A FRAMEWORK TO ASSESS THE ECONOMICS OF WIND POWER GENERATION USING HORIZONTAL AXIS WIND TURBINES

by

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Abstract

The paper describes an analytical approach to evaluate the economics of wind power generation. In this context, the model developed is presented.

The model enables the evaluation of the wind potential and economic assessment of wind power at a particular site. The performance characteristics of different wind energy generation systems (WEGS) on the site can be evaluated. Economics of the grid connected wind farm with different WEGS can be assessed in comparison to the cost of generation of an additional unit of energy (Long Range Marginal Cost - LRMC).

A case study for a site in Boondala using the data from Hambantota is also presented. The results can serve as the basis for further studies in determining the economic feasibility of wind electricity generation in this region.

1.0 Introduction

Increasing dependence of mankind on the availability of electricity, the recognition of the finiteness inherent in non- renewable sources of energy and the environmental impact of utilization of such sources has focussed the attention of energy planners on renewable sources, as an alternative source of energy. This has paved the way for development in the usage of energy. This has paved the way for development in the usage of wind power for electricity generation.

Sri Lanka, being a country where there is much potential for alternative sources of energy such as wind, solar etc., has been engaged in this area of research for the past decade. The Energy Unit of the Ceylon Electricity Board, having launched a study on wind resource in Sri Lanka was keen on developing a framework to determine the economic feasibility of wind power generation systems. As a result a case study for a grid connected windfarm to be sited in Boondala was started as an undergraduate project.

Wind, in effect a form of solar energy, is the flow of air due to the differential heating of oceans and land mass. Approximately 2% of the sunlight falling on earth is converted to the kinetic energy of wind. This is very much more than the total energy consumption of the entire globe. Wind machines, wind mills and wind turbines are essentially, devices that convert extracted kinetic energy contained in the wind, to a usable form of energy. Water pumping and generation of electricity are two major areas in which wind machines are utilised.

1.1 Generation of Electricity using Wind Turbines

A wind turbine needs to be coupled to a generator to produce electrical power. High speed turbines are generally used for this kind of application. Firstly, the high speed machines are lighter in weight and therefore are

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cheaper than the low speed ones. Secondly, the high speed of operation also results in simpler gear boxes and lower starting torques for the electrical generator.

Direct current generators, Alternators (synchronous generators) and Induction generators (asynchronous generators) are commonly used with wind turbines. The suitability of each type however, entirely depends on the application. Mechanical regulation is incorporated in all wind generators delivering power at constant frequency. This is usually in the form of adjustment in the pitch of the blade or applying of an aerodynamic or mechanical brake.

1.2 What the future holds for wind power generation

The use of electricity producing wind machines may expand rapidly with the rising prices of conventional sources of energy and the falling cost of wind machines. Despite the extensive research and pilot projects during the past decade, the MW class machine is yet to reach technical maturity. The development of low and medium power classes have shown rapid growth and will continue to do so with the concept of wind farms.

Wind energy by no means is a simple solution to all of the world's energy problems. There are many areas lacking sufficient wind potential and many energy needs for which wind power is inappropriate. However, in most countries, wind energy could play a valuable role in providing an economical source of power. They have already proven competitive in remote islands with small grids based on diesel generators.

The technology for harnessing the wind has come a long way. There are signs that most of the credibility problems that originally shadowed the technology, are being overcome.

1.3 Wind the alternative ?

The present generation system in Sri Lanka, operates predominantly with hydro plants being used to meet the base loads, and thermal plants being used for base as well as peak shaving during periods of low hydro. It is in this scenario that the study on the economic feasibility of wind powered generation systems is being carried out. Wind being a variable source of energy, would provide a continuously varying supply of energy. The degree of variation could be minimised by matching the wind turbines to the site characteristics, to operate at rated power of the turbine, most of the time.

As the search for viable options for electricity generation continues, the constraints on the future development of generating systems should also be borne in mind. Potential for hydro schemes is not unlimited, thermal options have their high fuel cost as an inherent deterent. It is also doubtful whether nuclear power could be economical for the national grid in the near future due to the comparatively small base load. Under such conditions the search for viable renewable energy systems for Sri Lanka is of prime importance, especially since we can benefit from the experience of many countries that have gone beyond the experimental stage and are successfully operating such systems to meet their energy needs. Additionally, wind energy generating systems stand out far ahead of conventional energy generating plants when environmental considerations are taken into account.

In the present study, only horizontal axis wind turbines have been considered for the analysis.

2.0 The Theoretical Basis

2.1 Available wind power

In a wind Energy Generation System, it is necessary to quantify the energy extractable from a given site. It can be shown that the effective power output of a wind turbine is given by equation (2.1) [vide : Appendix A1].

$$P = \tfrac{1}{2}\, \eta\, C_p\, r\, v^3 A \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

where

η = efficiency of the electrical system
Cp = power coefficient (= 16/27)
ρ = air density (kg/m^3)
v = undisturbed wind velocity (m/s)
A = swept area of rotor blades (m^2)

2.2 Factors effecting Wind Speed

Some of the factors that need to be considered in the analysis of a wind regime are, Windshear which is the slowing down of wind near the ground due to the surface roughness of the ground, Turbulence which is the variation of wind flow behind buildings, trees, ridges etc. and the Acceleration or retardation on top of hills, ridges etc.

Out of these factors, the effect of the windshear cannot be neglected in a study carried out to investigate the wind characteristic of a wind regime.

The rate of increase of wind speed with height strongly depends on the terrain and the changes in its roughness. The effect of the terrain on the wind speed is generally represented by an equivalent height Zo which is called the "roughness height".

Table 1 shows the roughness heights for different terrains, used in this model [1].

The logarithmic profile of the wind shear[1] was selected to be the matching profile. This is given by the standard equation (2.2).

$$\frac{v(z)}{v(z_r)} = \frac{\ln (z/z_o)}{\ln (z_r/z_o)} \quad \text{.............} \quad (2.2)$$

This relates the wind velocity v(z) at a height z to wind velocity $v(z_r)$ at a reference height z_r.

Comparison of wind velocities at two different locations is usually based on the assumption that the wind speed at the 60m height is unaffected by the roughness. This assumption leads to the equation (2.3).

$$\frac{v(z)}{v(z_r)} = \frac{\ln(60/z_{or})\ \ln(z/z_o)}{\ln(60/z_o)\ \ \ln(z_r/z_{or})} \quad \text{........} \quad (2.3)$$

where

z_{or} = roughness height at reference location with wind speed measured at height z_r.

Table 1 -
Classification of Terrains and their Roughness Heights

TYPE	DESCRIPTION	ROUGHNESS HEIGHT Zo
Flat	Beach, ice, snow, landscape, ocean	0.005 m
Open	Low grass, air ports, empty crop land, high grass, low crop	0.03 m
Rough	Tall row crops, low woods	0.25 m
Very rough	Forests, orchards	0.50 m
Closed	Villages, suburbs	1.0 m
Towns	Town centres, open spaces in forests	> 2.0 m

2.3 Mathematical Model of Wind Regime

The mathematical model of a wind regime uniquely characterises the regime and enables the interpretation of details such as available amount of wind power, time fraction that a wind mill could produce more than a given power and total extractable energy during a given period of time. Such information is best provided by a frequency distribution curve of the wind speeds based on hourly wind data of a site.

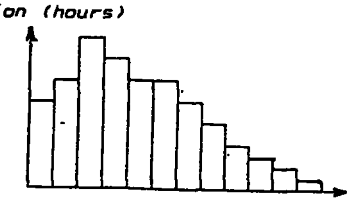

Figure 1
Typical frequency distribution of wind speed

Analyses carried out for various wind regimes have shown [1] frequency distributions of similar shape (Figure 1). The "Weibull Statistical Model [1]" was selected, and assumed to have a good match to the frequency distribution curve of wind speeds and is thus used to characterize wind patterns.

It can be shown that for practical values of k, the Weibull distribution can be approximately expressed by equation (2.4) [vide: Appendix A2].

$$v = c(0.568 + 0.434/k) \qquad (2.4)$$

where

c = scale parameter (m/s) and
k = shape parameter of the Weibull Model

3.0 Prospective site at Boondala

The feasibility of a wind energy conversion system as an alternative source of energy supply to the grid, will basically depend on

- Selection of site and
- Matching of wind turbine to the site selected.

A prospective site at Boondala in the Hambantota region was selected for testing the model developed based on the following factors.

(a) Available wind data proved this area to be windy.
(b) Hourly wind data required for the evaluation was available for a reasonable period of time, in the Hambantota region. (hourly data during the day from 6.00 a.m. to 6.00 p.m., and three hourly data during the night 6.00 p.m. to 6.00 a.m.)
(c) Boondala was used as a test case though in a wildlife reserve.
(d) The possibility of connection to grid within closed proximity.

Established studies have shown that the best match is obtained when the ratio of the rated wind speed of the turbine to the mean wind speed of the wind regime falls between 1.41 and 2. A number of commercially available kW class wind turbines were chosen as candidate machines for the analysis. Although actual machines available on the market were considered for the study, their trade names have been withheld since the authors do not wish to pass an overall judgement on their performance, based only on a study of economics.

Due to the lack of experience in projects related to Wind Energy Conversion systems in Sri Lanka, the costs involved in building the infrastructure, construction of the system, operation and maintenance were based on a similar project implemented in India[2]. The costs involved in the transmission system such as the cost of sub stations and transmission lines, were taken to be those available with the Ceylon Electricity Board at the time this study was done.

Comparison of candidate turbines is based on their individual performance, as well as the performance of a cluster in a wind farm. The number of wind machines in a farm was determined on the concept of break even operation; marginal point at which the cost of a unit of electricity generated at the wind farm drops down to the Long Range Marginal Cost (LRMC - inclusive of capacity and energy cost) of producing an additional unit of energy, for the present system.

Data processing and analysis of each candidate turbine with respect to the regime was handled by a software package developed by the authors. The first three stages being developed on TURBO PASCAL Version 4.0 and stage four in LOTUS spread sheet format. [vide : Appendix A3]

The program gives the user, rankings based on different performance characteristics. The user is at liberty to choose which ever turbine that may be suited to his needs, depending on the weightage he places on each of these performance characteristics given by the analysis.

4.0 Results

For the case study at the Boondala site, a summary of the extracted results from the analysis, forming the basis of the conclusions drawn, are given in the Tables 2 and 3.

5.0 Conclusion

The results of the analysis for the Boondala site, indicates that the model WEGS11 gives an overall superior performance as satisfied by all the criteria considered. A windfarm with this type of machine shows that four turbines is sufficient for break even operation. This proves the practical possibility of implementing such a wind farm.

The break even windfarm, has also shown to be economically feasible, giving an Internal Rate of Return of 13.63% . The Economical Internal Rate of Return (EIRR) has been selected, because many leading funding organisations require candidate projects to prove feasibility in this aspect.

Two sensitivity analysis carried out for a windfarm consisting of twenty WEGS11 turbines, Table 4 and Figure 2, indicates, that the EIRR is hypersensitive to the following parameters in the order given.

(a) Cost of turbine
(b) Exchange rate
(c) Energy generated from farm
(d) Value of additional unit of energy

It can be expected that with the falling turbine prices on the international market, and the increasing value of additional energy generated (due to the rise in fuel prices), the case for wind as an alternative source of energy would become stronger.

The purpose of this study was to build up an analytical framework to evaluate the economics of wind power generation. The authors have used wind data that was available at the Meteorological Station at Hambantota to test the model developed. It shows that economic indicators of wind power generation in a particular site with different Wind Energy Generating Systems can be obtained using this model along with their economic performance in a windfarm.

TABLE 2 - COMPARISON OF THE PERFORMANCE OF THE CANDIDATE TURBINES IN THE SITE AT BOONDALA

WIND MACHINE	WECS 1	WECS 2	WECS 3	WECS 4	WECS 5	WECS 6	WECS 7	WECS 8	WECS 9	WECS 10	WECS 11
TURBINE DETAILS											
Cutin wind speed (m/S)	4	3.7	4	6	3.5	3.5	3.5	3.5	3.5	3.5	3
Rated wind speed (m/S)	14	13	12.8	14	15	15	15	15	15	15	13
Rated power (kW)	75	60	300	300	66	66	66	95	95	95	300
Rotor Diameter (m)	16	16	30	26.5	15.5	15.5	15.5	17	17	17	30.8
Hub height (m)	24	20	30	35	18	22	24	18	22	24	30.8
Cost of turbine (US$)	70000	70500	375000	425000	48600	50900	51900	57800	60300	61800	309100
PERFORMANCE AT A SITE IN BOONDALA											
Energy Extractable per turbine (kWh/yr)	114358.00	103420.25	585725.39	489256.78	78632.08	83344.90	85553.80	113182.54	119968.15	123145.61	571718.52
Energy Cost (Rs/kWh)	11.45	12.68	5.36	7.03	15.03	14.43	14.04	10.97	10.47	10.27	4.81
Hours in operation (hrs/yr)	6300.36	6528.65	6386.36	4598.11	6699.00	6763.91	6785.48	6699.00	6763.91	6785.48	7312.56
Hours in operation(% of total hrs)	71.9%	74.5%	72.9%	52.5%	76.5%	77.2%	77.5%	76.5%	77.2%	77.5%	83.5%
Hour in operation at rated power(hrs/yr)	425.91	433.05	674.63	532.64	193.78	233.99	240.09	193.78	223.99	240.09	674.63
Hours in operation at rated power											
as a % of total hours	4.9%	4.9%	7.7%	6.1%	2.2%	2.7%	2.7%	2.2%	2.6%	2.7%	7.7%
as % of hours in operation	6.8%	6.6%	10.6%	11.6%	2.9%	3.5%	3.5%	2.9%	3.3%	3.5%	9.2%
Plant Factor	17.4%	19.7%	22.3%	18.6%	13.6%	14.4%	14.6%	13.6%	14.4%	14.8%	21.8%
Energy Ext. during peak load hrs(kWh/yr)	8260.00	7732.00	46735.00	37650.00	5328.00	5730.00	5910.00	7669.00	8247.00	8508.00	44611.00
PERFORMANCE OF BREAK EVEN WIND FARM											
Farm Size (number of turbines)	50	50	50	50	50	50	50	13	12	11	4
Capacity of Substation for farm (KVA)	5040	3780	18900	18900	4410	4410	4410	1890	1890	1890	1890
Energy Cost for farm (Rs/kWh)	3.9	4.31	3.95	5.33	4.04	3.97	3.94	3.78	3.75	3.8	3.69
Economic Internal Rate of Return (EIRR)	11.86%	11.54%	12.20%	8.65%	11.62%	11.83%	11.79%	12.58%	12.53%	12.46%	13.63%

Table 3 - Summary of the results of STAGE1

HUB HEIGHT (in m)	WEIBULL PARAMETERS		MEAN WIND SPEED (m/s)
	SHAPE FACTOR C (m/s)	SCALE FACTOR k	
18	1.64	8.05	6.69
20	1.64	8.16	6.84
22	1.64	8.24	6.86
24	1.64	8.32	6.94
30	1.64	8.58	7.15
35	1.65	8.77	7.29

However, technical details such as the possibility of integrating a Wind Energy Generation System to the existing network, generation expansion, capacity displacement etc. have not been studied. Hence there is the necessity of further work, taking into consideration the above technical factors. In this effect this model developed by the authors provides an adequate analysis of economics, and a basis for further inquiry into the feasibility of wind power generation.

6.0 References

[1] Lysen, E.H., "Introduction to wind energy" Steering Committee Wind Energy Developing countries (SWD), Netherlands, May 1983.

[2] Jagadeesh A., "Integration of Wind power into the public power system in India", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 27 (1988), Netherlands.

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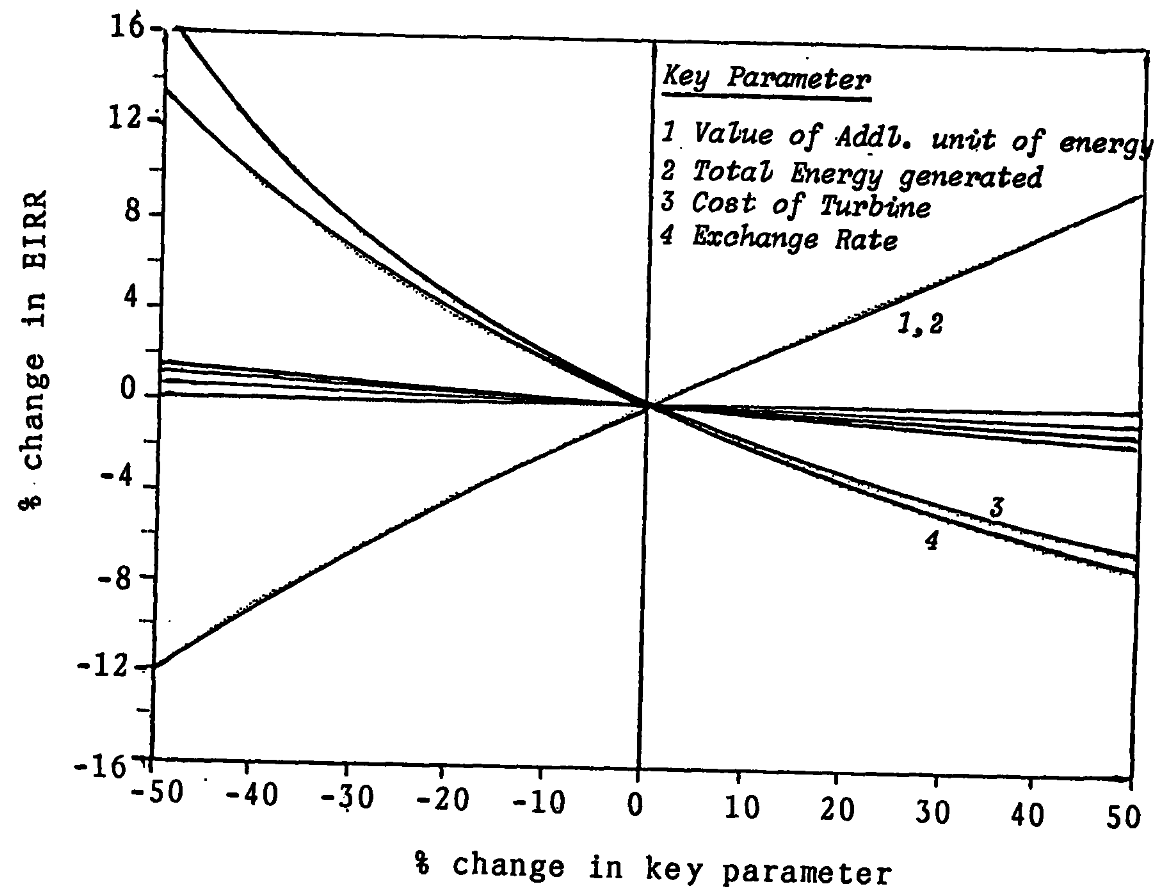

Figure 2 - Variation of EIRR with Key Parameter

TABLE 4 - SENSITIVITY ANALYSIS FOR A WIND FARM OF 20 TURBINES
THE EIRR FOR PERCENTAGE VARIATIONS OF KEY PARAMETERS

* WEGS 11

Key Parameter	Present Value	Present EIRR	Persentage Change in Key Parameter									
			-50%	-40%	-30%	-20%	-10%	+10%	+20%	+30%	+40%	+50%
Cost of Turbines (US$)	6182000	14.37%	27.75%	23.90%	20.82%	18.30%	16.18%	12.79%	11.39%	10.14%	9.01%	7.99%
Exchange Rate (Rs/US$)	33.00	14.37%	-	-	-	-	-	12.58%	11.03%	9.66%	-	-
Installation cost excluding infrastructure cost (as % of capital cost)	15%	14.37%	-	-	-	-	-	14.14%	13.92%	13.70%	13.49%	13.28%
Infrastructure Cost (Rs)	375000.00	14.37%	-	-	-	-	-	14.37%	14.36%	14.36%	-	-
Freight and Insuarance (US$)	42500.00	14.37%	-	-	-	-	-	14.14%	13.91%	13.69%	-	-
O & M Cost (Rs) as a % of Capital Cost	3.0%	14.37%	-	-	-	-	-	14.07%	13.77%	13.47%	13.17%	12.86%
Transmission Line Length (km)	20	14.37%	14.80%	14.72%	14.63%	14.54%	14.45%	14.28%	14.20%	14.11%	14.03%	13.95%
Value of Additional Unit of Energy (Rs)	3.80	14.37%	-	-	7.77%	10.09%	12.27%	16.40%	18.37%	20.31%	22.22%	24.11%
Interest Rate	8.7%	14.37%	-	-	-	-	-	14.37%	14.37%	14.37%	14.37%	14.37%
Total Energy Generated (kWh)	13561687	14.37%	-	-	-	-	12.27%	16.40%	18.37%	20.31%	-	-
Substation and Transmission Line Costs (Rs)	16229984	14.37%	-	-	-	-	-	14.23%	14.10%	-	-	-

Appendix A1 - Available wind power

For a Wind Energy Conversion System, it becomes necessary to quantify the energy extractable from a given site.

The flow of kinetic energy per second P_{kin} is given by equation (A1.1) [1].

$$P_{kin} = ½ (\rho Av)\, v^2 = ½ \rho Av^3 \qquad (A1.1)$$

where

ρ = air density (kg/m^3)
A = swept area of rotor blades (m^2)
v = undisturbed wind velocity (m/s)

As the rotor extracts energy by slowing down the wind, the wind speeds are lower behind the rotor. Since too much slowing down of the wind causes air to flow around the rotor rather than through it, maximum power extraction P_{max} is reached when the wind velocity in the wake of the rotor is one-third of the undisturbed wind velocity v [1], as given in equation (A1.2).

$$P_{max} = ½ \{A(2/3)v\}v^2 - ½ \{A(2/3)v\}\ \{(1/3)v\}^2 \qquad (A1.2)$$

which may be simplified as $P_{max} = (16/27)\ \{½ \rho Av^3)$

Wind rotors in practice extract a maximum of about 40% of this available power. This fraction of power extracted is called the power coefficient C_p. Subsequent conversion into electrical power gives rise to further reduction in effective power output P [1] given by equation (A1.3).

$$P = ½ \eta C_p \rho v^3 A \qquad (A1.3)$$

where

η = efficiency of the electrical system

Appendix A2 - The Weibull Distribution

The Weibull distribution is characterised by 2 parameters namely the shape parameters k (dimensionless) and scale parameter c (m/s).

The cumulative distribution F(v) of the above statistical model [1] indicating the time fraction or probability that the wind speed v is less than or equal to given wind speed v is given by equation (A2.1).

$$F(v) = P\{v < v\} = 1 - \exp\{1 - (v/c)^k\} \qquad (A2.1)$$

The probability density function f(v) is given by (A2.2).

$$f(v) = dF(v)/dv = (k/c)\,(v/c)^{k-1}\ \exp\{1-(v/c)^k\} \qquad (A2.2)$$

The average wind speed $\bar{v}$ can be obtained from the integral equation (A2.3).

$$\bar{v} = v\ f(v)\ dv \qquad (A2.3)$$

$$\bar{v} = v\,(k/c)\,(v/c)^{k-1}\,\exp\{1 - (v/c)^k\}\,dv$$

$$v = k(v/c)^k\,\exp\{1 - (v/c)^k\}\,dv$$

Simplication of the standard solution [1] in terms of the Gamma function Γ leads to equation (A2.4).

$$v = c\,\Gamma^k(1+1/k) \qquad \text{(A2.4)}$$

where Γ = gamma function

Thus the cumulative distribution F(v) and the probability density function f(v) may be expressed as in equations (A2.5) and (A2.6).

$$F(v) = 1 - \exp\{-\Gamma^k(1+1/k)\,(v/\bar{v})^k\} \qquad \text{(A2.5)}$$

$$f(v) = (k/v)\,(v/\bar{v})^k\,\Gamma^k(1+1/k)\,\exp\{-\Gamma^k(1+1/k)\,(v/\bar{v})^k\} \qquad \text{(A2.6)}$$

For practical values of k, the Gamma integral $\Gamma^k(1+1/k)$ may be approximated to the numerical expression G given in equation (A2.7).

$$G = 0.568 + (0.434/k) \qquad \text{(A2.7)}$$

The Weibull statistical parameters, scale factor c and shape factor k for a particular regime may be derived from the frequency distribution of a set of data for the regime under consideration.

From the hourly data extracted for the site and corrected for terrain and the height of the wind turbine, frequency and cumulative frequency for different classes of wind speeds should be calculated [Table A2.1].

The cumulative frequency distribution of the Weibull Statistical Model [1], may be rewritten as in equation (A2.8).

$$[1 - F(v)]^{-1} = \exp\{(v/c)^k\} \qquad \text{(A2.8)}$$

Taking the natural logarithm twice, gives equation (A2.9).

$$\ln[\ln\{1 - F(v)\}^{-1}] = k{*}\ln v - k{*}\ln c \qquad \text{(A2.9)}$$

Table A2.1
Frequencies and cumulative frequencies of wind speeds

CLASS	FREQUENCY	CUMULATIVE FREQUENCY
$0 - v_1$	$f(v_1)$	$F(v_1)$
$v_1 - v_2$	$f(v_2)$	$F(v_2)$
$v_2 - v_3$	$f(v_3)$	$F(v_3)$
.	.	.
.	.	.
.	.	.
$v_{n-1} - v_n$	$f(v_n)$	$F(v_n)$

A linear regression carried out for the actual data to match the linear equation given in expression (A2.9) will result in best fitting scale and the shape parameters of the weibull model characterizing the wind pattern of the site at the turbine height.

Appendix A3 - Details of Software

(1) STAGE 1 - Modifies raw hourly wind data for reference anemometer location to proposed site location and turbine hub heights. Processes modified data to obtain frequency distribution and Weibull parameters.

(2) STAGE 2 - Matches wind distribution at site with turbine operating characteristics. Calculates energy cost, energy output, hours in operation and plant factor for single turbine. Estimates energy cost, windfarm size and required power system capacities for break even windfarm.

(3) STAGE 3 - Performs a ranking of turbines based on Energy cost for single turbine, Energy extractable Total hours in operation, Hours in operation at rated power, Plant factor, Presents the variation of average power output during peak load hours.

(4) STAGE 4 - Performs an economic evaluation of the candidate break even windfarm.