of wind farms in America and Europe is continuously increasing. Meanwhile, the rapid development of power electronics and the application of different kinds of generators in wind power generation have led to the stable development of wind power technologies.

At a specific site, the electricity generated by a wind power generation system depends on the mean value and the standard deviation of wind speed as well as the location of installation. Though it is hard to precisely predict the mean wind speed every year, there are still some meaningful indications. The characteristics of wind speed change during a year can still be expressed in terms of probability distribution. Weibull distribution [1-3] and Rayleigh distribution are the most commonly used methods nowadays to describe the wind-speed variations of wind farms. Weibull distribution uses two parameters, scale parameter c and shape parameter k, to show yearly mean wind speed and associated standard deviation, which may appropriately exhibit the probability distribution of wind speed.

The generation of electricity by a WTG at a specific site depends upon several factors except wind itself. Those factors include different wind speed characteristics of the WTG such as cut-in wind speed (v_C), rated wind speed (v_R), cut-out wind speed (v_F), and hub height (h). However, the values for v_C and v_F are respectively set to be 4 m/s and 25 m/s for most wind turbines control construction at different wind sites. This paper considers hub heights under different scale parameters and shape parameters of Weibull distribution function to influence some qualities at the same wind farm. These analyzed results are different from the ones shown in [4-6]. This paper uses two variables, rated wind speed v_R and hub height h, to analyze capacity factor CF at different wind farms.

II. Wind Speed And Capacity Factor Of Wind Turbines

The surface of the earth consists of various layers with different characteristics. Each layer is affected by different fluid parameters. Due to the deformity of the ground wind, wind speed increases with the increase of height. When the wind is above the ground 20-120 m, the information about wind speed is the essential basis of determining the quality of a wind farm and the capacity of a WTG. It seems useless to obtain the information of wind speed when the height is 10 m above the ground. If there is an equation using the wind speed of lower height to estimate the one at higher height, it often appears in papers of fluid mechanics. The above equation involves many variables and it does not apply to general researches. As a result, a simpler equation is proposed to fit actual results. Though this equation is not verified by theories, it is usually used and it has good effects in some respects such as wind speed prediction. The simpler equation is

$$\frac{v(h_2)}{v(h_1)} = (\frac{h_2}{h_1})^{\alpha} \qquad (1)$$

where v is the wind speed, h_1 is the measuring height, which is usually 10 m, h_2 is the height of predicted wind speed, and friction coefficient α comes from experimental value.

It is hard to predict yearly mean wind speed, especially since the atmospheric environment has been destroyed gradually. In general, however, wind speed does not change much every year. Thus, the characteristics of wind speed

Tai-Her Yeh and Li Wang are with the Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan 70101, Republic of China (e-mail: liwang@mail.ncku.edu.tw).

change every year can still be shown by probability distribution. Weibull distribution is more applicable in this area and it has been verified that Weibull distribution can get correct mean wind speed and associated standard deviation within one year in many wind farms. Weibull cumulative distribution function of wind speed is described by

$$F(v) = \exp\left[-(\frac{v}{c})^k\right] \tag{2}$$

where $F(v)$ is the fraction of time for which the hourly mean wind speed exceeds v. Equation (2) is characterized by two parameters, a scale parameter c and a shape parameter k, that describes the variability deviated from the mean value. This can be derived by considering the probability density function

$$f(v) = -\frac{dF(v)}{dv} = k\frac{v^{k-1}}{c^k}\exp\left[-(\frac{v}{c})^k\right] \tag{3}$$

where $k > 0$, $v > 0$, and $c > 1$. The mean wind speed and the associated standard deviation are expressed by

$$\bar{v} = c\Gamma(1+\frac{1}{k}) \tag{4}$$

$$\sigma = c\sqrt{\Gamma(1+\frac{2}{k}) - \Gamma^2(1+\frac{1}{k})} \tag{5}$$

where Γ is a gamma function and $\bar{v}$ is the cubic mean wind speed (*CMWS*).

The current research [5] stated that using *CMWS* for wind speed v rather than arithmetic average wind speed in Weibull distribution function can estimate the wind power of a wind farm more accurately. So far the wind power generation systems in both Heng-Chuen and He-I, Taiwan, have been operated for more than one year. Using *CMWS* rather than arithmetic average wind speed can estimate the yearly wind generator capacity of the whole turbine set more effectively and precisely. Combining the relationship between the output power and the wind speed, it can obtain the mean output power of a wind farm or a WTG, $P_{e.ave}$, which is an important parameter of a wind power generating system and it can also be used for the generated wind power and effective electricity. The mean output power is a more economical efficient index than rated output power and it is defined by

$$P_{e.ave} = P_{eR}(CF) = \eta_o \frac{1}{2}\rho A v_R^3 (CF) \tag{6}$$

where P_{eR} is the rated output power of a wind turbine, v_R the rated wind speed of a wind turbine, η_O the overall efficiency, ρ the air density, A the swept area of wind blades, and CF the capacity factor of a WTG [6]. The CF can be defined by

$$CF = \frac{1}{v_R^3}\int_{v_C}^{v_R} v^3 f(v)dv + \int_{v_R}^{v_F} f(v)dv \tag{7}$$

It is seen from (7) that the selected rated wind speed v_R is an important part of wind turbine design. For a given wind farm with known c and k parameters, we may select v_R, v_C and v_F to maximize the average power and thereby maximize the total energy production. According to the most modern WTG, this paper uses v_C as 4 m/s, v_F as 25m/s, and v_R as a variable parameter. If the rated wind speed is chosen too low, too much energy generated under higher wind speeds will be lost. If the rated wind speed is selected too high, the WTG will seldom operate at rated capacity and too much generated energy under low wind speeds will be lost. Hence, the average power output of WTG may reach a maximum at a specific rated wind speed.

III. Economical Analysis Methods

A wind energy system should be considered as an investment that produces revenue prior to WTG installation. An economic analysis [7-8] is used to calculate the profitability of a wind energy project and alternative investments may be clearly compared. Economic analysis methods can be applied for wind energy systems, assuming that one has a reliable estimate for the capital costs and operation and maintenance (O&M) costs. The general purpose of such methods is not only to determine the economic performance of a given design of wind energy system but also to compare it with conventional and other renewable energy based systems. This section compares three different economic analysis methods for the studied WTG.

A. Simple Payback Period Method

For a preliminary estimate of a wind energy system's feasibility, it is desirable to have a method for a quick determination of its relative economic benefits. A payback calculation compares revenue with costs and determines the duration of time required to recoup an initial investment. The payback period (in years) is equal to the total capital cost of the wind power generation system divided by the average annual return from the produced power and it is expressed by

$$SP = \frac{C_c}{AAR} \tag{16}$$

$$AAR = E_a \times P_e \tag{17}$$

$$SP = \frac{C_c}{E_a \times P_e} \tag{18}$$

where SP is the simple payback period, C_c is the installed capital cost, AAR is the average annual return, E_a is the annual energy production (in kWh/year), P_e is the price obtained for electricity (in \$/kWh).

B. Cost of Energy Method

From a power generating business or utility perspective, the previous definition of cost of energy can be used for a first estimate of utility generation costs for a wind farm. The cost of energy COE is defined as the unit cost to produce energy from the wind energy generation system and it is expressed by

$$COE = \frac{C_c \times FCR + C_{O\&M}}{E_a} = FCR \times \frac{C_c}{E_a} + \overline{C_{O\&M}} \tag{19}$$

where FCR is the fixed charge rate including utility debt and equity costs, state and federal taxes, insurance and property taxes, $C_{O\&M}$ is the annual operation and maintenance cost, and $\overline{C_{O\&M}}$ is cost of operation and maintenance normalized per unit of energy. Some limitations of this method include

1) It assumes that a debt term life equals to the life of the power plant.
2) It does not readily allow for variable equity return, variable debt repayment, or variable costs.

C. Discounted Cash Flow (DCF) Method

The cash flow method is based on the use of an accounting type spreadsheet requiring an annual input of estimated income and expenses over the lifetime of the project. The mechanics of *DCF* analysis are simple and the calculation may be implemented easily on a spreadsheet while the main functions are often included in commercially available packages. For a given discount rate of r, the value of a sum in n years time is

$$V_n = V_P(1+r)^n \tag{20}$$

The present value of a sum received or paid in the future is

$$V_P = \frac{V_n}{(1+r)^n} \tag{21}$$

where V_n is the value of a sum in year n and V_p is the present value of the sum. For a payment stream lasting m of years, we have

$$V_P = \sum_{n=1}^{n=m} \frac{V_n}{(1+r)^n} \tag{22}$$

This is a geometric series which, for equal payments (A), sums to

$$V_P = \frac{1-(1+r)^{-n}}{r} A \tag{23}$$

This allows the calculation of the present value of any sum of money which is either paid or received in the future. The net present value (*NPV*) is simply the summation of all the present values of future income and expenditures. Though there is a another method, life-cycle costing (*LCC*) [9], that is commonly used for the economic evaluation of energy producing system based on the principles of the time value of money. The *LCC* method summarizes expenditures and revenues occurring over time into a single parameter so that an economically based choice can be made. Because it includes too many unknown parameters such as loan interest rate, general inflation rate, period of loan, lifetime of system, and down payment on system costs, etc., this paper does not use this method to analyze whether wind farm is good or not.

IV. Simulation Results

Owing to capturing wind power, the manufactures of commercial WTG such as ENERCON, VESTAS, GE, etc. are developing various WTG types with different values for capacity, rated wind speed, and tower height as listed in Table 1. This research provides scale parameters c and shape parameters k in five wind farms in Taiwan and their names are Tai-Chung Port, Jang-Bin, Shin-Jue Shiang-Shan, He-I, and Mai-Liao. Tables 2-6 respectively list the associated parameters of these five wind farms when the tower heights are 30, 45, 65, 70, and 80 m. All data listed in Tables 2-6 are obtained by the Central Weather Bureaus of Taiwan and Taiwan Power Company's field measurements using statistical data of annual wind speed [10], (4), (5), and (7). Since current commercial capacity of WTG is constantly increased, different WTG sets have different hub heights h and different WTG rated wind speeds v_R to capture maximum wind power. To promote the use of renewable energy resources, various rated wind speeds of WTG are selected to get *CF* at the five wind farms whose parameters are listed in Tables 2-6.

Table 1 Specifications of various commercial WTG.

No	Make-Type	Wind speeds (m/s)			Turbine	Generator	h (m)
		v_C	v_R	v_F	RD (m)	P_{eR} (kW)	
1	MICON	4	14	25	30	200	30
2	NEPC-MICON	4	15	25	31	400	30.5
3	ENERCON-E40	2.5	13	25	44	600	46
4	VESTAS-V47	5	15	25	35	660	45
5	VESTAS-V52	4	17	25	52	850	55
6	GE-1.5S	4	14	25	70.5	1500	64.7
7	VESTAS-V88	3.5	13	24	82	1650	VARY
8	NEG-NICON	3.5	16	25	60	1650	70
9	VESTAS-V66	4	16	25	62	1750	60
10	VESTAS-V80	4	16	25	76	1800	60
11	ZEPHYROS-Z72	3	16	25	71.2	2000	65
12	GAMESA EOLICA-G80	4	16	25	70	2000	67
13	GE-2.3	3	14	25	94	2300	100
14	GE-2.5	3.5	15	25	88	2500	85
15	GE-2.7	3.5	16	25	84	2700	70

Table 2 Parameters of the studied five wind farms. (h = 30 m and v_R = 14 m/s)

No	Name of Wind Farm	CMWS (m/s)	σ	k	c	CF
1	Tai-Chung port	8.30	4.41	1.9639	9.3620	0.3106
2	Jang-Bin	8.74	5.10	1.7705	9.8198	0.3389
3	Shin-Jue Shiang-Shan	8.45	5.38	1.6089	9.4295	0.3170
4	He-I	8.32	4.09	2.1395	9.3924	0.3088
5	Mai-Liao	8.15	4.61	2.0371	9.1986	0.2982

Table 3 Parameters of the studied five wind farms. (h = 45 m and v_R = 15 m/s)

No	Name of Wind Farm	CMWS (m/s)	σ	k	c	CF
1	Tai-Chung port	9.03	4.80	1.9631	10.1854	0.3185
2	Jang-Bin	9.67	5.64	1.7715	10.8650	0.3508
3	Shin-Jue Shiang-Shan	9.20	5.86	1.6081	10.2260	0.3190
4	He-I	8.48	4.17	2.1395	9.5576	0.2777
5	Mai-Liao	8.84	4.56	2.0371	10.0271	0.3083

Table 4 Parameters of the studied five wind farms. (h = 65 m and v_R = 14 m/s)

No	Name of Wind Farm	CMWS (m/s)	σ	k	c	CF
1	Tai-Chung port	9.76	5.19	1.9622	11.0086	0.4073
2	Jang-Bin	10.60	6.19	1.7690	11.9091	0.4332
3	Shin-Jue Shiang-Shan	9.94	6.33	1.6084	11.0919	0.3880
4	He-I	8.66	4.26	2.1395	9.7811	0.3351
5	Mai-Liao	9.57	4.90	2.0317	10.7392	0.3947

Table 5 Parameters of the studied five wind farms. (h = 70 m and v_R = 15 m/s)

No	Name of Wind Farm	CMWS (m/s)	σ	k	c	CF
1	Tai-Chung port	9.91	5.27	1.9626	11.1795	0.3724
2	Jang-Bin	10.80	6.30	1.7709	12.1351	0.4028
3	Shin-Jue Shiang-Shan	10.10	6.43	1.6080	11.2712	0.3614
4	He-I	8.70	4.28	2.1395	9.7114	0.2863
5	Mai-Liao	9.66	4.98	2.0317	10.8996	0.3588

Table 6 Parameters of the studied five wind farms. (h = 80 m and v_R = 15 m/s)

No	Name of Wind Farm	CMWS (m/s)	σ	k	c	CF
1	Tai-Chung port	10.20	5.42	1.9637	11.5051	0.3883
2	Jang-Bin	11.17	6.52	1.7700	12.5498	0.4144
3	Shin-Jue Shiang-Shan	10.39	6.61	1.6102	11.5953	0.3680
4	He-I	8.78	4.32	2.1395	9.9126	0.2991
5	Mai-Liao	9.92	5.11	2.0371	11.1945	0.3748

According to the parameters listed in Tables 2-6, the following tentative observations can be concluded.

A. Different locations with identical tower height

1) The value of k becomes smaller when σ increases.
2) The value of c becomes larger when CMWS increases.
3) The values of c and CF are not related with the values of k and σ.

B. Various tower heights under identical location

1) The values of *CMWS*, σ, c, and CF become larger when h becomes higher. Though there are except conditions owing to different rated wind speeds.
2) The value of k almost maintains a constant value, so it affects CF very little.
3) The value of CF becomes smaller when rated wind speed becomes higher.

Capital costs of WTG include the costs of blades, hub, nacelle, gearbox, generator, control systems, tower, all electric instruments, infrastructure cost, installation and test cost, etc. The annual energy production considers CF of wind farm and WTG availability. According to the operating conditions and experiences of installed WTG running over one year in Taiwan, this paper adopts average availability of 0.9, constant operation and maintenance cost of US$0.01/kWh, fixed charge rate (*FCR*) of 0.1 [9], and discount rate of 5%.

The capital costs of WTG in Taiwan under different tower heights were derived from field construction experiences over the past four years. Table 7 lists capital cost for several WTG under different tower heights. Table 8 lists simple payment years of several WTG with various tower heights, Table 9 lists *COE* results of several WTG with various tower heights. Tables 10-12 respectively list *NPV* (US$) results of several WTG with various tower heights after different years.

C. Analysis of Simple Payback Period (SP)

1) The value of *SP* of WTG at Jang-Bin (No. 2) is the lowest in Table 8 and it is the best wind farm location since it has the largest CF value in five wind farms listed in Tables 2-6.
2) A WTG with P_{eR} of 2000 kW, *RD* of 80 m, v_R of 15 m/s, and h of 70 m whose *SP* is 7.5276 years is an obvious good choice at Shin-Jue Shiang-Shan (No. 3) owing to larger values for c and σ.
3) The value of *SP* of WTG at He-I (No. 4) is the largest in Table 8 and it is the worst wind farm owing to the smallest values for c and σ as listed in Tables 2-6.
4) The calculation of *SP* omits many factors such as operation & maintenance, loan costs, depreciation on capital costs, and variations in the value of delivered electricity and it acquires a better and lower payback year values.

D. Analysis of Cost of Energy (COE)

The comparative results of *COE* for several WTG under different tower heights are listed in Table 9. Because all WTG in Taiwan were purchased from foreign countries, the values of *COE* listed in Table 7 are obviously higher than the one of market value.

1) The values of *COE* of WTG at Jang-Bin (No. 2) are lower than US$0.0656/kWh which is the tariff of purchasing wind electricity sale of Taiwan government and it does not include tax benefits and environmental benefits. Jang-Bin is approved to be a very good wind farm.
2) To promote the acquiring wind power, a WTG with P_{eR} of 2000 kW, *RD* of 80 m, v_R of 15 m/s, and h of 70 m in place of a WTG with P_{eR} of 1500 kW, *RD* of 70 m, v_R of 14 m/s, and h of 65 m is an evident good choice at Shin-Jue Shiang-Shan (No. 3).
3) For Tai-Chung port (No. 1) and Mai-Liao (No. 5), a WTG with P_{eR} of 2000 kW, RD of 80 m, v_R of 15 m/s, and h of 70 m or a WTG with P_{eR} of 1500 kW, *RD* of 71 m, v_R of 14 m/s, and h of 65 m is more suitable. However, the employment of WTG with smaller or larger capacity with larger tower height is not a good choice.
4) For He-I (No. 4), a WTG with P_{eR} of 660 kW, *RD* of 35 m, v_R of 15 m/s, and h of 45 m is the only choice, or it does not reach economic benefit which are lower than US$0.0656/kWh.

E. Analysis of Discounted Cash Flow Method (DCF)

1) Life time n is an important factor as listed in Table 10. When n equals 10, all *NPV* results are negative for the five wind farms and it can not acquire economic benefit.
2) If life time n is 15, all positive *NPV* results can be obtained at Tai-Chung port (No. 1) and Jang-Bin (No. 2). Especially, Jang-Bin is a better wind farm as listed in Table 11.
3) To acquire economic benefit and promote renewable energy captured, selection of WTG with P_{eR} of 2000 kW, *RD* of 80 m, v_R of 15 m/s, and h of 70 m is a good choice at Tai-Chung port (No. 1), Shin-Jue Shiang-Shan (No. 3), and Mai-Liao (No. 5) as listed in Table 11.
4) If life time n is 20, it is suitable to select WTG with P_{eR} of 1500 kW, *RD* of 70 m, v_R of 14 m/s, and h of 65 m in order to acquire economic benefit at He-I (No. 4) as listed in Table 12.

V. Conclusions

This paper has employed Weibull distribution's two parameters, scale parameter c and shape parameter k, wind turbine's rated wind speed (v_R), hub height of wind tower (h) and set current commercial wind turbine cut-in speed (v_C) as 4 m/s, cut-out wind speed (v_F) as 25 m/s, and analyzed whether capacity factor (CF) is economical or not under various hub heights at five wind farms in Taiwan by means of three different economic methods. Through the simulation results of these methods, it can be realized that the influence of Weibull distribution's parameters, how to choose various wind turbines at different wind farms, and how to identify the quality of wind farms. From the simulated *CF* results at different wind farms, it can be observed that the scale parameter *c* is the primary cause of affecting cubic mean wind speed (*CMWS*) and generated wind power.

This paper also draws some important conclusions as follow.

(1) For better wind farms, the employment of larger wind turbines is more suitable. However, for worse wind farms, the utilization of small wind turbines is the only choice for economic benefit.
(2) The value of k becomes smaller when σ increases.
(3) The values of *CMWS*, σ, c, and *CF* become larger when tower height h becomes higher.
(4) The value of *CF* becomes smaller when rated wind speed becomes higher.
(5) Through the simulation results of three economic methods, it is found that *CF*, lifetime, capital costs, discount rate, and operation and maintenance cost can affect economic benefits.

According to the above analyzed results, to select proper rated wind speed and wind turbine capacity is more important than raising the hub height all the way at different wind farms. Finally, selection of good wind farms for wind turbines installation, suitable scale parameter and shape parameter, and wind turbine capacity are identically important.

Table 7 Capital costs (US$) of several WTG with different tower heights.

200 kW	660 kW	1500 kW	2000 kW	2000 kW	2000 kW
RD = 30 m	*RD* = 35 m	*RD* = 70 m	*RD* = 71 m	*RD* = 80 m	*RD* = 80 m
v_R=14m/s	v_R=15m/s	v_R=14m/s	v_R=16m/s	v_R=15m/s	v_R=15m/s
h = 30 m	*h* = 45 m	*h* = 65 m	*h* = 65 m	*h* = 70 m	*h* = 80 m
272,842	900,377	2,253,570	2,589,089	2,814,003	3,442,998

Table 8 SP (year) results of several WTG with various tower heights

No	200 kW	660 kW	1500 kW	2000 kW	2000 kW	2000 kW
	RD = 30 m	*RD* = 35 m	*RD* = 70 m	*RD* = 71 m	*RD* = 80 m	*RD* = 80 m
	v_R=14m/s	v_R=15m/s	v_R=14m/s	v_R=16m/s	v_R=15m/s	v_R=15m/s
	h = 30 m	*h* = 45 m	*h* = 65 m	*h* = 65 m	*h* = 70 m	*h* = 80 m
1	8.4924	8.2817	7.1321	7.7469	7.3052	8.5721
2	7.7832	7.5192	6.7057	7.0468	6.7539	8.0322
3	8.3209	8.2687	8.5943	7.9085	7.5276	9.0450
4	8.5419	8.2687	8.6687	9.9524	9.5022	11.1286
5	8.8254	8.5362	7.3430	7.5649	7.5649	8.8607

Table 9 COE (US$/kWh) results of several WTG with various tower heights

No	200 kW	660 kW	1500 kW	2000 kW	2000 kW	2000 kW
	RD = 30 m	*RD* = 35 m	*RD* = 70 m	*RD* = 71 m	*RD* = 80 m	*RD* = 80 m
	v_R=14m/s	v_R=15m/s	v_R=14m/s	v_R=16m/s	v_R=15m/s	v_R=15m/s
	h = 30 m	*h* = 45 m	*h* = 65 m	*h* = 65 m	*h* = 70 m	*h* = 80 m
1	0.0657	0.0643	0.0568	0.0610	0.0579	0.0662
2	0.0611	0.0593	0.0540	0.0562	0.0543	0.0627
3	0.0646	0.0642	0.0591	0.0619	0.0594	0.0693
4	0.0660	0.0642	0.0669	0.0753	0.0723	0.0830
5	0.0679	0.0660	0.0582	0.0630	0.0596	0.0681

Table 10 NPV (US$) results of several WTG after ten years.

No	200 kW	660 kW	1500 kW	2000 kW	2000 kW	2000 kW
	RD = 30 m	*RD* = 35 m	*RD* = 70 m	*RD* = 71 m	*RD* = 80 m	*RD* = 80 m
	v_R=14m/s	v_R=15m/s	v_R=14m/s	v_R=16m/s	v_R=15m/s	v_R=15m/s
	h = 30 m	*h* = 45 m	*h* = 65 m	*h* = 65 m	*h* = 70 m	*h* = 80 m
1	-62580	-188850	-185610	-401810	-292980	-814340
2	-43420	-116700	-54110	-184510	-87190	-637650
3	-58240	-187740	-537460	-446490	-367450	-951770
4	-63800	-187700	-552200	-886500	-875900	-1418200
5	-70970	-211640	-249580	-497270	-385050	-905730

Table 11 NPV (US$) results of several WTG after fifteen years.

No	200 kW	660 kW	1500 kW	2000 kW	2000 kW	2000 kW
	RD = 30 m	*RD* = 35 m	*RD* = 70 m	*RD* = 71 m	*RD* = 80 m	*RD* = 80 m
	v_R=14m/s	v_R=15m/s	v_R=14m/s	v_R=16m/s	v_R=15m/s	v_R=15m/s
	h = 30 m	*h* = 45 m	*h* = 65 m	*h* = 65 m	*h* = 70 m	*h* = 80 m
1	9800	56060	526210	351070	574780	90480
2	35550	153060	702970	643180	851420	327980
3	15620	57560	53240	291010	474680	-94250
4	8160	57560	33450	-300480	-208710	-721230
5	1480	25430	440210	222770	451020	-32370

Table 12 NPV results of several WTG after twenty years

No	200 kW	660 kW	1500 kW	2000 kW	2000 kW	2000 kW
	RD = 30 m	*RD* = 35 m	*RD* = 70 m	*RD* = 71 m	*RD* = 80 m	*RD* = 80 m
	v_R=14m/s	v_R=15m/s	v_R=14m/s	v_R=16m/s	v_R=15m/s	v_R=15m/s
	h = 30 m	*h* = 45 m	*h* = 65 m	*h* = 65 m	*h* = 70 m	*h* = 80 m
1	66500	248000	1083900	941000	1254700	799400
2	97400	364400	1296200	1291700	1586800	1084600
3	73500	249800	516100	868900	1134500	577600
4	64540	249760	492310	158710	314000	-175140
5	53000	211200	980700	786900	1106100	651900

VI. Nomenclature And Abbreviation

General

WTG	wind turbine generator
CF	capacity factor of wind turbine
CMWS	cubic mean wind speed
RD	rotor diameter
DCF	discounted cash flow
v	instantaneous wind speed
h	tower height
$f(v)$	probability density function of wind speed
$F(v)$	Weibull distribution function of wind speed
c, k	scale and shape parameters of Weibull distribution function
σ	standard deviation of wind speed
v_C, v_R, v_F	cut-in, rated, and cut-out wind speeds
α	friction coefficient tower height of wind tower
$P_{e,ave}$	output power of wind turbine generator
ρ	air density
A	swept area of wind blades
P_{eR}	rated electrical power output
η_O	rated overall efficiency
Γ	gamma function
SP	simple payback period
AAR	average annual return
P_e	price obtained for electricity
COE	cost of energy and
FCR	fixed charge rate
C_c	installed capital cost and
E_a	annual energy production
$C_{O\&M}$	average annual operation and maintenance cost

$\overline{C_{O\&M}}$	average operation and maintenance cost/kWh
V_n	value of a sum in year n
V_p	present value of the sum
n	number of year
r	discounted rate
NPV	net present value
LCC	life-cycle costing

VII. References

[1] C.G. Justus, "Nationwide assessment of potential power output from aero-generators," *Second U.S. National Conference on Wind Engineering Research*, Ft. Collins, Colo., June 22-25, 1975.

[2] G.L. Johnson, "Economic design of wind electric systems," *IEEE Trans. Power Apparatus and Systems*, March/April 1978, pp. 554-62.

[3] J.P. Hennessey, Jr., "Some aspects of wind power statistics, and performance analysis of a 6 MW wind turbine-generator," *Journal of Applied Meteorology*, vol. 16, no. 2, February 1997, pp. 119-28.

[4] S.H. Jangamshetti and V.G. Rau, "Normalized power curves as a tool for identification of optimum wind turbine generator parameters," *IEEE Trans. Energy Conversion*, vol. 16, no. 3, September 2001, pp. 283-288.

[5] S.H. Jangamshetti and V.G. Rau, "Optimum siting of wind turbine generators," *IEEE Trans. Energy Conversion*, vol. 16, no. 1, March 2001, pp. 8-13.

[6] S.H. Jangamshetti and V.G. Rau, "Site matching of wind turbine generators: A case study," *IEEE Trans. Energy Conversion*, December 1999, pp. 1537-1543.

[7] A.S. Malik and A. Awsanjli, "Energy fuel saving benefit of a wind turbine," *IEEE MELECON*, May 12-15 2004, Dubrovnik, Croatia.

[8] L. Neij, "Cost dynamics of wind power," *ENERGY*, vol. 24, 1999, pp. 375-389.

[9] J.F. Manwell, J.G. Mcgowan, and A.L. Rogers, *Wind Energy Explained Theory, Design and Application*, New York: John Wiley and Sons Ltd., 2002.

[10] T.-H. Yeh and L. Wang, "Selection of wind generator capacity for capturing maximum wind energy in wind power generation systems," *Proceedings of the Eighth IASTED International Conference on Power and Energy Systems, Renewable Generation*, Paper 492-061, Marina Del Rey, USA, October 2005, pp. 137-142.

VIII. Biographies

Tai-Her Yeh was born in Kaohsiung, Taiwan, on October 8, 1965. He received his MSc degree from Department of Electrical Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan, in 2003. He is currently pursuing his PhD degree at National Cheng Kung University, Tainan, Taiwan. He has been with the department of Wind Power Project of Taiwan Power Company from 1991 till now. Those works he had ever done comprise power plants construction such as combine cycle, fossil, emergency diesel engine, coal convey, and wind turbine. His interests include electric machine, transform power, distribution power, and instrument control. His current position is the Chief of Machine and Electric Section.

Li Wang (S'87-M'88-SM'05) was born in Changhua, Taiwan, on December 20, 1963. He received a Ph.D. degree from Department of Electrical Engineering, National Taiwan University (NTU), Taipei, Taiwan, in June 1988. He has been an associated professor and a professor at the Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan in 1988 and 1995, respectively. He was a visiting scholar of School of Electrical Engineering and Computer Science, Purdue University, West Lafayette, IN, in 2000 and a visiting scholar of School of Electrical Engineering and Computer Science, Washington State University (WSU), Pullman, WA, in 2004. At present, his interests include power systems dynamics, power system stability, and AC machines analyses. He is an IEEE Senior Member.