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GENERATION OF ELECTRICITY BY WIND TURBINES AT MUNRO

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ABSTRACT A monitoring and feasibility study of wind power utilization at Munro College, Jamaica, has been performed using observed wind speeds and direction and the operational characteristics of a 225 kW wind turbine generator (Vestas 27-225), installed at the College. The analysis of the data collected over a period of approximately one year indicates that the estimated net annual energy from the turbine is 4.68×10^5 kWh and the average capacity factor is 35%. Based on the estimated net annual energy and the average capacity factor, wind power at Munro is technically feasible. However, it appears that the turbine average power output is approximately 7% lower than expected. This may be due to the terrain and roughness elements, and the turbulence intensity of wind at Munro. The fluctuation in power output is also a major draw back. The estimated costs of energy production show promise in competition with the present local costs of production at private power plants. The economic advantage of using wind turbines at Munro will depend largely on the initial investment scenario and the economics may become more favourable if larger turbines are used to capture wind energy at lower speeds. An inspection of the environmental feasibility of the wind turbine at Munro indicates that adverse environmental impacts would not appear to be issues of concern.

INTRODUCTION

Jamaica is not endowed with domestic reserves of fossil fuel, such as oil and gas, consequently the country is heavily dependent on the importation of these fuels. Approximately 89% of commercial electrical energy comes from petroleum and the remainder from bagasse, hydropower and coal as mentioned in the work of Wright[1]. For economical and environmental reasons, solar and wind energy are attractive alternatives or supplementary sources of energy. Chen et al. have mapped the average solar radiation available to Jamaica and the results indicate a bright prospect for solar photovoltaic applications in the future[2]. Wind energy on the other hand is already at the stage where its application can compete with fossil fuel plants, as stated in Flavin and Lenssen[3]. With this in mind, Chen et al. performed an analysis of wind power in Jamaica by updating the results of previous wind energy resource studies and incorporating other available data[4]. The results of this work showed the area between Munro and Spur Tree to be one of the sites with potential for the application of wind energy.

Munro is located in the parish of St. Elizabeth on one of the peaks of the Santa Cruz Mountain at an altitude of 762 m. Because of its relatively flat (actually undulating) terrain, it is a favourable site for capturing wind energy. It captures the sea-breeze that is funneled through the Essex Valley and very importantly, it also experiences relief winds both night and day because it is situated above a valley. Thus the site can be expected to produce electricity 24 hours per day, unlike a coastal site which is driven primarily by the daytime sea-breeze. In addition, the effect of the hills can result in a speeding up of the wind in cases where the atmosphere is unstable[5]. Measurements done by Chen et al.[6] have shown the atmosphere in the vicinity of Mandeville to be unstable and that in the vicinity of Munro can be expected to behave similarly.

The Munro College community has long recognized the abundance of wind at the school and in the early 90's the Board of Governors of Munro College set into motion a plan which resulted in the installation of a Vestas V27-225 wind turbine at the school in February 1996. It was hoped that this would be the first phase of an overall project which could lead to the establishment of a wind farm at Munro. The overall project was seen as a long-term financial plan for generating funds to supplement the Government's subvention to the College. The project was partially supported by the Environmental Foundation of Jamaica (EFJ).

EFJ invited the Physics Department, University of the West Indies (UWI), to carry out a project to monitor the wind and evaluate the performance of the wind turbine at Munro. This paper presents the results of the work done under that project.

Aims of the Project

The aims of the project were: to collect and analyze the wind data and estimate the output of the turbine operating at Munro based on the data; to compare the estimated turbine output with the actual output and to use these results to obtain estimated outputs for other types of turbines; and to assess the potential of the site as a wind farm.

EXPERIMENTAL

Turbine (Vestas V27-225 kW)

The V27-225 kW is a wind turbine generator manufactured by Vestas, Denmark. The rotor of diameter 27 m sweeps out an area of 573 m^2. The turbine is mounted 31.5m above the ground. It starts up when the wind speed at hub height (31.5 m) reaches 3.5 ms^{-1} and delivers a constant maximum power when the wind speed equals or exceeds 14.5 ms^{-1}. It shuts down at a wind speed of 25 ms^{-1} or greater for safety reasons. These wind speeds are known as the cut-in wind speed, the rated wind speed and the cut-out wind speed respectively. The maximum constant power is known as the rated power.

The instantaneous power in the wind is given by the following equation:

$$P = \tfrac{1}{2}\,\rho S v^3 \qquad \text{Eq. 1}$$

where ρ = density of air, S = swept out area of turbine and v = wind speed.

The power output of a turbine is usually quoted by the manufacturer for an atmosphere at standard temperature and pressure. Figure 1 shows the power curve supplied by Vestas and the power curve corrected for the average air density at Munro (1.063 kg m^{-3}), based on an observed average temperature of 24 °C and a pressure of 907 mb.

Instrumentation and Data Collection

The turbine is situated on undulating land to the south east of the College proper. The monitoring instruments used in this project were located about 30 m to the south of the turbine. The instruments were mounted on a 30 m mast manufactured by Western Windpower. The instruments included 2 Maximum #40 anemometer and wind vane sets, herein referred to as A and B, and one R. M. Young anemometer and wind vane set, referred to as C. Sets A, C, B were located at heights of 30, 20 and 10 m above ground respectively. The output power from the Vestas turbine was monitored by a PC5 Watt transducer manufactured by Ohio Semitronics, Inc. The outputs from sets A, B and the power transducer were recorded and processed on a Second Wind NOMAD data logger. The NOMAD data logger was programmed to give average, maximum and minimum values and standard deviations according to the schedule outlined in Table 1. The output from set C were recorded on a Campbell Scientific 21X data logger, which was also used to collect data from other instruments set up at the site. Average and standard deviation values were then calculated after data were collected from the 21X data logger. Data were collected from the site approximately every three weeks.

DATA ANALYSIS

Description and Methodology

Using the data collected several analyses were carried out to obtain values for the display of wind roses, monthly reports, power curves, wind speed distributions, hourly and daily averages with standard deviations, time series and expected energy. These analyses were done either by using the software WinSite[7] designed by Second Wind or by in-house programming and calculations.

The wind rose (Appendix 1) is a graphical display of the wind speed and direction distribution around the 16 compass points during a given time interval. The center of the rose can be considered to be the tail of an arrow, whose other end points are in the direction from which

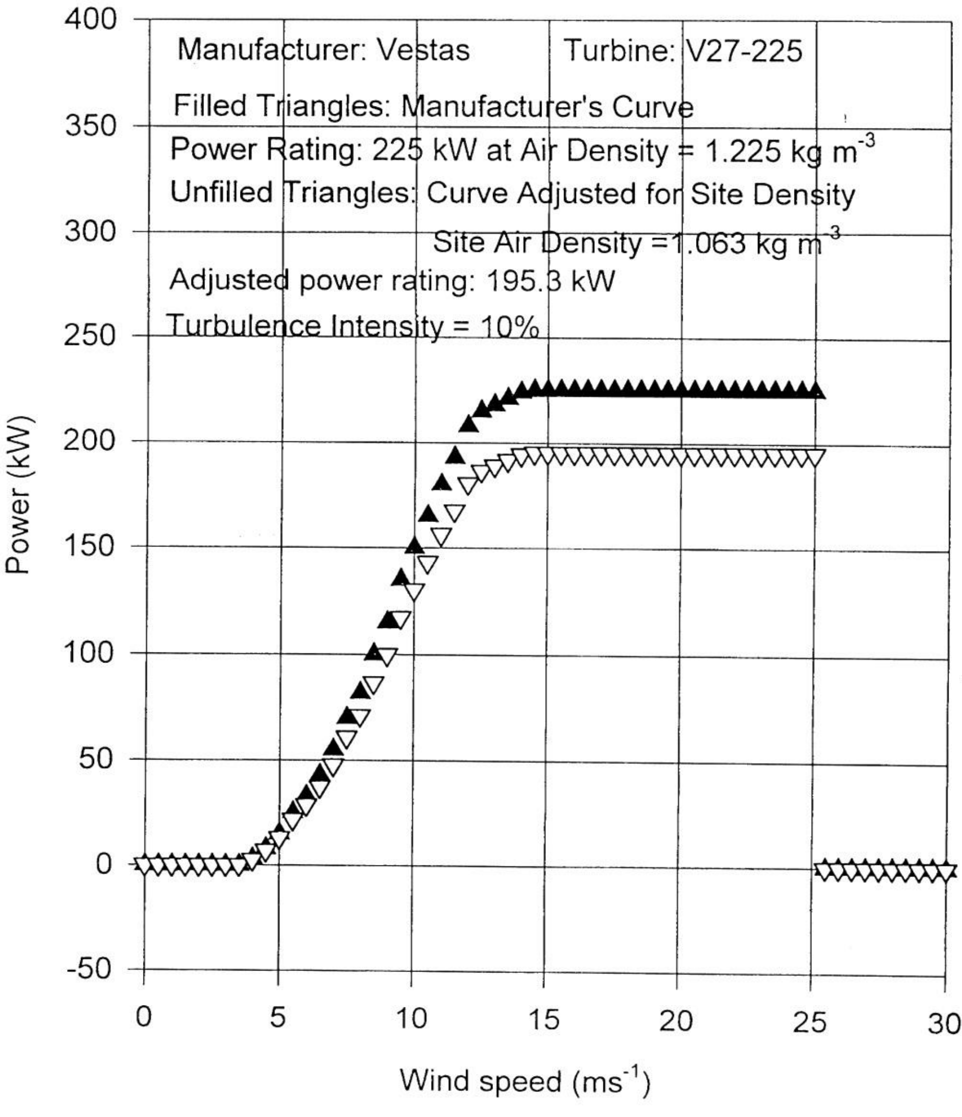

FIGURE 1 Vestas V27-225 Power Curve Supplied by the Manufacturer (Filled Triangles) and the Power Curve Adjusted for the Average Density at Munro (Unfilled Triangles)

TABLE 1 **Schedule for Obtaining Average Values, Standard Deviations, Maximum and Minimum Values on NOMAD Datalogger**

Program	Anemometer A	Anemometer B	Vane A	Vane B	Power Transducer	Datalogger Temperature
10 minute average value	X	X	X	X	X	
10 minute average standard development	X	X	X	X	X	
Maximum value in 10 minutes	X	X				
Minimum value in 10 minutes	X	X				
1 hour average value			X	X		X
1 hour average standard development	X	X				
Operating period [(a)]	P1	P1	P1	P2	P3	P1

[(a)] P1 is from July 10, 1996 to August 17, 1997; P2 is from July 10 to August 20, 1996; P3 is from July 31, 1996 to May 5, 1997 the wind is blowing (in terms of the 16 sectors of compass). The magnitude of the arrow represents the percentage of time the wind direction fell in a given sector and can be gauged by the radii of the concentric circles. Surrounding the rose are 16 graphs, each graph representing one of the 16 points of the compass. The horizontal axis gives the wind speed and the vertical axis gives the number of hours a particular wind speed was recorded. The percentage at the top of each graph gives the percentage of the time the wind emanated from the particular direction. The power curve gives the measured output power of the turbine as a function of wind speed and can be compared with the manufacturer's power curve as in Figure 6. It also includes the wind speed distribution, which gives the percentage of data points at each wind speed over the time interval under consideration to indicate the fraction of time a given power can be expected. The hourly average gives the average value and ± 1 standard deviation of a parameter for each hour of the day for any time period. The time series (Figure 2) provides a line graph that shows data trends over time. The expected energy report (Appendix 2) gives the total energy in kilowatt-hours (kWh) that can be expected based on the wind speed distribution at the site, assuming that the turbine output replicates 100% performance predicted by the manufacturer's power curve.

RESULTS

Period of Operation and Trouble Shooting

The monitoring of the site started July 10, 1996 and continued until August 17, 1997. About 2 months into the operation, the anemometer of set C at 20 m malfunctioned and so its output was not used in the analysis. However, the wind vane of set C continued to operate satisfactorily. On February 15, 1997 the circuit on wind vane B was found to be shorting to ground. A careful analysis of the wind vane data showed that the problem started on August 20, 1996. Although both wind vanes A and B were giving readings, they were not correct, since the short on wind vane B caused a drop in the voltage output of wind vane A. The problem was corrected by disconnecting wind vane B, at which point wind vane A began to give correct readings. The readings given by wind vane A from August 20, 1996 to February 15, 1997 were corrected using an algorithm which compared the values of wind vanes A and C before August 20, 1996 and those of A and C between August 20, 1996 and February 15, 1997. This was possible since wind vane C was unaffected by the shorting of wind vane B. At all times the crucial wind speed measurements remained intact.

On May 5, 1997 the power transducer became inoperable and this disabled the comparison between the actual power output from the turbine and the output estimated from the wind speeds. This was not a serious problem since there were 9.25 months of data to do the comparison.

On September 9, 1997 the NOMAD data logger was found inoperable, and the power cable burnt out, probably due to a lightening strike. This was so in spite of a lightening rod and heavy grounding cable on the mast. The periods of operation of each instrument are listed in Table 1.

Wind Speed, Turbine Power, Energy and Wind Direction

Figure 2 depicts the daily average wind speed at 30 m for the period July 10, 1996 to August 17, 1997. The daily average fluctuated between 2 and 15 ms^{-1} for the entire period with a mean of 7.4 ms^{-1}. A study of the hourly average wind speed at 30 m (Figure 3) showed that the average wind speed for each hour of the day did not show substantial variation (within ± 1 standard deviation) from the mean wind speed of 7.4 ms^{-1} throughout the day. Thus the hourly average variation was significantly different from those of coastline sites, where there is variation characteristic of the sea breeze, with a maximum near mid-day and a minimum at nights. Figure 4 depicts the frequency distribution of wind speed at 30 m. This distribution is based on 10 minute averages, not daily averages as in Figure 2. The mean wind speed was the same (7.4 ms^{1}) as in Figure 2, but the speed can be seen to vary from 0 to over 17.5 ms^{-1}, although only a small fraction of the wind speed occur near these "tails".

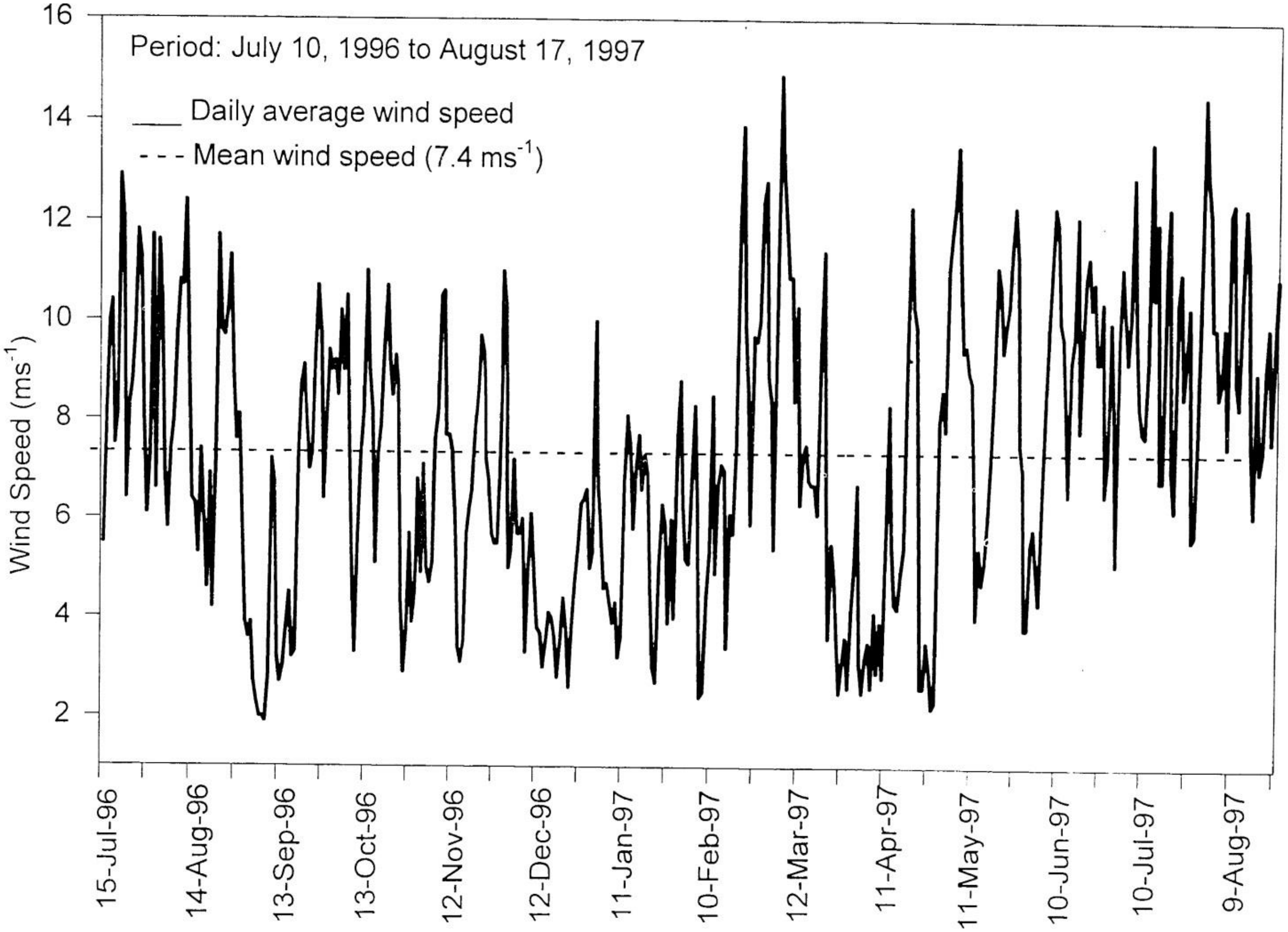

FIGURE 2 Daily Average Wind Speed at 30 m, from July 10, 1996 to August 17, 1997, Based on 10 minute Averages

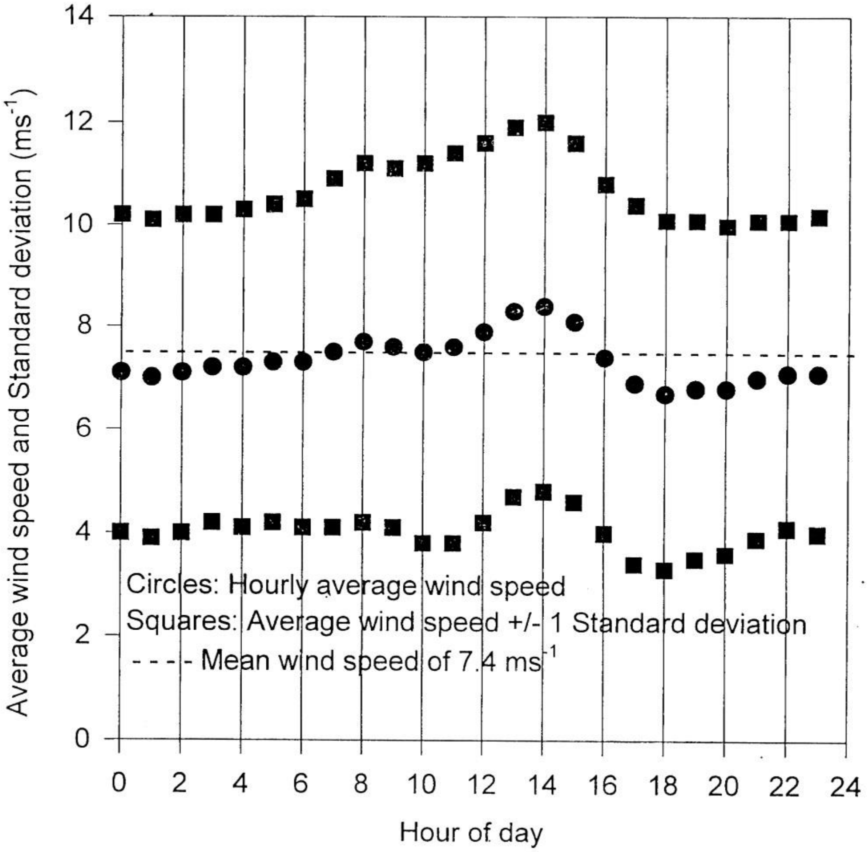

FIGURE 3 **Hourly Average Wind Speed (± 1 Standard Deviation) at 30 m Based on 10 minute Averages**

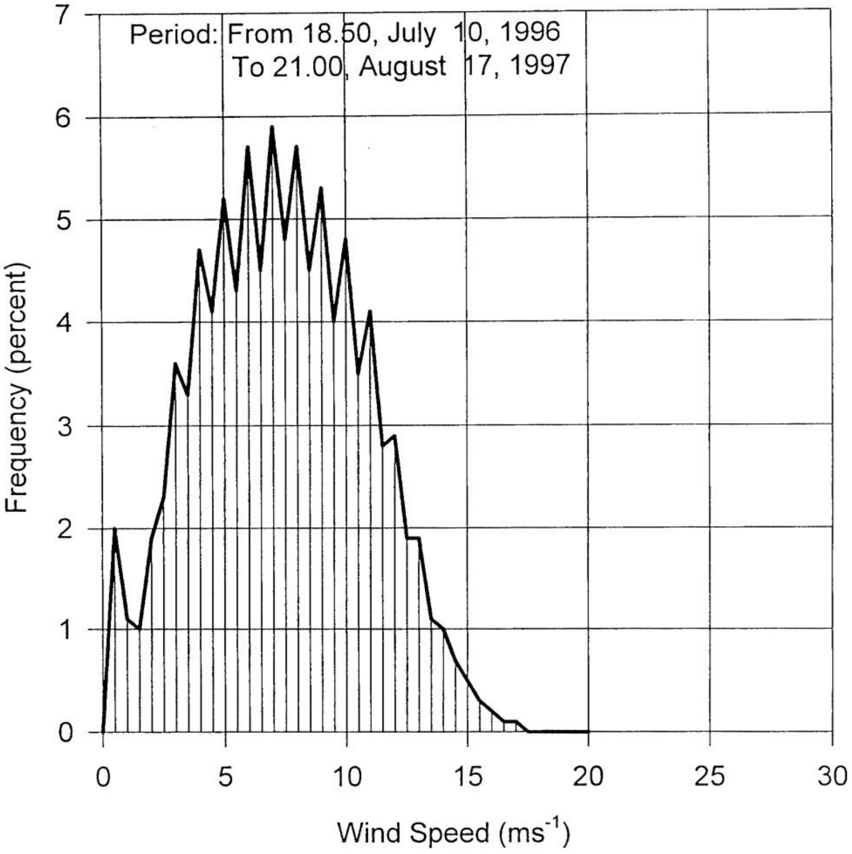

FIGURE 4 Wind Speed Distribution at 30 m Based on 10 minutes Averages

Daily average turbine output shown in Figure 5 can be seen to fluctuate significantly. It rarely reached the rated power and has a mean of 43 kW for the period July 31, 1996 to May 5, 1997. A careful analysis of 10 minute averages of power output, as detected by the power transducer, showed that during the above period the turbine was out of operation, presumably for servicing, approximately 4.7% of the time. If this downtime is taken into consideration, then the average power output is approximately 45 kW. As with wind speed in Figure 3, the hourly average turbine power at 30 m did not vary significantly from the mean throughout the day. However, it was observed that the standard deviation was quite high (45.4 kW < standard deviation <61.8 kW), as would be expected from the high daily average fluctuations shown in Figure 5.

Figure 6 shows manufacturer's reference power curve corrected for density, actual power output, and the wind speed distribution. Up to the rated speed, the actual power differed from the referenced power by 0 to 17%. The difference is due mainly to losses in converting the captured wind energy to electrical energy. The hatched area, which represents the wind speed distribution, shows that for approximately half the time, the turbine does not generate useful power from the wind. The fluctuations in actual power output at wind speeds above the rated speed of 14.5 ms^{-1} are due to the large changes (standard deviation 1.8 to 2.7 ms^{-1}) in the wind speed during the small fraction of time (about 42 hours during 9.25 months) at which the wind speed exceeded the rated speed. Large fluctuations in wind speed are associated with turbulence and result in large changes in generated power.

Table 2 shows the total expected energy and power, net energy, average wind speeds, mean standard deviation in wind speed and turbulence intensity for various periods. These periods are: (i) a full year of operation August 1, 1996 to July 31, 1997, (ii) the period during which the power transducer was operating, from July 31, 1996 to May 5, 1997 and (iii) the entire period from July 10, 1996 to August 17, 1997. From Table 2 it is apparent that the average expected power of 68 kW for the period (i) is greater than the average expected power of 56 kW for the period (ii). This is presumably because of the higher than average winds in May, June and July 1997, as shown in Figure 2, due to summer heating. The average expected power of 56 kW for period (ii) reduces to 44.3 kW when it is corrected for downtime (4.7%) and losses (17%). This agrees quite closely (within 3%) with the mean measured turbine power of 43 kW during period (ii). The mean wind speed at 10 m is 5.7 ms^{-1} compared to 7.4 ms^{-1} at 30 m for period (iii). These two wind speeds suggest a ratio of upper to lower wind speed of 1.30. For a flat terrain, the ratio would be approximately 1.17 using a scaling factor of $(30/10)^{1/7}$ based on the 1/7th power law mentioned in Sedefian[8]. Thus the site at Munro exhibited a larger vertical wind shear, than what would be expected according to the 1/7th power law.

Table 3 shows the wind direction distribution in terms of the 16 compass points. The readings from the wind vane B covers only the period July to August 1996 when both vanes A and B were operating. The results show that the wind is mainly an easterly wind.

Economics

The cost of energy is usually given in terms of the cost per kilowatt-hour (kWh) of electricity. The total cost of electricity to the customer consists of three (3) components, which are: the cost of producing electricity at the plant, the cost to transmit and distribute electricity and the cost of customer service, administration and return on assets. The Jamaica Public Service Company (JPSCo) estimated that the cost of producing electricity was US$0.06, US$0.069 and US$0.55 per kWh in 1995/6, 1996/7 and 1997/8 respectively. At the same time JPSCo bought electricity from Jamaica Energy Partners (JEP) and Jamaica Private Power Company (JPPC) at prices ranging from US8.36 cents to US11.27 cents per kWh[9].

The cost of producing electricity at Munro was estimated using the following equation from Swift-Hook[10].

$$G = C(R + M)/(W(hF)) \qquad \text{Eq. 2,}$$

Where G = cost of producing electricity per kWh

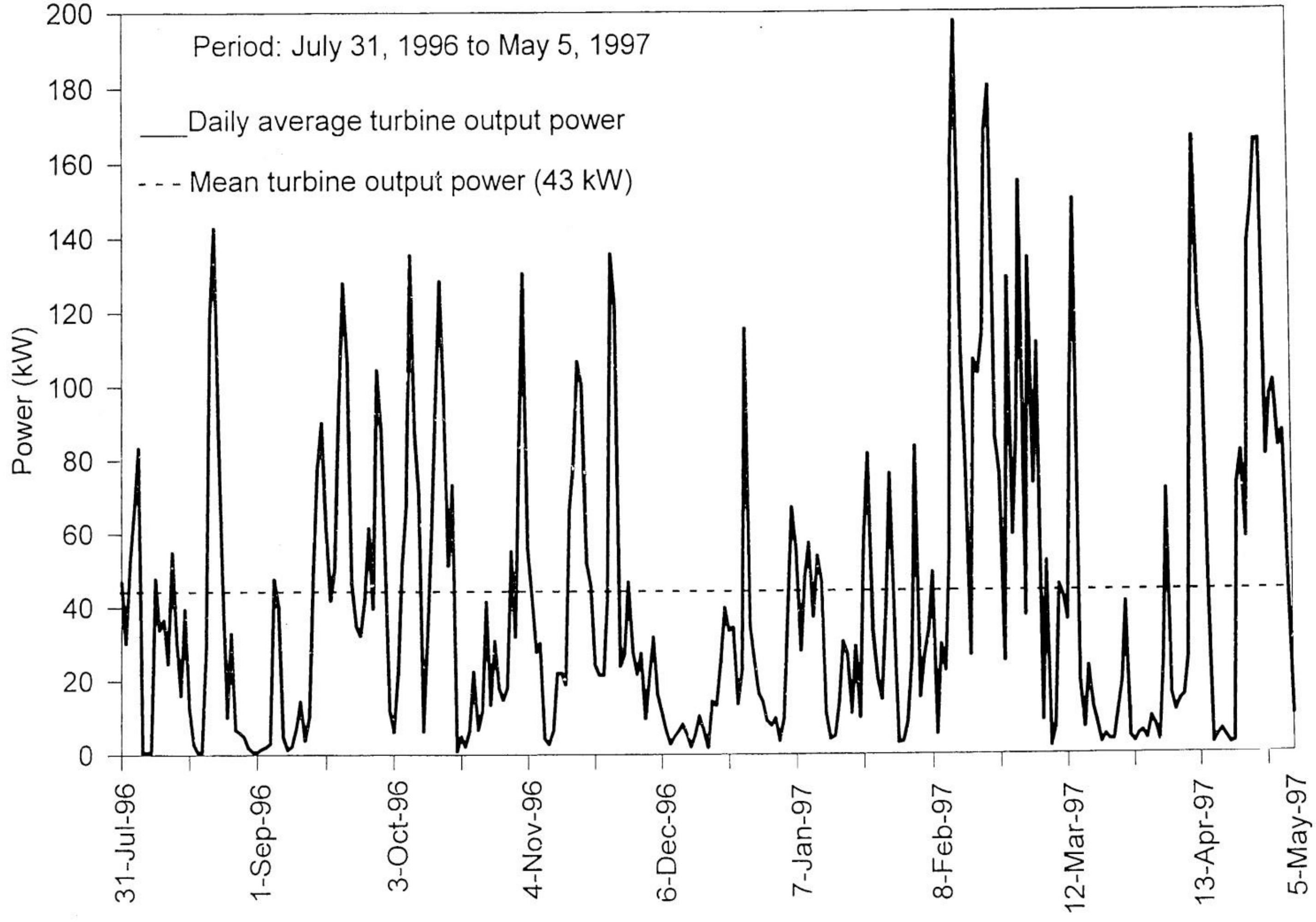

FIGURE 5 Daily Average Turbine Output Power, from July 31, 1996 to May 5, 1997, Based on 10 minute Averages

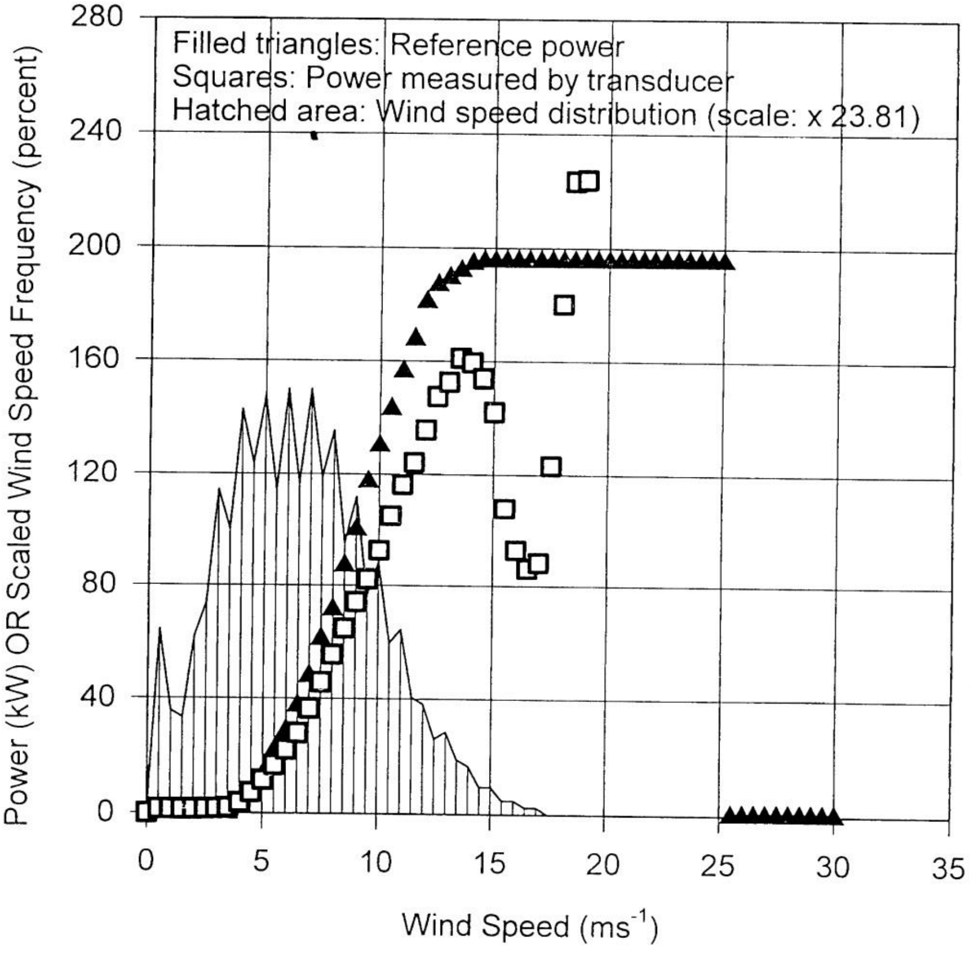

FIGURE 6 Reference Power Curve (Filled Triangles) Corrected for Density and Actual Average Output Power (Squares) from July 31, 1996 to May 5, 1997, along with the Wind Speed Distribution (Hatched Area). The Wind Speed Distribution has been Scaled up for better Viewing

TABLE 2 **Annual Expected Energy and Net Energy, Average Expected and Measured Turbine Power, Mean Wind Speeds at 30 and 10 m, Mean Standard Deviation in Wind Speed and Turbulence Intensity**

Parameter	Value
Annual expected energy (August 1, 1996 to July 31, 1997)	591,951.4 kWh
Annual net energy[(a)] (- do -)	468,227.6 kWh
Average expected power (- do -)	68 kW
Average expected power (July 31, 1996 to May 5, 1997)	56 kW
Average measured power (- do -)	43 kW
Mean wind speed at 30 m (July 10, 1996 to August 17, 1997)	7.4 ms^{-1}
Mean wind speed at 10 m (- do -)	5.7 ms^{-1}
Mean standard deviation in wind speed at 30 m (- do -)	1.1 ms^{-1}
Average turbulence intensity[(b)] at 30 m (July 10, 1996 to August 17, 1997)	15%

(a)Annual net energy = Annual expected energy * availability (0.953) * efficiency (0.83)
(b)Average turbulence intensity at 30 m = (mean standard deviation/mean wind speed)

TABLE 3 **Wind Direction Distribution in Terms of the 16 Compass Points, at 30 and 10 m**

Compass Points N to NNW	Distribution (%) at 30 M (July 10, 1996 to August 17, 1997)	Distribution (%) at 10 m (July 10, 1996 to August 20, 1997)
N	1.0	0.1
NNE	2.8	0.2
NE	9.7	1.9
ENE	18.7	12.8
E	38.9	48.0
ESE	17.1	31.9
SE	3.4	3.5
SSE	1.2	0.1
S	0.9	0.1
SSW	1.3	0.4
SW	1.4	0.1
WSW	1.2	0.3
W	1.0	0.2
WNW	0.7	0.2
NW	0.4	0.1
NNW	0.3	0.1

C = initial capital cost of turbine

R = annual charge rate on capital

M = annual operation and maintenance cost as a fraction of the initial capital

C(R + M) = annual cost of capital and maintenance

W = rated power of wind turbine in kW

h = number of hours in a year (8760)

F = overall load factor

hF = effective number of hours in a year during which the turbine operates at rated power

W(hF) = annual energy produced in kWh

The annual charge rate can be expressed in terms of the interest or discount rate (r) and the repayment term (n years) as given in Eq. 3 below.

$$R = r/\{1 - (1 + r)^{-n}\} \qquad \text{Eq. 3}$$

The overall load factor can be expressed as,

$$F = LAa \qquad \text{Eq. 4}$$

L = ratio of expected wind power extracted by turbine to the rated power and is called the capacity factor

A = fraction of time the turbine is operating, is called the availability factor

a = efficiency with which the machine converts wind energy extracted to electricity

Figure 7 gives the graphs of the cost of energy G, as a function of different repayment periods. In all calculations the following assumptions were made:

C = J$10M (approximately US$300,000). This cost includes purchase, shipping, installation costs, transformer cost and cost of connection to the grid[11]

W = 195.3 kW, the rated power of the turbine corrected for the site density

M = 2%, including insurance costs

h = 8760 hours

L = 0.35 (the average expected power, 68 kW in Table 2 divided by the rated power, 195.3 kW)

A = 0.953 (the actual downtime of 4.7% was used to obtain this value)

a = 0.83 (based on the 17% difference between the rated power and the actual power output as in Figure 6)

The filled triangles give calculated values of G assuming an interest rate of 15%. From this graph it can be seen that, for a repayment period of 10 years and interest rate of 15%, the cost of producing one kWh of energy would be about 12.7 US cents. The graphs show that, except for the unrealistic case of 0% interest rate, it would be impossible to repay any of the other loans by selling electricity at 5.0 US cents per kWh. On the other hand, at an interest rate of 8% and 10%, and a selling price of 10.0 US cents per kWh, the repayment periods would be 10 and 11 years respectively. After repayment of initial capital, the cost of production would be 1.2 US cents for all cases during the rest of the turbine's lifetime. The estimated lifetime of a turbine is assumed to be at least 20 years.

Since much of the wind speeds are centered below the rated wind speed of the V27-225 turbine, the economics may become more favourable if a larger turbine was used to capture the energy at these lower speeds. This would be especially true if there was also a reduction in the capital cost per unit of energy as the capacity increases. Figure 8 shows the power curves for one such turbine, the M1800-600 kW turbine manufactured by Micon while Figure 9 shows the M1800-600 kW and V27-225 kW turbine along with the wind speed distribution at 30 m. From these figures it is apparent that M1800-600 kW turbine has a slightly lower cut-in speed and captures more energy at lower wind speeds than V27-225 kW turbine.

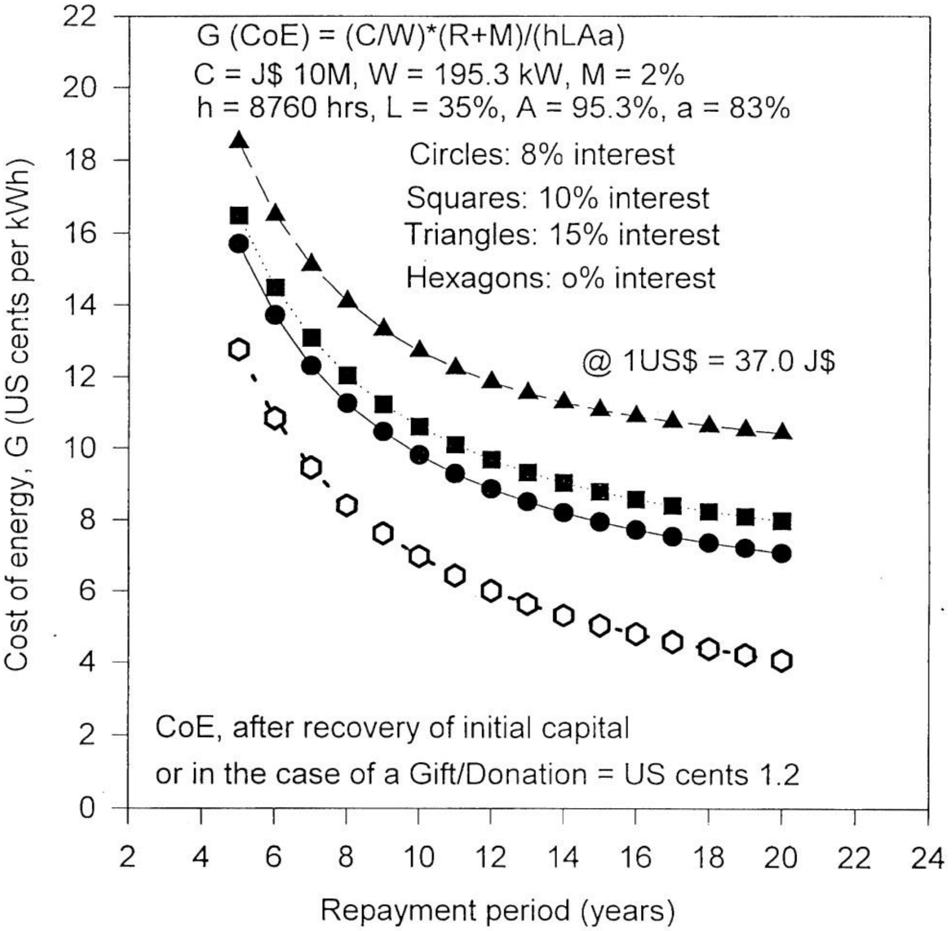

FIGURE 7 Plots of the Cost of Energy G, as a Function of Different Repayment Years N, for Different Interest Rates Using the Vestas V27-225 Turbine

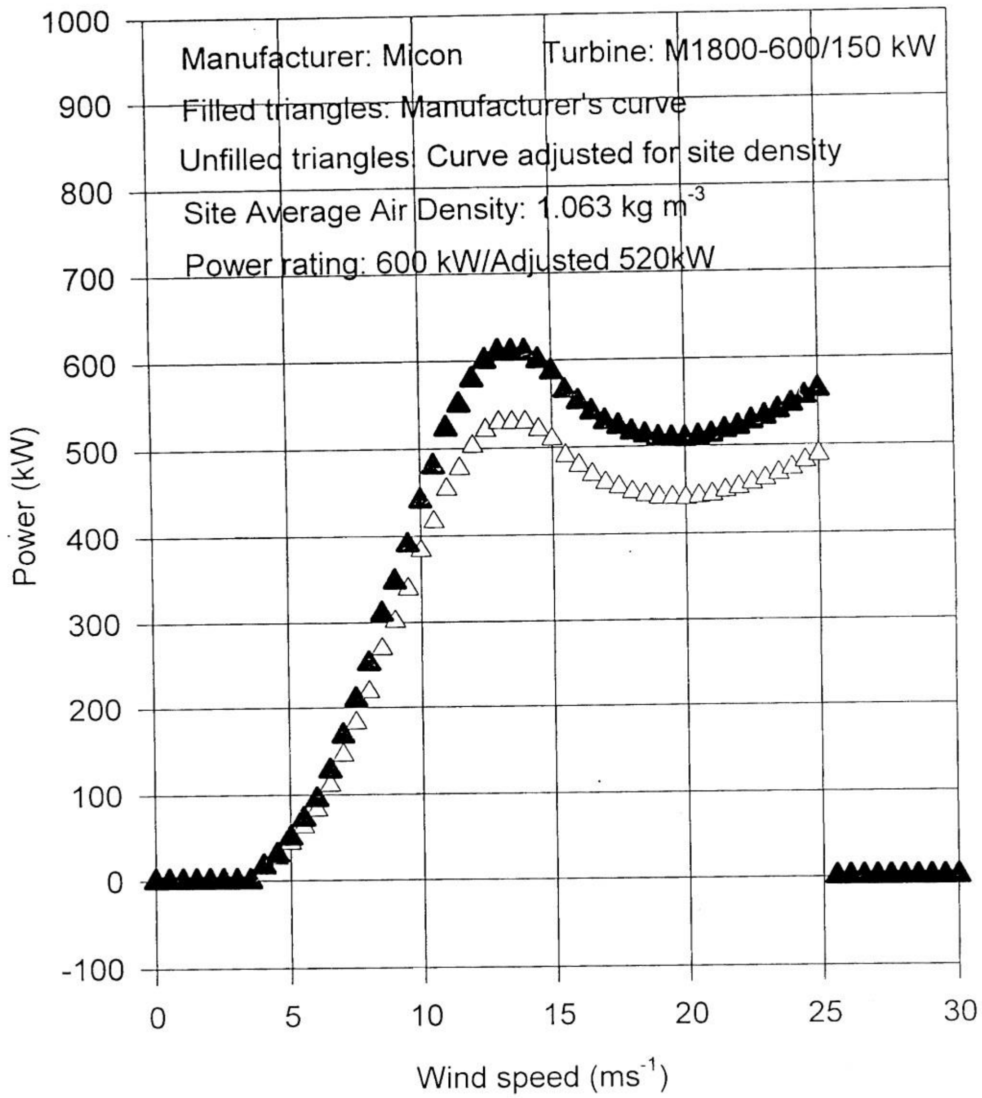

FIGURE 8 Manufacturer's Power Curve (Filled Triangles) and the One Adjusted for Average Density at Munro (Unfilled Triangles), for the Micon M1800-600 Turbine

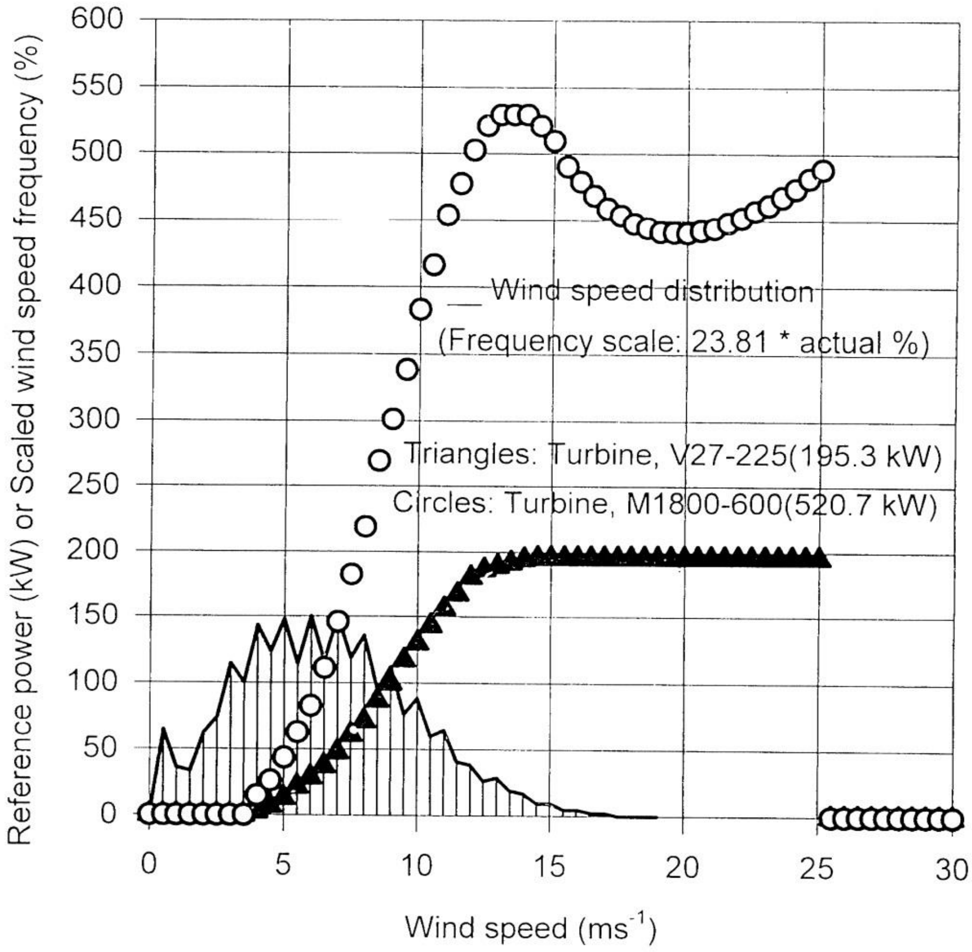

FIGURE 9 Vestas V27-225 and Micon M1800-600 Turbine Power Curves Adjusted for the Average Density at Munro along with the Wind Speed Distribution. The Wind Speed Distribution has been Scaled up for better Viewing

Figure 10 gives the graphs of cost of energy production using the M1800-600 kW turbine as a function of the repayment period n. The assumptions are the same as those in Figure 7, except for the rated power corrected for density and the capital cost, which are 520.7 kW and US$1,100 per kW[12], respectively. As for the Vestas V27-225 turbine, it would be impossible to repay any of the loans by selling electricity for 5.0 US cents per kWh, except for the case of 0% interest. However for the interest rates of 8% and 10%, and a selling price of 10.0 US cents per kWh, the repayment periods would reduce to approximately 8 and 9 years respectively.

DISCUSSION

Technical Feasibility

Wind power is undoubtedly technically feasible. Worldwide, the installed capacity has increased from 2600 MW in 1994/95 to over 9000 MW in 1998. The installation and operation of the Vestas 27-225 at Munro was a test case for Jamaica and the results seem to be mainly positive. There were no major problems in installing and maintaining the turbine. Useful energy was produced most, if not all, of the time, the estimated annual net energy being 4.68 x 10^5 kWh. Also note that the use of a turbine like Micon M1800-600 will provide a higher energy yield.

There are a few negative aspects that have to be noted as well. The large distance separating Munro and the nearest grid point at Spur Tree would be a major technical problem, as well as an economic one. Also the following comments, based on the results of the wind measurements, are pertinent to the technical feasibility of the turbine at Munro. The turbine's average power output is somewhat lower than expected. Normal losses in converting captured wind energy to electricity are approximately 10% as documented by Cranfield University Wind Research Group[13]. Based on the expected power and the observed turbine power output, the losses at Munro are estimated to be about 17%. There are two possible reasons for the greater loss. Firstly, because of the terrain and roughness elements at Munro, the vertical wind shear is greater than expected, as previously stated in reference to the ratio of the mean wind speeds at 30 and 10 m. The shear results in unsteady blade bending and hence low power. Secondly, the turbulent intensity in the wind causes uneven movement of the turbine blades, which again causes loss in power. The average turbulent intensity estimated in this work was 15% (Table 2). The manufacturer's power curve is based on a turbulent intensity of 10%.

While the output from wind turbines are not expected to be constant, the turbine at Munro rarely operated at the rated wind speed, where output power is constant. Consequently, there were large fluctuations in the power output. This could pose a problem in large scale generation of electricity when power is being generated for consumers who require steady power. There are possible solutions to this problem, although a power generating and distributing company, such as JPSCo, may not find them practical. Firstly, Daniel and Chen[14] have shown that it is possible to accurately predict the wind several hours ahead. On days when the wind is expected to be down or highly turbulent, backup power (for example, gas turbines) could be brought into the system based on the wind forecast. Secondly, it has been noted by Chen et al.[4] that the wind regime varies with location in Jamaica. It may be possible to find sites, which complement each other, such that when the wind is low at one site, it is high at another.

Environmental Feasibility

There are several possible negative environmental impacts to be taken into consideration at a wind site.

Noise - Noise generated by a wind system arises from two sources. Firstly, broad band noise can be produced by air passing through and over the blades of the turbine, in the form of a rhythmic swishing sound. Secondly, there is the single frequency noise which is produced by mechanical rotating elements such as occurs in the gearbox and generator. Fortunately, since 1992 the wind turbine industry has placed much emphasis on noise reduction by focusing on noise insulation. This noise reduction has been effected in the turbine at Munro. There have radio, television and other communication links. However, the turbine at Munro is located far from transmission sites, and thus will cause little interference.

Safety - Wind turbines are mounted on towers 30 m high and above and have blades of 15 m length or more. There is always the fear of a failure of the blade structure. The turbine at Munro is built to withstand hurricane force winds and will automatically shut down in winds of over 25 ms^{-1}. It is situated away from established communities and even in the event of collapse will not be endangering.

Visual and Landscape Impact - The turbine at Munro is so situated as to cause no significant negative impact on the beauty of the landscape. Adverse environmental impact would not appear to be an issue at Munro.

Wind Farms

The results of this project would have to be modified in at least two (2) ways in considering the establishment of a wind farm at Munro. In the first place there will be a wind speed reduction in the center of a large cluster of wind turbines since the turbines effectively act as roughness elements. For a squared array of turbines, the reduction does not become negligible until the separation of the turbines is about 20 times the rotor radius[15]. On the other hand, turbine costs and maintenance may become less, per unit of energy generated, for a wind farm. The authors unfortunately do not have experience in dealing with wind farms and are unable to say whether or not these factors will nullify each other or otherwise. Also the data at present, especially the extent of the wind field and the available land for wind power development at Munro, is inadequate to provide a conclusive statement on the economic feasibility of wind farms at Munro.

Economic Feasibility

From the analysis displayed in Figures 7 and 10, it is obvious that the economic advantage of electricity at 10 US cents p

investment would be economically feasible since, after a repayment period of close to 10 years, there will be approximately 10 years of profit, based on a turbine lifetime of at least 20 years. After the initial capital cost has been recovered, and the cost of maintenance (approximately 1.2 US cents per kWh) is accounted for, the profit will be approximately 8.8 US cents per kWh.

The annual energy in kWh expected to be produced by the turbine can be given by:

$$\text{Annual energy produced in kWh} = WhLAa \qquad \text{Eq. 5}$$

Therefore the annual profit in US$ is given by:

$$\text{Profit} = 0.088\ WhLAa \qquad \text{Eq. 6}$$

Equation 5 can be obtained using Eq. 4 and the relation, annual energy produced in kWh = W(hF).

The profits calculated using Eq. 6 are approximately US$41,000 per year for a Vestas V27-225 turbine and US$111,000 per year for a Micon M1800-600 turbine, when the values for W, h, L, A and a listed in Figures 7 and 10 are used. If one assumes full capitalization from a lending agency sympathetic to alternative energy, so that there is no initial outlay from the wind power developer, then the prospect is for profits of US$41,000 or US$111,000 per year, after an initial payback period.

Table 4 gives estimates of repayment periods and profit for the remaining life time of the turbine, for selected costs of electricity production using interest rates of 15%, 10% and 8% respectively for the Vestas V27-225 and assuming that JPSCo purchases electricity at the production rate. Table 5 gives the corresponding estimates for the Micon M1800-600. The profits quoted are from a single turbine. A 10 megawatt wind farm would require approximately 51 Vestas V27-225 or 19 Micon M1800-600 turbines. One can expect more

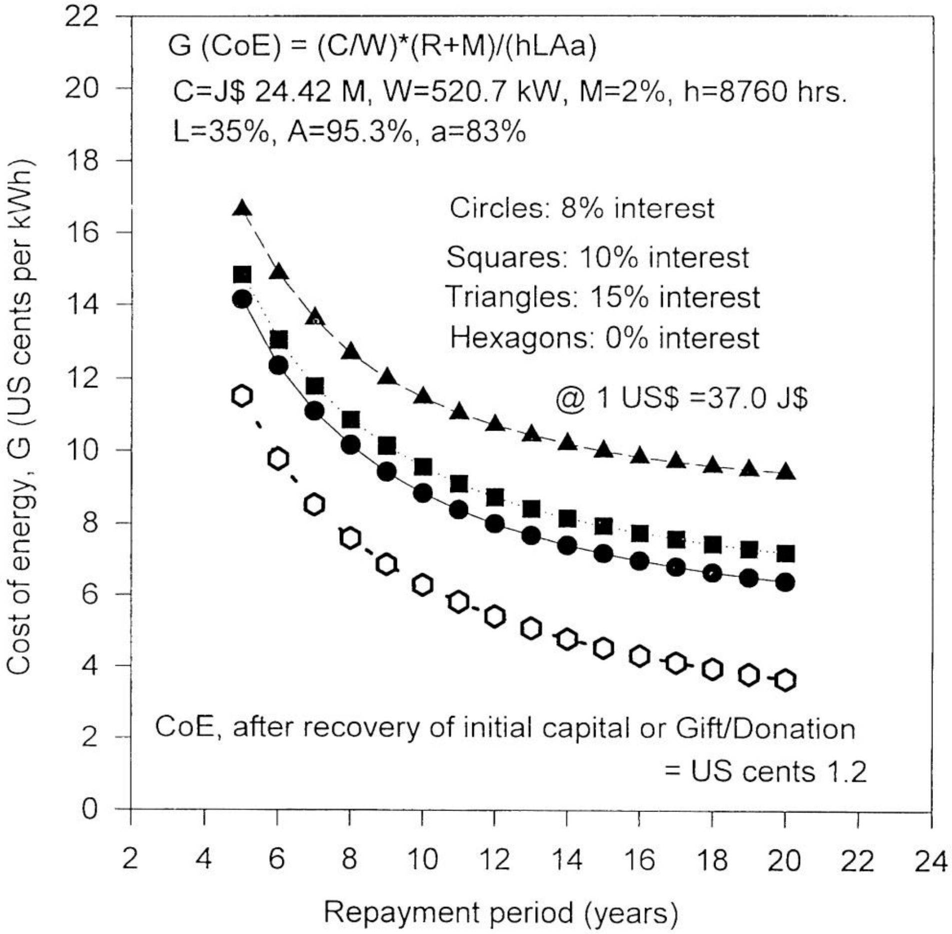

FIGURE 10 **Plots of the Cost of Energy G, as a Function of Different Repayment Years N, for different Interest Rates Using the Micon M1800-600 Turbine**

TABLE 4 **Estimates of Repayment Time and Profit for the remaining Lifetime of the Vestas V27-225 Turbine for Selected costs of Electricity Production Using Interest Rates of 15%, 10% and 8%**

Parameter	Energy Cost US cents/kWh	15% Interest	10% Interest	8% Interest
	15.00			
Repayment time (yrs.)		7	6	5.5
Profit for remaining life time (US$)		533,000	574,000	594,000
	10.00			
Repayment time (yrs.)		>20	11	10
Profit for remaining life time (US$)		none	369,000	410,000
	8.00			
Repayment time (yrs.)		>20	20	15
Profit for remaining life time (US$)		none	none	205,000

It is Assumed that Electricity Would be Purchased by the Distributor (JPSCo.) at the Same Cost at which it is Produced. The Initial Capital Cost is Approximately US$3000,000 and a Lifetime of 20 Years is Assumed

TABLE 5 **Estimates of Repayment Time and Profit for the Remaining Lifetime of the Micon M1800-600 Turbine for Selected Costs of Electricity Production Using Interest Rates of 15%, 10% and 8%**

Parameter	Energy Cost US cents/kWh	15% Interest	10% Interest	8% Interest
	15.00			
Repayment time (yrs.)		6	5	5
Profit for remaining life time (US$)		1,554,000	1,665,000	1,665,000
	10.00			
Repayment time (yrs.)		15	9	8
Profit for remaining life time (US$)		555,000	1,221,000	1,332,000
	8.00			
Repayment time (yrs.)		>20	16	12
Profit for remaining life time (US$)		none	444,000	888,000

It is Assumed that Electricity would be Purchased by the Distributor (JPSCo.) at the Same Cost at which it is Produced. The Initial Capital Coast is Approximately US$660,000 and a Lifetime of 20 Years is Assumed profits the greater the number of turbines, but the scaling up factor for profits would also depend on the factors discussed in the section on wind farms.

CONCLUDING REMARKS

This work finds that the use of wind power to generate electricity at Munro is technically feasible but not problem free, the inability to provide steady power being a major concern. There are also no major concerns about environmental impact. However, wind power can be economically utilized only under certain investment scenarios. If it is assumed that the power distributor, JPSCo., purchases electricity at 10.00 US cents per kWh (the purchasing rate of US cents 10.00 per kWh considered here is an average of the price paid by JPSCo. to independent power generating companies in the period 1995 to 1998) and the life span of a turbine is 20 years, then the following scenarios may be economically feasible. In the case of a turbine like Vestas V27-225, the wind power is economically feasible if the initial capital could be obtained at 10% interest or lower. Under that scenario, the repayment period would be about 10 years or less and half or more of the life span of the turbine is left for the investor to make a profit. In the case of a turbine like Micon M1800-600, the corresponding repayment period under an initial capital with a 10% interest or lower is 9 years or less, and more than half of the life span of the turbine is left for the investor to make a substantial profit. Even at an interest rate of 15%, a reasonable profit, albeit reduced, will be possible. On the other hand, if JPSCo. is willing to pay only 5 US cents per kWh, then the profit made would be minimal. Keep in mind also that there probably are funding agencies, such as the World Bank, which are very amenable to funding environmentally friendly projects, such as wind farms, on a national level and there may well be smaller agencies willing to fund individuals or communities for such projects. If one assumes full capital investment from such an agency, then the prospects for profits is high after recovery of the initial cost. This scenario could be appealing to Government or to some institutions, such as schools or universities.

It is quite possible that there are areas other than Munro, especially in the parishes of St Elizabeth and Manchester, where the winds are more favourable to producing electricity by wind turbines, both in terms of wind power and proximity to the national grid. The Petroleum Corporation of Jamaica is investigating the feasibility of some of these sites and the Physics Department has plans to look at other sites. Notwithstanding the present capacity of JPSCo. to adequately provide for Jamaica's current energy needs, the search for wind energy sites should not be laid aside for several reasons. Firstly, Jamaica is a signatory to the Kyoto Agreement to promote a cleaner environment. The development of wind energy in Jamaica would be a right step in keeping with the Kyoto Accord. Secondly, with less reliability on fossil fuel, Jamaica may be able to sell its emission credits to the larger energy consuming countries, such as the US. Thirdly, the case for wind energy will become stronger as fuel prices increase and wind turbines become more efficient. Projections suggest that in the US wind generated electricity will drop from a 1997 cost of 5 cents per kWh to 2 cents per kWh by the year 2010 (Department of Energy[16]). Additionally, the phasing in of wind energy for electricity production can be a gradual one, replacing old fossil fuel plants at the end of their useful life. The case for wind energy, however, does not stop at the production of electricity. There is also a documented case (Chen[17]), for using wind energy for irrigation purposes, which could prove to have economic advantage in view of the advances in wind technology.

ACKNOWLEDGEMENTS

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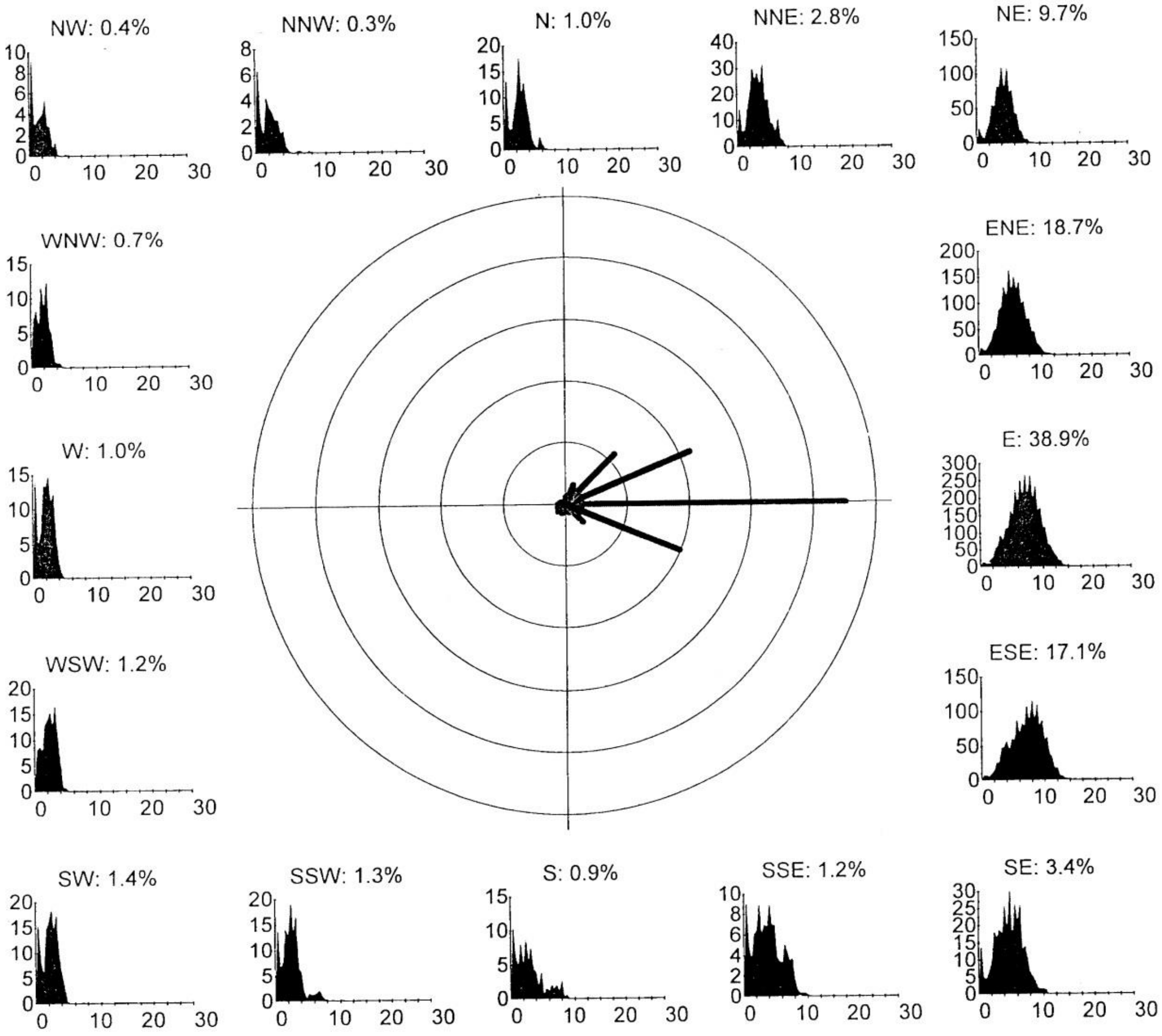
1.5 95.3 0.0 0.0

Appendix 1: Wind Rose at 30 m



Site: MONROE, #1
Inputs: Anem A, Vane A
From: 18:50, July 10,1996
To: 21:00, August 17,1997
Notes: Wind Rose is based on 10 minute averages

Total Hours : 9674.2
Data Hours : 9666.0
Percentage : 99.9%

munro

WinSite 2.1 02/23/00
Second Wind Inc. © 1996

Appendix 2: Expected Energy for 1 year at 30 m

Wind Speed (m/s)	Hours	Power (kW)	Energy (kWh)
0.0	0.0	0.0	0.0
0.5	188.0	0.0	0.0
1.0	108.0	0.0	0.0
1.5	95.3	0.0	0.0
2.0	186.2	0.0	0.0
2.5	221.0	0.0	0.0
3.0	343.8	0.0	0.0
3.5	312.7	0.0	0.0
4.0	438.8	2.6	1142.3
4.5	382.0	6.9	2652.2
5.0	480.2	13.0	6250.8
5.5	387.7	21.7	8410.8
6.0	513.0	28.6	14691.8
6.5	403.5	37.3	15057.4
7.0	521.8	47.7	24908.1
7.5	416.0	60.8	25272.4
8.0	501.8	71.2	35713.0
8.5	383.7	86.8	33298.0
9.0	453.0	99.8	45211.2
9.5	336.7	117.2	39444.5
10.0	401.7	130.2	52289.0
10.5	287.5	143.2	41169.4
11.0	329.8	156.2	51525.2
11.5	218.5	167.5	36598.5
12.0	215.7	180.5	38931.3
12.5	147.8	186.6	27584.4
13.0	146.3	189.2	27685.5
13.5	90.8	191.8	17421.7
14.0	84.7	194.4	16459.4
14.5	53.7	195.3	10479.5
15.0	43.8	195.3	8559.3
15.5	24.2	195.3	4719.0
16.0	19.3	195.3	3775.2
16.5	6.8	195.3	1334.3
17.0	4.3	195.3	846.2
17.5	1.2	195.3	227.8
18.0	0.8	195.3	162.7
18.5	0.5	195.3	97.6
19.0	0.2	195.3	32.5
19.5	0.0	195.3	0.0
20.0	0.0	195.3	0.0
20.5	0.0	195.3	0.0
21.0	0.0	195.3	0.0
21.5	0.0	195.3	0.0
22.0	0.0	195.3	0.0
22.5	0.0	195.3	0.0
23.0	0.0	195.3	0.0
23.5	0.0	195.3	0.0
24.0	0.0	195.3	0.0
24.5	0.0	195.3	0.0
25.0	0.0	195.3	0.0
25.5	0.0	0.0	0.0
26.0	0.0	0.0	0.0
26.5	0.0	0.0	0.0
27.0	0.0	0.0	0.0
27.5	0.0	0.0	0.0
28.0	0.0	0.0	0.0
28.5	0.0	0.0	0.0
29.0	0.0	0.0	0.0
29.5	0.0	0.0	0.0
30.0	0.0	0.0	0.0
Total	8,750.8		591,951.4

Wind Direction	Energy (kWh)
N	453.5
NNE	3887.3
NE	23774.7
ENE	90138.8
E	305634.3
ESE	148164.0
SE	13561.1
SSE	3065.9
S	1471.3
SSW	922.5
SW	301.9
WSW	245.7
W	134.4
WNW	59.3
NW	40.9
NNW	95.8
Total	591,951.4

Site: MONROE, #1
Input(s): Anem A, Vane A
Reference: Vestas V27-225
From: 00:00, August 01,1996
To: 23:00, July 31,1997
Notes: Density=1.063 kg/m^3, A=100%, a=100%

Total Hours : 8759.0
Data Hours : 8750.8
Percentage : 99.9%

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