An Optimal Selection Method for a Wind Energy Conversion System

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There is much interest in using renewable energy sources such as wind, wave and sun to generate electrical energy. The local power companies, Trinidad & Tobago Electricity Commission (T&TEC) and Power Generation Company of Trinidad & Tobago (Powergen), have expressed an interest in wind power generation and integration to supplement its conventional fossil fuel, i.e., natural gas approach. The Caribbean island of Tobago was chosen for investigation into its wind power potential mainly due to its better alignment to the prevailing winds, i.e., the North-east Trades, than Trinidad. This paper focuses on an optimal selection method of matching a Wind Energy Conversion System (WECS) to wind regimes, such as Tobago. It incorporates various techniques and economical deicisions that are to be considered and used when sizing available commercial WECS's to potential wind regimes.

1. Introduction

There is considerable interest in using novel methods to generate electrical energy including wind, wave, tidal and solar energy sources. The main reason is that conventional fuels are limited and expensive whereas these other forms, known as the renewables are limitless and cheap to operate. Renewable energy is expected to capture a growing percent of world energy market over the next 20 years. The key drivers of the "Renewable Energy Revolution" are:

(a) Increasing global energy demand.
(b) Concerns about carbon emissions.
(c) Concerns about energy independence.
(d) Falling cost of renewable energy.

The economic viability of a Wind Energy Conversion System (WECS) for a particular wind regime depends on the success with which the system extracts the maximum possible energy in the most efficient way. A WECS can operate effectively only if it is designed for the wind regime where it is to be set up. Rated power, cut-in speed u_c, rated speed u_r and furling speed u_f should all be specified according to the local wind regime. The system can be designed to either: [1]

(a) Maximise the annual energy output or
(b) Minimise the time during which output is not being produced.

Thus, optimum performance demands a close match between the wind speed distribution and WECS performance characteristics. This paper considers this complex relationship and incorporates the economic benefits in order to determine WECS selection.

The island of Tobago has an approximate area of 304 km^2. The climate is tropical with basically a wet and a dry season and is placed in the prevalent North-east Trades belt of the southern Caribbean. The hilly regions generally have winds of good intensity and high regularity during most of the year. Tobago is entirely reliant on Trinidad for its electricity supply. This is achieved by means of a submarine power cable. Wind power generation is seen as a viable means of providing an independent source of energy, thereby, increasing the reliability of the electricity supply. Trial systems are to be placed in operation and studies are being conducted in order to identify the wind profile of Tobago.

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Pertinent discussion will be published in July, 2000 West Indian Journal of Engineering if received by May, 2000.

2. Wind Speed Frequency Distribution

The identification of the wind speed frequency/probability distribution is important for assessment of the wind resource. In the case of historical wind data, the best method of constructing this distribution is by means of a mathematical model. For a given wind pattern, such a statistical model facilitates:

(a) The estimation of the average power density.
(b) The extrapolation of wind speeds.
(c) The making of a scientific judgement of the wind resource.

There are several probability density functions (PDF's) which can be used to model the wind speed frequency/probability distribution. The two-parameter Weibull distribution is considered the most reliable model to characterise a very wide range of wind patterns because:

(a) It allows for satisfactory estimates of the skewness of the wind speed distribution.
(b) The fit of the Weibull is generally very good in the tail of the distribution,
(c) It fits better than other 2-parameter distributions such as Log-Normal and Gamma, and
(d) For most cases, the Weibull distribution gives a reasonable overall fit to actual data.

In theory, the hydrid Weibull density distribution is a more accurate model in that it properly accounts for periods of calms. However, this is not important in that the WECS output is zero below some cut-in speed. The wind speed, u, is Weibull distributed if its PDF is:

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} e^{-\left(\frac{u}{c}\right)^{k}} \quad (k > 0, u > 0, c > 1) \tag{1}$$

where u = measured wind speed (m/s).
c = scale parameter (m/s).
k = shape factor (dimensionless).

c and k are adjustable parameters and can be made to fit a wide range of observed data.

The (annual) mean wind speed, $\bar{u}$, is related to c by the expression:

$$\bar{u} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{2}$$

where Γ is the gamma function.

Other useful statistics of the Weibull distribution are the long-term variance

$$\sigma^2 = c^2\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right] \tag{3}$$

and the standard deviation $S.D. = \sqrt{\sigma^2}$ (4)

Hennessy [2] quotes U.S. data to suggest that $1.1 \le k \le 2.6$, Bossanyi et al [3] found that $1.49 \le k \le 1.95$ for 5 sites (4 in the Northern Sea); Carlin and Diesendorf [4] found that $1.85 \le k \le 2.64$ for a number of sites in South Australia and Halliday [5] suggested that $1.09 \le k \le 2.55$ from 14 sites in the U.K. Thus, it seems clear that generally k lies between 1.5 and 2.7.

2.1 Parametric Estimation

The parameters c and k of the Weibull model can be estimated by the following methods:

(a) Method of Moments.
(b) Linear Least Squares.
(c) Maximum Likelihood Method.

Methods (a) and (c) tend to be the most accurate in estimating the parameters to fit a Weibull distribution to a given set of wind speed data. However, method (c) gives great uncertainty in the linearising process. An acceptable approximation for the method of moments over the range $1 \le k \le 10$ is [6]:

$$k = \left(\frac{\sigma}{\bar{u}}\right)^{-1.086} \tag{5}$$

However, Justus [6] examined the wind speed distributions at 140 sites across the continental United States measured at heights of 10 m, and found that

$$k = d_1\sqrt{\bar{u}} \tag{6}$$

The proportionality constant d_1 is a site specific constant with an average value of 0.94 when the mean wind speed is given in m/s. The average value is normally adequate for wind-power calculations and eqn. (6) can be used to satisfactorily estimate k when the variance is not known.

Once k has been determined, c can be solved whereby:

$$c = \frac{\bar{u}}{1\left(1+\frac{1}{k}\right)} \qquad (7)$$

Wind data must be collected at the site in order to determine the parameters σ and $\bar{u}$.

2.2 Data Sets

The wind is a geographically variable resource; wind readings taken at two sites separated by a few kilometres can show large differences in speed. The energy in the wind available to the WECS is proportional to the cube of the wind velocity and, if the velocity doubles, the amount of energy in the wind increases eightfold. The phenomena of wind shear and turbulence influences the wind speed and, hence, the energy output of the wind turbine whereby the wind speed is low close to the ground increases with increasing height above the ground. The effects of wind shear and turbulence diminish with height and can be largely overcome by putting the WECS sufficiently high above the ground. In this paper, analyses at the hubheights 24, 30 and 37m will be conducted in order to determine the best hubheight for economic energy production. Thus, it is essential, that one knows precisely how and when the wind blows over a region being considered for wind turbines. Basic wind data needed for analysis comprises of hourly mean wind speed readings and the associated wind direction measurements. Wind data is essential for estimating the Weibull distribution and accurate parameter estimation requires at least 1 year of data. Data collection is achieved by installing meteorological stations strategically at potential wind sites. Each meteorological station should consist of at least two anemometers for wind speeds comparison at different heights above the ground (wind shear analysis), a wind vane and a data acquisition system. **Figure 1** [7] illustrates a state of the art data collection procedure using equipment NRG Systems Inc., Vermont, U.S.A. Industry standard reports provide a complete wind resource assessment of the regime.

Wind data is only recorded at the Crown Point International Airport for the sole purpose of information about wind speed variations. The wind speed measurement records are representative of the actual wind speeds since the siting of the anemometers conforms to the ideal exposure as defined by the World Meteorological Organisation (WMO); i.e., the anemometer is sited in open level terrain,

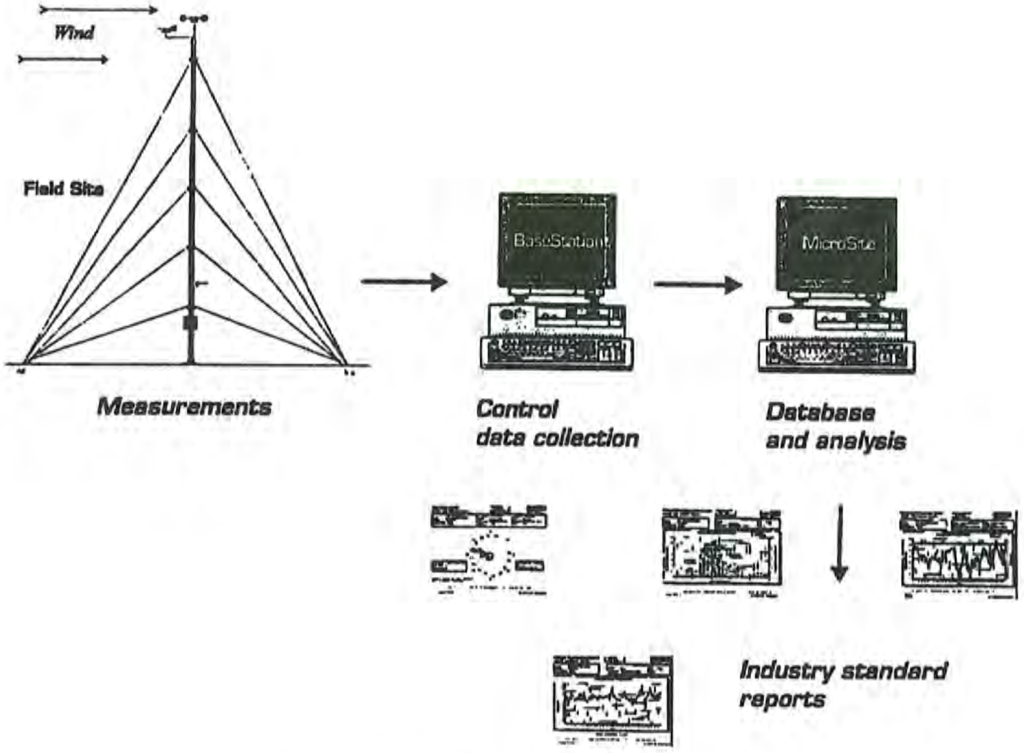


FIGURE 1: *Data Collection Procedure*

at an elevation of 10m and at a distance, at least 100m away from the nearest obstruction. Due to the absence of wind data for the wind potential sites, the 1994 data set recorded at the Crown Point International Airport will be used for illustration purposes.

From the data set, the annual mean wind speed, $\bar{u}$ = 5.93 m/s. Since, the variance is not known, the estimated shape factor, k, is 2.29 from eqn. (6) and the scale parameter, c, is 6.7 m/s from eqn. (7). However, the Weibull parameters are desired at the WECS hubheight other than the 10m anemometer level. Thus, the c and k values, c_a and k_a, determined at anemometer height, z_a m, can be adjusted to any desired height, z m, by the relations proposed by Justus et al [8].

$$c(z) = c_a\left(\frac{z}{z_a}\right)^n \tag{8}$$

$$k(z) = \frac{k_a\left[1 - 0.088 In\left(\frac{z_a}{10}\right)\right]}{\left[1 - 0.088 In\left(\frac{z}{10}\right)\right]} \tag{9}$$

where the power law exponent, n, is given by

$$n = \frac{\left[0.37 - 0.088 In\, c_a\right]}{\left[1 - 0.088 In\left(\frac{z_a}{10}\right)\right]} \tag{10}$$

Table 1 presents the Weibull parameters for the hubheights under consideration.

TABLE 1: *Weibull Parameters for Crown Point Site*

Hubheight/m	k	c/ms^{-1}
34	2.48	8.00
30	2.54	8.37
37	2.59	8.73

3. WECS Performance Characteristics

In the absence of an actual power curve from the wind turbine manufacturer, it is necessary to approximate the performance characteristic of a WECS by one of several mathematical models. A typical performance characteristic is shown in **Figure 2**.

The WECS produces no net useful output until the wind speed has reached a critical "cut-in speed", u_c. As the wind speed increases, output also increases until at the "rated speed" u_r the WECS is producing its maximum design output. At speeds greater than u_r, the output is controlled to be constant until a limiting "furling speed" u_r is reached, at which output ceases for reasons of mechanical or electrical safety.

Bossanyi et al [3] suggested that three models will cover most types of WECS characteristics (**Figure 3**). The difference between the models lies in the manner in which the output power in the wind speed range ($u_c < u < u_r$) is expressed.

Type 1: "Idealised" wind turbine with no losses in transmission or generation.

Type 2: A wind generator, made more realistic by allowing for transmisison and generation losses, which are assumed to vary with power output.

Type 3: Fixed-geometry, constant-speed machine whose aerodynamic efficiency must vary continuously with wind speed.

Diesendorf and Fulford [9] used the following two performance models:

Type 4: A cubic response model, somewhat similar to Type 2 above (except that furling speed u_r is considered). Power output varies with u^3 between u_c and u_r, i.e., a fixed C_p over this range.

Type 5: A linear response model with power output rising linearly with u between u_c and u_r.

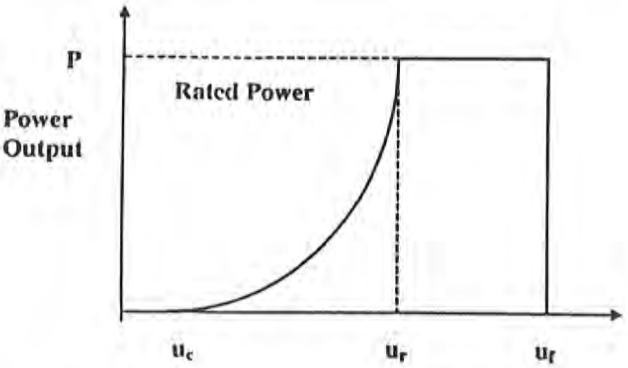
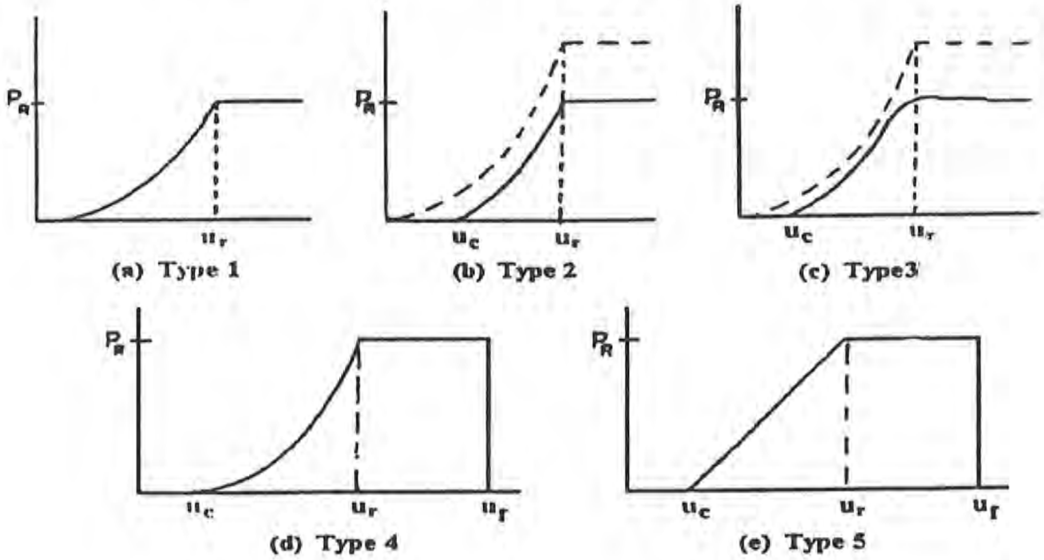


FIGURE 2: *General WECS Performance Characteristics*



(a) Type 1 (b) Type 2 (c) Type3

(d) Type 4 (e) Type 5

FIGURE 3: *WECS Performance Characteristic Models*

A closed form expression for energy production can be obtained if $P_e(u)$ is assumed to vary as u^k between u_c and u_r. This model is described by the following equations:

$$
\begin{aligned}
P_e &= 0 && u < u_c \\
P_e &= a + bu^k && u_c \leq u \leq u_r \\
P_e &= P_{eR} && u_r < u < u_r \\
P_e &= 0 && u > u_r
\end{aligned}
\tag{12}
$$

where k = Weibull shape factor.

$$a = \frac{P_{eR} u_c^{\,k}}{u_c^{\,k} - u_r^{\,k}} \tag{13}$$

$$b = \frac{P_{eR}}{u_c^{\,k} - u_c^{\,k}} \tag{14}$$

This model is more suitable for describing the performance characteristic of the WECS in that:

(a) It is the most accurate model after the Type 4 model that requires data from the manufacturer.

(b) The closed form expression conveniently allows for the capacity factor to be derived [10].

(c) Numerical integration is required if the other models are used.

This model is suitable to simulate the power curve of a pitch-controlled wind turbine and will be used in this paper.

4. Optimal Selection of a WECS

There are many factors which must be considered in order to determine the optimal method of WECS selection. The design of the WECS should be made specifically to match the wind pattern.

4.1 The Wind Electric System

A basic block diagram of a typical wind electric system is shown in **Figure 4**.

The power in the wind, P_w, passing through an area, A, perpendicular to the wind is:

$$P_w = \frac{1}{2} \rho A u^3 \ W \tag{15}$$

where ρ = air density (kg/m^3)

The fraction of power extracted from the power in the wind by a wind turbine is given by the coefficient of performance, C_p. An actual wind turbine cannot extract more than 59.3% (Betz coefficient) of the power in an undisturbed tube of air. In practice, the fraction of power extracted will always be less because of mechanical imperfections. An average value for C_p lies in the range .35 - .40.

FIGURE 4: *Wind Electric System*

Actual mechanical power output

$$P_m = C_p(\frac{1}{2}\rho \mathrm{A} u^3) = C_p P_w \tag{16}$$

C_p varies with the:

(a) Tip speed ratio, $\lambda = \frac{r_m \; \omega_m}{u}$ (17)

where r_m = maximum radius of the rotating turbine (m).

ω_m = mechanical angular velocity of the turbine (rad/sec).

(b) Turbine blade parameters such as angle of attack and pitch angle.

Transmission output power $P_t = \eta_m \; P_m$ (18)

Generator output power

$$P_e = \eta_g \; P_t = C_p \; \eta_m \; \eta_g \; P_w \tag{19}$$

Where η_m = transmission efficiency.

η_g = generator efficiency.

At rated wind speed, the rated electrical power output

$$P_{er} = C_{pr} \; \eta_{mr} \; \eta_{gr} \; \frac{\rho}{2} A \, u_r^3 \tag{20}$$

where C_{pr} = coefficient of performance at rated wind speed u_r.

η_{mr} = transmission efficiency at rated power.

η_{gr} = generator efficiency at rated power.

The efficiency of the turbine at rated power is

$$\eta_o = C_{pr} \; \eta_{mr} \; \eta_{gr} \tag{21}$$

This efficiency is valid only at the rated wind speed. The efficiency at lower wind speeds is also essential to determine the overall energy production of the turbine. Thus, the individual efficiencies (of the transmission and generator) must be determined across the output range. These efficiencies also help determine what type of transmission and generator to select for the WECS.

4.2 Transmission Selection

Transmission losses are due primarily to viscous friction of the gears and bearings turning in oil. The transmission loss is a fixed percentage of the low-speed shaft rated power. A reasonable value is 2% of rated power per gear stage although it depends also on the quality of transmission and lubricant viscosity.

The transmission efficiency,

$$\eta_m = \frac{P_t}{P_m} = \frac{P_m - (.002)q \; P_{mr}}{P_m} \tag{22}$$

where P_{mr} = rated turbine shaft power and q = the number of gear stages.

Eqn. (22) is plotted in **Figure 5**.

It can be seen that η_m is poor for low power inputs. Thus, it is desirable to choose ratings such that the transmission is operating above the knee of the curve.

4.3 Generator Selection

The mean wind speed for this site indicates that it is not a windy location and, thus, only small-sized wind turbines are suitable for generation purposes. Small-sized turbines range from .25 - 20 kW.

Generator losses can be divided into fixed and variable. Fixed losses are:

(a) Hysteresis and eddy currents: functions of the operating voltage and frequency.

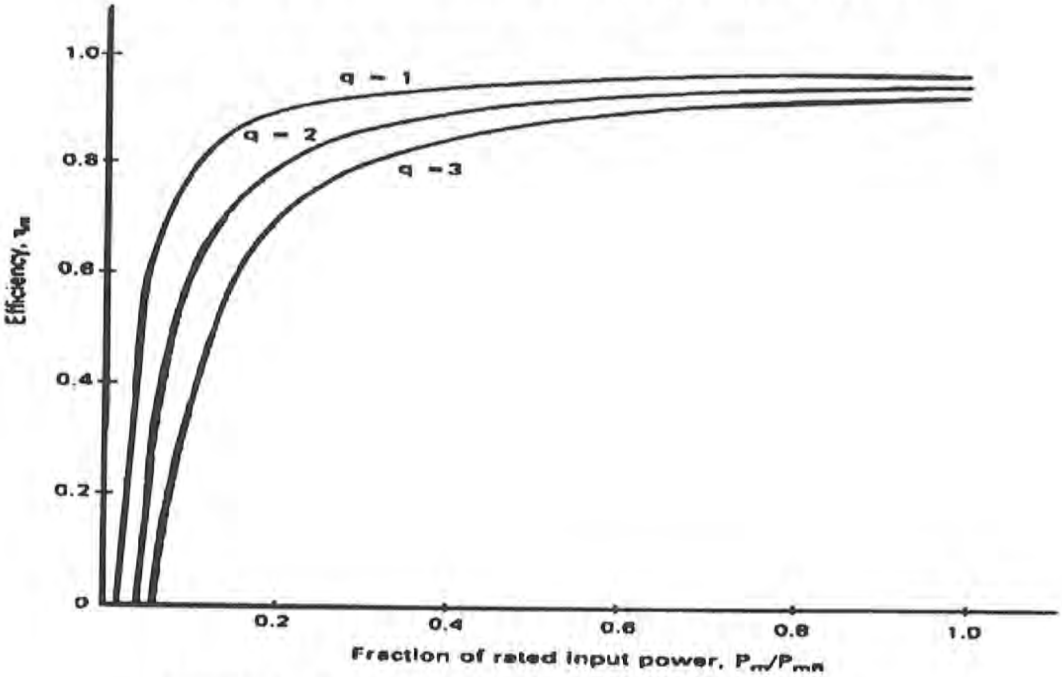


FIGURE 5: *Transmission Efficiency for 1, 2 and 3 Stages (2% Loss/Stage)*

(b) Windage and bearing friction: vary with rotational speed but can be considered fixed for fixed speed turbines.

Copper losses are variable and vary approximately as the square of the load or output current. Fixed and variable losses are found to be approximately equal when the generator is delivering rated power. Large generators are inherently more efficient than smaller generators. Some losses are proportional to the surface area of the rotor, while the rated electrical power is related to the volume. The ratio of volume to area increases with physical size. Good quality generators may have typically full load efficiencies of 0.85 for a 2 kW rating, 0.90 for a 20 kW, 0.93 for a 200 kW and 0.96 for a 2 MW rating. Thus, the differences between very small and large generators are significant.

Generator efficiency can be expressed by the empirical equation in terms of the input shaft power to the generator by [11]:

$$\eta_g = \frac{X - (0.5)Y(1-Y)(X^2+1)}{X} \qquad (23)$$

$$\text{where } X = \frac{P_t}{P_{tr}} \text{ and } Y = 0.05\left(\frac{10^6}{P_{er}}\right)^{0.215} \qquad (24)$$

P_{tr} = rated mechanical power input of the generator.

= rated electrical power output.

Eqn. (17) is plotted in **Figure 6** for three small-sized generator sizes: 5 kW, 20kW and 1 MW.

The curves are similar to the transmission efficiency curves and ratings are chosen in a similar manner. From **Figure 6**, it can be noted that the full load efficiencies increase with generator size. However, the cost and weight also increases and, thus, the generator with the best $/kW should be selected. The electrical generator power output and the overall efficiency can be determined from the proposed WECS model. Design values of turbine-rated rotational speed and rated sizes of the transmission and generator can be varied and the process repeated. Optimum values can be determined that will maximise the energy production per unit invested. The selection of ratings is somewhat of an artform because commercial products are available only in discrete size increments. Factors that influence generator choice are safety, operational life of component, cost and weight and average system efficiency.

4.4 Rated Rotational Speed

A higher rotational speed means that a given value of λ will occur at a higher wind speed, and this results in an increase in shaft power. For a 25% increase in wind speed,

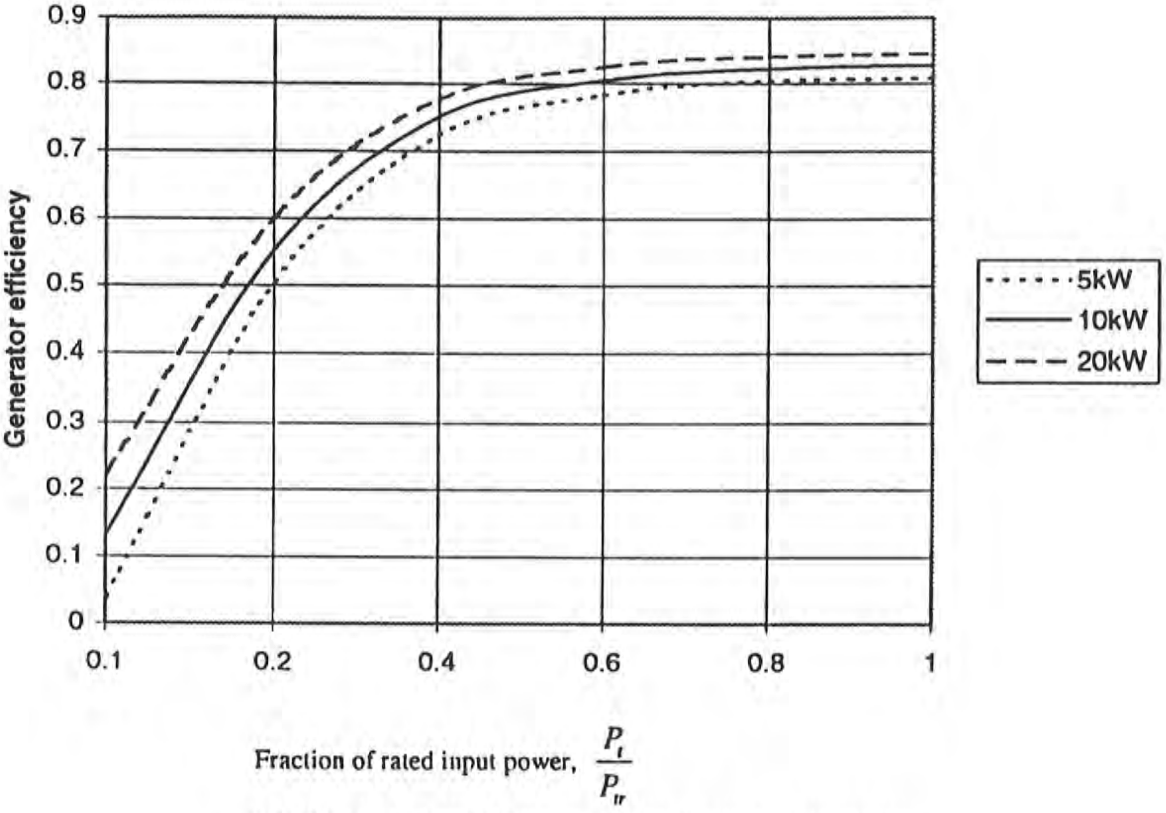


FIGURE 6: *Generator Efficiency for Three Small-sized Generators*

power in the wind increases by $(1.25)^3 = 1.95$. Thus, a 42 r.p.m. turbine operating at the 25% higher rotational speed 52.5 r.p.m. will deliver approximately twice the peak shaft power. The higher rotor speed is not necessarily a better choice as the extra power is available at the higher wind speeds and at lower wind speeds, the power output may be reduced. Consequently, the additional power output generated at higher wind speeds may be more than offset by reduced output at lower wind speeds. Thus, the choice of rated rotational speed depends critically on the wind regime. A site with a mean speed of 9 m/s (high) may justify increasing the rotor speed of a turbine designed for a nominally lower mean wind speed. Thus, the Crown Point site will justify the available commercial WECS with a low-rated rotor speed.

4.5 Optimum Ratio of u_r, u_c, u_f to Weibull Parameters

The average power output of a turbine at a given site is a key parameter since it determines the total energy production and the total income. It is a much better indicator of the energy yield and, hence, the economics, than the rated power which can be highly misleading.

The average power output which is to be expected from a WECS is:

$$P_{e,ave} = \int_{o}^{\infty} P_e(u) f(u) du \tag{25}$$

where f(u) = PDF of hourly mean wind speed.

Substituting eqns. (12) and (1) into (25) yields:

$$P_{e,ave} = \int_{u_c}^{u_r} (a + bu^k)\, f(u) du + P_{er} \int_{u_r}^{u_f} f(u) du \tag{26}$$

$$= P_{er} \left[\frac{e^{-(\frac{u_c}{c})^k} - e^{-(\frac{u_r}{c})^k}}{(\frac{u_r}{c})^k - (\frac{u_c}{c})^k} - e^{-(\frac{u_f}{c})} \right] \tag{27}$$

Eqn. (27) shows that, for a given wind regime with known Weibull parameters, we can select u_r, u_c, and u_f to maximise the average power and, thus, the total energy production. However, the relationships amongst u_r, u_c, and u_f must be considered if realistic results are expected:

(a) The wind must contain enough wind power at u_c to overcome the system losses. A u_c of 0.5 u_r implies that the gearbox and generator losses at cut-in = $(0.5)^3 = 0.125\ P_r$. Alternatively, a u_c of 0.4 $u_r \Rightarrow 0.064\ P_r$. It will take a particularly efficient generator and transmission combination to have losses of less than 6.4% rated power while losses of 12.5% indicates a mediocre design. It can be concluded that, u_c will lie in the range $0.4u_r \leq u_c \leq 0.5u_r$ most of the time.

(b) A u_f of twice the rated wind speed implies that the turbine control system is able to maintain a constant power output over an 8:1 range of wind power input. This is quite an engineering challenge. The difficulty of building WECS's which can survive operation in wind speeds greater than perhaps 25 m/s means that u_f will not normally be above 2 u_r, unless u_r happens to be chosen unusually low for a special application.

Thus, we want to select u_r so that the average power will be as large as possible for a given turbine area. The capital investment in the turbine will be proportional to the turbine area. Thus, maximising the average power will minimise the cost per unit of energy produced.

4.6 Selecting the WECS Optimum Rated Wind Speed

From the discussion in Section 4.5, it is clear that selecting u_r is central to effective turbine design as it basically determines u_c and also imposes certain limitations on u_f. If the u_r is chosen too low, too much energy will be lost in the higher speed winds and vice versa. The average power output will reach a maximum at a specific value of rated wind speed and this can be done by evaluating eqn. (27) for various values of u_r and P_{er}. The quantity inside the brackets of eqn. (27) is called the capacity factor, CF or the plant factor.

Combining eqns. - (20), (21) and (27)

$$P_{e,ave} = P_{er}(CF) = \eta_o \frac{\rho}{2} A u_r^3 (CF) \tag{28}$$

The choice of rated wind speed will not depend on the rated overall efficiency, air density or the turbine area and can be normalised out. Likewise, eqn. (28) is normalised by dividing by c^3 to get the term $\left(\frac{u_r}{c}\right)^3$ which defines the normalised average power

$$P_N = \frac{P_{e,ave}}{\eta_o(\frac{\rho}{2})Ac^3} = (CF)(\frac{u_r}{c})^3 \tag{29}$$

Figure 7 shows plots of P_N for values of k within the practical design range $0.4 \leq u_r \leq 0.5$.

The plots show that:

(a) Maximum power is reached at different values of $\frac{u_r}{c}$ for different values of k.

(b) For $u_c = 0.5u_r$, maximum power point varied from $\frac{u_r}{c} = 1.5$ to 2.5 as k decreases from 2.6 to 1.4. For $u_c = 0.4\ u_r$, maximum power point varies from $\frac{u_r}{c} = 1.6$ to 3.0.

(c) Curves are gently rounded near their maximum values, so small errors in selecting a u_r are not critical. A manufacturer can cover most of the potential market by having only two rated speeds for a given size of turbine.

(d) Regimes with lower k are superior to those with larger k. If two regimes have the same $\bar{u}$, the regime with the lower k will have the larger energy production.

Thus, optimum rated wind speed for optimum design for energy production can be found by finding c and k from the meteorological data acquired from the potential wind regime. The idea is to select $\frac{u_r}{c}$ to maximise the average power.

4.7 Capacity Factor Implications

The capacity factor, CF is important in selecting a WECS. Yearly energy production of a turbine is W = $P_{e,ave}$ (time) = (CF) P_{er} (8760) kWh. Rated power P_{er} will increase with u_r of a given turbine and this causes a decrease in CF. This has economic implications as a smaller u_r may be selected than that which produces maximum energy. Maximum energy production per unit invested is required and this may not coincide with the u_r which strictly maximises total energy output. Increasing P_{er} increases the costs of generator, transformer, switches, circuit breakers and distribution lines. In addition, the decrease in CF means that:

(a) Equipment are being used proportionately less of the time.

(b) If the WECS is grid connected, power will be supplied to the grid in an intermittent fashion. This forces conventional generating plants to cycle more, causing them to operate at lower efficiencies than at more constant power levels.

The economic optimum, when the entire grid is considered, may be at an even lower rated wind speed and high CF. This is particularly true for smaller grid systems where the impact on conventional plant will be more significant. A lower average output, but one which is more reliably available, may well be preferable in these circumstances. A pragmatic design procedure will be to use the $\frac{u_r}{c}$ ratio at which the normalised power is about 90% of the peak normalised power for a given site. This will yield a total energy production close to the maximum at a much better CF. Thus, a tradeoff exists where a decrease in CF must be balanced against an increase in total energy production to obtain the desired economic optimum.

5. Application of Techniques

The local power company acquired the 10 kW BWC Excel WECS with the intention of installing and modifying, if possible, the system at the best of the four wind potential sites in Tobago. The main specifications for the 10 kW WECS are seen in **Table 2**.

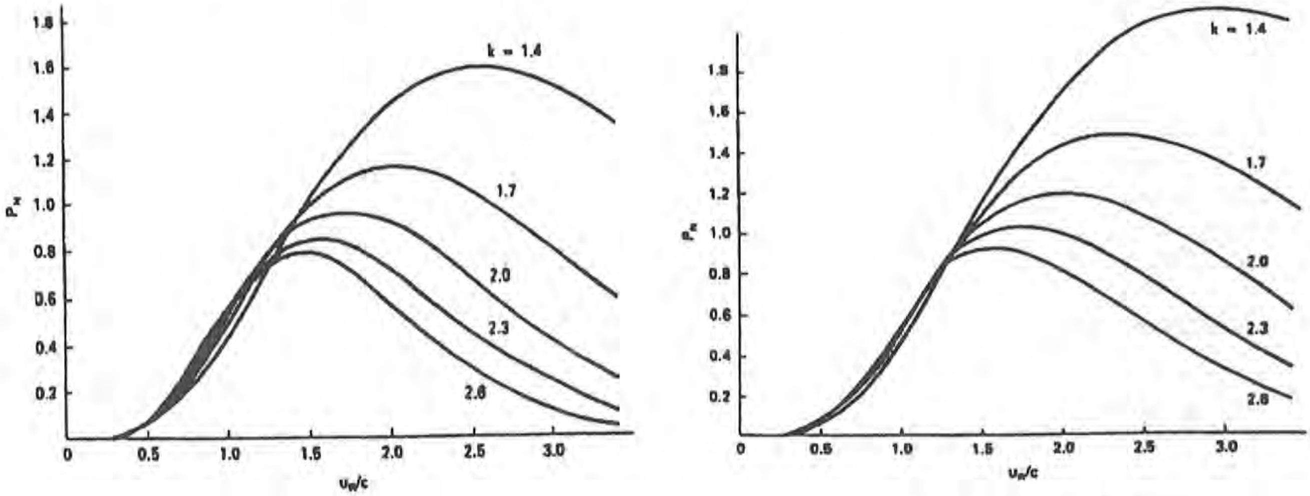
TABLE 2: *BWC EXCEL 10 kW WECS Specifications*

Cut-in wind speed, u_c	3.5 m/s
Rated wind speed, u_r	12.4 m/s
Furling wind speed, u_f	15.7 m/s
Rated power, P_w	10 kW
Rotor speed	0 - 350 r.p.m.
Generator	Permanent magnet alternator

However, for illustration purposes, the techniques developed in this paper will be used to illustrate the matching of a commercial WECS to the Crown Point site. **Table 3** presents the results for the unmodified 10 kW WECS.

For the modified WECS, the $\frac{u_r}{c}$ ratios for maximum energy recovery are extracted from **Figure 8** whereby the conservative estimates $u_c = .5u_r$ and $u_f = u_r$ are used.

Using these $\frac{u_r}{c}$ ratios, **Table 4** presents the results for the modified WECS.



(a) $u_c = 0.5u_r$, $u_f = 2u_r$

(b) $u_c = 0.4u_r$, $u_f = 2u_r$

FIGURE 7: *Normalised Power vs. Normalised Rated Speed*

TABLE 3: *Unmodified WECS Results*

Hubheight /m	CF	$P_{e,ave}$/W	Yearly Energy Production/ k Wh
24	.221	2.21	19360
30	.250	2.50	21900
37	.280	2.80	24528

Comparing **Tables 3** and **4**, an appreciable increase in total energy production occurs when the WECS hubheight is increased from 24m to 37m. This is desirable as the marginal cost of increasing the BWC guyed-lattice tower height is small and the additional performance gained is more than sufficient to justify the higher first cost. Thus, the best hubheight for the WECS is 37 m. Optimising the WECS at the 37 m hubheight for this site has increased the total energy production and the rated power by approximately 15% and 36% respectively. The substantial increase in total energy production is desirable but it must be achieved in a cost-effective manner whereby the basic BWC Excel structure must be adequate to accommodate the larger power-rating without structural changes. However, if the structure must be changed, the additional cost could easily exceed the additional benefit. The CF for the standard WECS is higher than that for the optimised system which means that the latter will be operating in a more intermittent fashion. Thus, trade-offs are inevitable and, a much better CF that will yield total energy production close to the maximum can be obtained if the pragmatic design procedure of using the $\left(\frac{u_r}{c}\right)$ ratio at 90% peak normalised power for the Crown Point site is applied. This can be extracted from **Figure 8** and the subsequent results are yielded:

Comparing **Tables 4** and **5**, when the pragmatic design procedure has been used, it has:

(a) Appreciably increased the CF by approximately 62%.

(b) Only reduced the total energy production by approximately 2.2% and it is still substantially greater than the unmodified case.

(c) Lowered the optimum rated wind speed, u_r for the WECS.

(d) Reduced the rated power, P_{er} and the average power output, $P_{e,ave}$ of the WECS by approximately 40% and 8% respectively.

TABLE 4: *Modified WECS Results*

Hubheight/m	$\frac{u_r}{c}$	CF	P_{er}/W	$P_{e,ave}$/W	Yearly Energy Production/k Wh
24	1.52	.241	11.03	2.66	23286
30	1.50	.240	12.31	2.95	25881
37	1.49	.235	13.64	3.21	28079

TABLE 5: *Pragmatic Design Results*

$\frac{u_r}{c}$	1.26
CF	.380
P_{er}/kW	8.25
$P_{e,ave}$/kW	3.14
Yearly Energy Production/k Wh	27464

Thus, applying this procedure has created a scenario whereby no major changes in the structure are required and only a small investment in the electrical system is necessary for the desirable situation of a good CF and total energy production.

6. Conclusions

The paper presents the factors involved in selecting and optimising/modifying a WECS for a specific wind regime. The steps in the WECS optimal selection are:

(a) Determine the regime Weibull parameters from collected meteorological data.

(b) Select a commercial WECS for the wind regime based on transmission, generator and rated rotational speed selection factors.

(c) Optimise/modify the WECS for the wind regime by:

    (i) Identification of the optimum u_r.

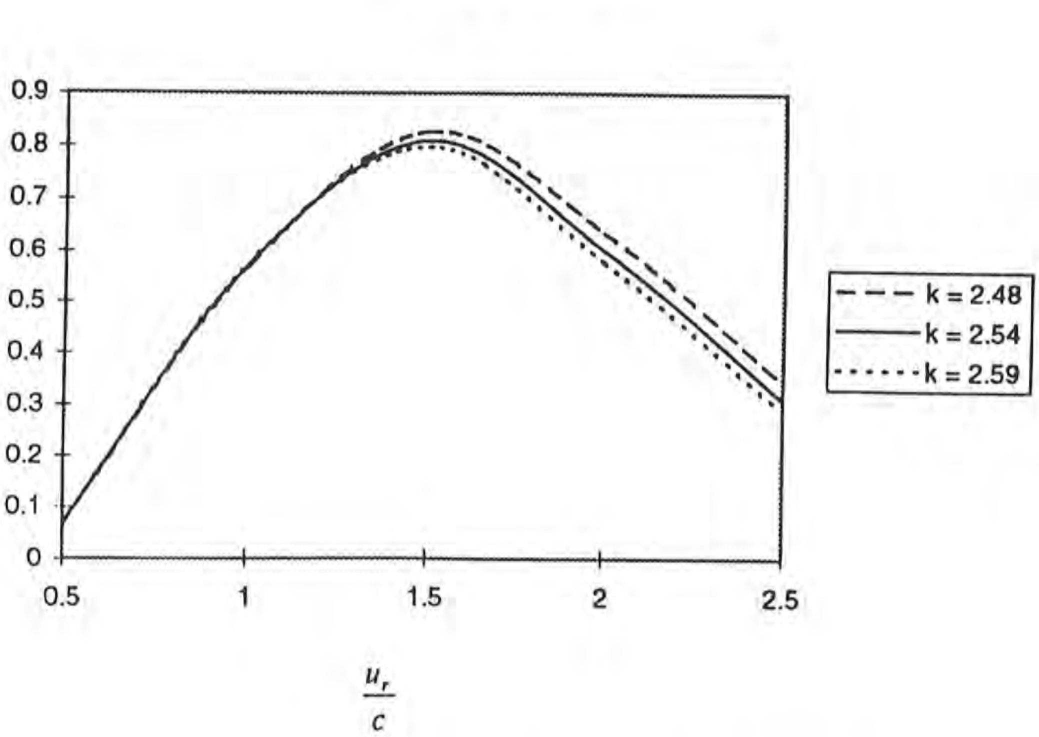


FIGURE 8: *Normalised Power vs. Normalised Rated Speed for Crown Point*

- (ii) Calculation of the capacity factor for the optimised/modified WECS.
- (iii) Calculation of the rated power, P_{er}, average power output $P_{e\,ave}$ and the yearly energy production.

(d) Perform the same computations as in (c) for the commercial/unmodified WECS.

(e) Compare the optimised/modified WECS results with the unmodified WECS results.

(f) Determine whether the optimised/modified WECS selection for the wind regime is better than the unmodified WECS from an economic and capacity factor perspective.

It is evident that rated power is not a satisfactory parameter for distinguishing between commercial WECS. Several pieces of information are needed to specify a WECS properly, including average power and CF in a variety of wind regimes. For illustration purposes, this methodology was used to optimise and match the available commercial BWC Excel 10 kW WECS to the Crown Point site. It was concluded that the WECS can be economically modified at the pragmatic design level of 90% of the peak normalised power for the site. Furthermore, this methodology will be used to select the most suitable commercial WECS for the best wind potential site in Tobago when the relevant amount of meteorological data is collected.

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