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RESEARCH ARTICLE

SMALL WIND TURBINES: A SIMULATION FOR OPTIMAL SELECTION IN UASIN-GISHU, KENYA

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Abstract

Six years (2004-2009) wind speed data from Eldoret meteorological station (0.53^{o}N, 35.28^{o}E) have been analysed for wind energy estimation. Extrapolation of the 2 m height data using the power law has been used to simulate the wind speeds and wind powers for heights of 10 m, 20 m, 30 m and 40 m. Estimated wind power densities at different hub heights range between 70 W/m^2 to 107.534 W/m^2 at 40 m height. The energy output for different commercially available small wind turbines from different manufacturers was simulated to generate their performance power curves for the different heights. The simulations reveal existence of varied energy productions for the different wind turbines. WINDWORKER-300H/WM-300 horizontal axis wind turbine with rated wind speed of 7 m/s and rated wind power of 300 W can be considered for small scale production of wind power. The generated power can be directly linked to household appliances and for basic domestic applications.

1. Introduction

The large gap between demand and supply of electricity, increasing cost of imported fossil fuels and worsening air pollution demand an urgent search for energy sources that are cost-effective, reliable and environment-friendly. There has been a lot of recent interest worldwide in developing renewable energy sources (Irfan & Andrew, 2010). The technology for exploiting wind energy, in particular, has matured to the point that electricity produced from wind turbines now competes in cost with that produced from conventional sources, especially when the cost of environmental damage is factored in. Due to its wide availability and low environmental impact, wind energy is the fastest growing energy resource today (Kamau, Kinyua & Gathua, 2010). The worldwide capacity of wind power generation reached 159, 213MW at the end of 2009, with a growth rate of 29% per year (Deng, 2008). Kenya is highly dependent on hydro electricity which is responsible for over 75% of all electrical output (Mathenge, 2009). Kenya currently does not produce crude oil, and must import all of what it consumes. Previous exploration attempts for a domestic source of oil have shown signs of oil especially in the northern part of the country. The main sources of energy in Kenya are electricity, wood fuel, petroleum and green energy mainly Geothermal in Ol Karia along the Rift Valley. Of the total energy requirements in the country, the bulk (68%) (Ministry of energy, 2008) of the country's primary energy consumption comes from wood fuel and other biomass sources which has resulted in one of the highest deforestation rate in the whole of Africa continent. This is followed by petroleum at 22%, electricity at 9% and other sources at 1%. Kenya's wind energy sector has until now been exploited only to a limited extent (current installed capacity is 5.1 MW) (Kamau et al,. 2010). Currently the electricity sector in Kenya only reaches an estimated 15% of her population despite major investments in the rural electrification program (Ministry of energy, 2008).

However, government in its search for renewable sources of energy has identified Marsabit District, near Lake Turkana as a good site to put up the Lake Turkana Wind Power (LTWP) Project. The wind farm will comprise 365 turbines of 850 kW capacity each to maximize the very high wind speed in the Turkana low jet stream corridor (Madeleine, Arno and Wil, 2006). Geothermal power has been exploited only to an extent with the current installed capacity of 128 MW although the country has a potential of 3000MW (Nicholas, 2002). Access to adequate energy services is essential in both rural and urban areas. Lack of such access reduces the potential for achieving major structural changes in rural economies required for income generating activities, poverty alleviation and achievement of vision 2030. Access to electricity in rural areas is only 4%, 47.5% in urban areas and an average of 15 % at the national level (Nicholas, 2002) one of the lowest in developing countries. At regions where the annual wind speed is not very high and are too crowded to build wind sites, miniature wind machines are preferable. Small scale wind turbine, however, often sets up and stands alone on the roofs of houses and buildings. With a rotor whose diameter is less than one metre, this kind of windmill normally are directly linked to local generators and appliances rather than connected to the grid. As its capacity is about several watts to several tens watts and its prime cost is not very high, it is common for household appliances. This household-size wind turbine has become increasingly attractive in the recent years.

2. Wind speed variation with height

In the surface boundary layer, there are many factors which influence the variation of wind speed with height above the ground, such as terrain roughness and atmospheric stability. The wind speed increases with the height above the ground, due to the frictional drag of the ground, vegetation and buildings. The wind speed at the surface is zero due to the friction between the air and the surface of the ground. The wind speed increases with height most rapidly near the ground, increasing less rapidly with greater height. At a height about 2 km above the ground the change in the wind speed becomes zero. The vertical variation of the wind speed (the wind speed profile), can be expressed by different functions. Two of more common functions which have been developed to describe the change in mean wind speed with height are based on experiments and are given below. (Rene et al., 2003, Rokenes et al., 2008, Mohamed et al., 2009).

(i) Power exponent function

$$U(z) = U_r \left(\frac{Z}{Z_r} \right)^{\beta} \tag{1}$$

where Z is the height above ground level, U_r is the wind speed at the reference height above ground level, U(z) is the wind speed at height Z , and β is an exponent which depends on the roughness of the terrain and can be calculated in approximation by using the formula:

$$\beta = \frac{1}{\ln \frac{Z}{Z_0}} \tag{2}$$

(ii) Logarithmic function

$$\frac{U(z)}{U(10)} = \frac{\ln\left(\frac{Z}{Z_0} \right)}{\ln\left(\frac{10}{Z_0} \right)} \tag{3}$$

where U(10) is the wind speed at 10 m above ground level and Z_0 is the roughness length. Both functions can be used for calculation of the mean wind velocity at a certain height, if the mean wind velocity is known at the reference height.

3. Determining the Weibull parameters

Basically, the scale parameter, c, indicates how windy a location under consideration is, whereas the shape parameter, k, indicates how peaked the wind distribution is (i.e. if the wind speeds tend to be very close to a certain value, the distribution will have high k value and be very peaked).

3.1. Graphical method

The common method for determining k and c is graphical method. In the graphical method, the cumulative distribution function is transformed into a linear form, adopting logarithmic scales. The expression for the cumulative distribution of wind velocity can be rewritten as

$$1-F(v)=\exp\left(-\frac{v}{c}\right)^{k} \tag{4}$$

Taking the logarithm twice, we get

$$\ln\{-\ln[1-F(v)]\}=k\ln(v)-k\ln c \tag{5}$$

Plotting the above relationship with ln (v) along the X axis and ln{-ln[1-F(v)]} along the Y axis, we get nearly a straight line. From equation (5), k gives the slope of this line and – k ln c represents the intercept. c is equal to exp(ln(v)), or v , where ln(-ln(F(v)) is zero.

3.2. Moment estimates method

The two significant parameters k and c are closely related to the mean value of wind speed $\bar{v}$ as (Mayhoub and Azzam, 1997)

$$\bar{v}=c\Gamma\left(1+\frac{1}{k}\right) \tag{6}$$

Where $\Gamma(\ )$ is the gamma function of $(\ )$ and can be found using mathematical tables and

$$k=\left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{7}$$

c and k can be determined using equations 6 and 7 if the mean wind speed and standard deviation for given data is known.

Mean wind speed $\bar{v}$ is calculated using equation 6 while standard deviation, σ is calculated from the relation given as

$$\sigma=\left[\frac{1}{n-1}\sum_{i=1}^{N}(v_i-\bar{v})^2\right]^{0.5} \tag{8}$$

The Gamma function is defined by the following integral equation, which can be solved by the standard formula;

$$\Gamma(x)=\int_0^{\infty}t^{x-1}\exp(-t)dt \tag{9}$$

As the scale and shape parameters have been calculated, two meaningful wind speeds for wind energy estimation, the most probable wind speed and the wind speed carrying maximum energy, can be easily obtained. The most probable wind speed denotes the most frequent wind speed for a given wind probability distribution and is expressed by

$$v_{MP}=c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{10}$$

The wind speed carrying maximum energy represents the wind speed that carries the maximum amount of wind energy and is expressed as follows (Akpinar, & Akpinar 2005)

$$v_{\max E} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{11}$$

4. Wind speed duration curves

To determine accurately the potential annual energy output of a wind energy conversion system (WECS) at a particular site, it is necessary to know the wind speed duration curves for that site. The speed duration curves could be used to determine the number of hours of operation of specific wind machines.

4.1. Optimum rated wind speed of wind machines

To determine the optimum rated wind speed of a wind machine for a site, the annual energy outputs are determined for different rated speeds. For determination of annual energy output corresponding to a rated speed of wind machine, we use the equation

$$v_{in} = (0.15)^{\frac{1}{3}} v_r = \sqrt[3]{0.15}v_r = 0.531329284v_r \approx 0.5313v_r \tag{12}$$

Where v_{in} is the cut-in velocity and v_{r} is the rated wind speed of a wind machine. Some of the most important parameters regarding the curves are:-

1. **cut-in velocity (v_{in})**

The minimum wind velocity which must be attained before the machine/turbine begins to operate.

2. **Rated wind speed (v_{r}).**

Rated wind speed is that velocity of wind which corresponds to the rated capacity of the generator to maintain a constant output.

3. **Full load**

Wind speed at which the machine/turbine reaches rated capacity and maintains constant electrical output for subsequently higher wind speeds.

4. **Cutout velocity (v_{c})**

Wind speed at which the machine/turbine is shut down to avoid damage due to high wind speeds.

4.2 Wind power density

It is well known that the power of the wind that flows at speed v through a blade sweep area A increases as the cube of its velocity and is given by (Akpinar. & Akpinar, 2005)

$$P(v) = \frac{1}{2}\rho A v^3 \tag{13}$$

where ρ is the air density. Wind power density is the amount of wind power available per unit of area perpendicular to the wind flow. Wind power density is given by the relation;

$$\text{WPD} = \frac{1}{2}\rho v^3 \tag{14}$$

Monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows:

$$P_W = \frac{1}{2}\rho c^3\left(1+\frac{3}{k}\right) \tag{15}$$

Setting k equal to 2, the power density for the Rayleigh density function is found to be

$$P_R = \frac{3}{\pi}\rho v^3{}_m \tag{16}$$

However, the errors in calculating the power densities using the distributions in comparison to those using the measured probability density distributions can be found using the following equation

$$Error(\%) = \frac{P_{W,R} - P_{m,R}}{P_{m,R}} \tag{17}$$

where $P_{W,R}$ is the mean power density calculated from either the Weibull or Rayleigh function used in calculation of the error and $P_{m;R}$ is the wind power density for the measured probability density distribution, which serves as 'the reference mean power density'. $P_{m;R}$ can be calculated from the following equation

$$P_{m,R} = \sum_{i=1}^{n} \left[\frac{1}{2} \rho v^{3}{}_{m,i} \, f(v_i) \right] \tag{18}$$

The yearly average error value in calculating the power density using the Weibull function is found by using the following equation

$$Error(\%) = \frac{1}{12} \sum_{i=1}^{12} \left| \frac{P_{W,R} - P_{m,R}}{P_{m,R}} \right| \tag{19}$$

4.3 Power output of wind turbines

To describe the available wind distribution of a region and analyse the energy exchange between the wind and a wind energy conversion system, the Weibull and Rayleigh distributions are commonly used. Matching the actual wind frequency distribution of the region with a suitable model of the wind energy conversion system can maximize the energy output. Therefore, a wind energy conversion system can operate at maximum efficiency only if it is designed for the region where it is to be applied, as rated power and cut in, rated and cut off wind speeds must be defined according to the region. These parameters can be chosen so as to maximize the delivered energy for a given amount of available wind energy. However, it is rather expensive to design a wind energy conversion system for one region, so usually; one chooses for a given region the best among existing machines. It is possible, nonetheless, to investigate the potentiality of a region in relation to a wind machine by means of a site effectiveness model of the energy exchange between the wind energy conversion system and the wind distribution.

Different wind generators have different power output performance curves, so the model used to describe the performance is also different. In most literature, the following equation is used to simulate the electrical power output of a model wind turbine (Nigim & Paul Parker, 2007).

$$P_e = \begin{cases} 0 & v < v_{in} \\ P_{eR} \dfrac{v^k - v_{in}^k}{v_R^k - v_{in}^k} & v_{in} \le v \le v_R \\ P_{eR} & v_R \le v \le v_c \\ 0 & v > v_c \end{cases} \tag{20}$$

where P_{eR} is the rated electrical power; v_{in} is the cut in wind speed; v_R is the rated wind speed; and v_c is the cut out wind speed. However, the average power output ($P_{e,ave}$) of a turbine is a very important parameter of a wind energy conversion system since it determines the total energy production and the total income.

$$P_{e,ave} = P_{eR} \left\{ \frac{e^{-(v_c/c)^k} - e^{-(v_R/c)^k}}{(v_R/c)^k - (v_c/c)^k} - e^{-(v_F/c)^k} \right\} \tag{21}$$

5 Results and discussions

Figures 1 shows the relationship between wind speeds and estimated wind power densities at heights of 2 m, 10 m, 20 m, 30 m and 40 m above the ground for the period 2004 to 2009. Figure 1 shows that the mean wind speed and wind power density increases with increase in height. Therefore, to obtain higher wind power, higher hub heights are preferred. In order to observe the relationship between wind speed and wind power density, the graph of wind speed (m/s) and wind power density (W/m^2) were plotted on the same axes. It can be seen from the fig. 2 that the annual mean wind speed is linear (almost the same). The trend of wind power densities estimated using both Weibull and Rayleigh density functions are almost the same. It is however notable that a small change in wind speed produces a drastic change in wind power density estimated using Rayleigh method due the fact that wind power density is proportional to the cube of mean wind speed. With the objective of looking for a good wind turbine for Uasin-Gishu region, different models of wind turbines were analysed whose power curves were reproduced using the mathematical model given by equation 20. The power curves for the wind turbines chosen are presented in figure 3.

Figure 1: Wind speed, Weibull and Rayleigh wind power densities for the period 2004-2009.

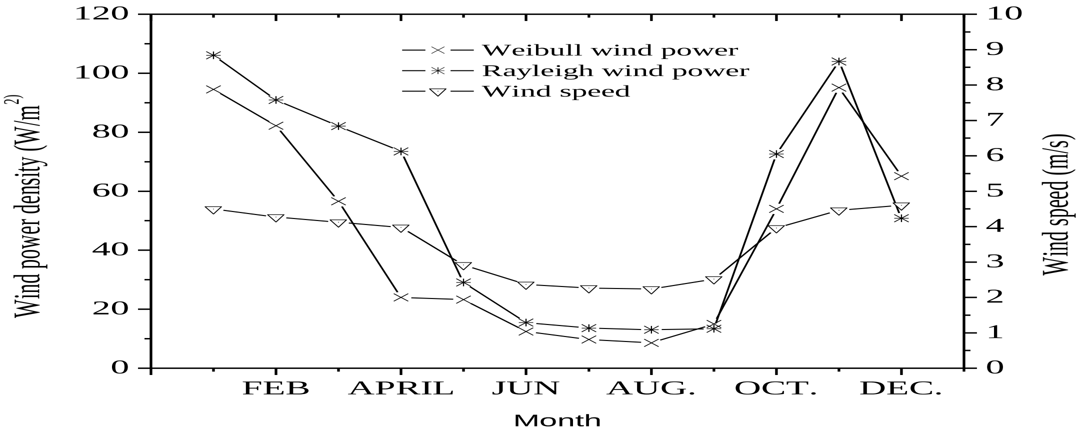

Figure 2: Variation of wind speed with height for the years 2004-2009.

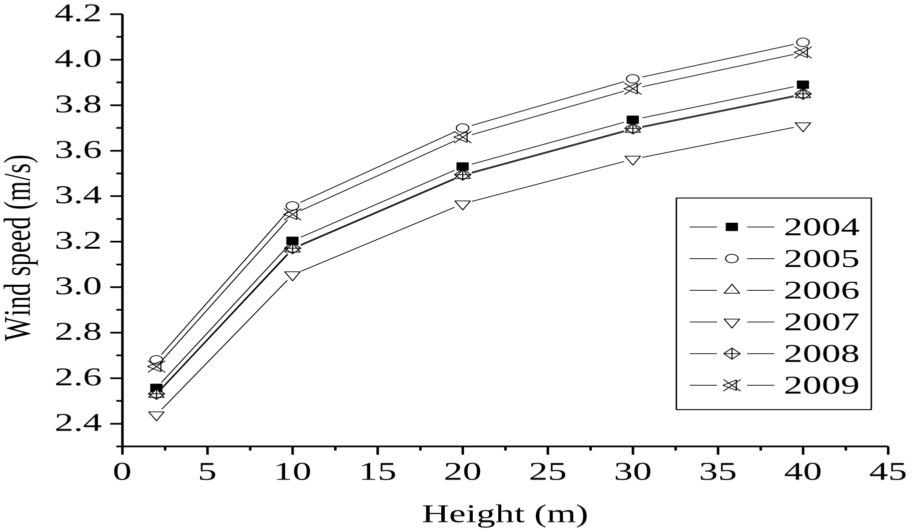

Figure 3: Variation of wind power with height for the years 2004-2009.

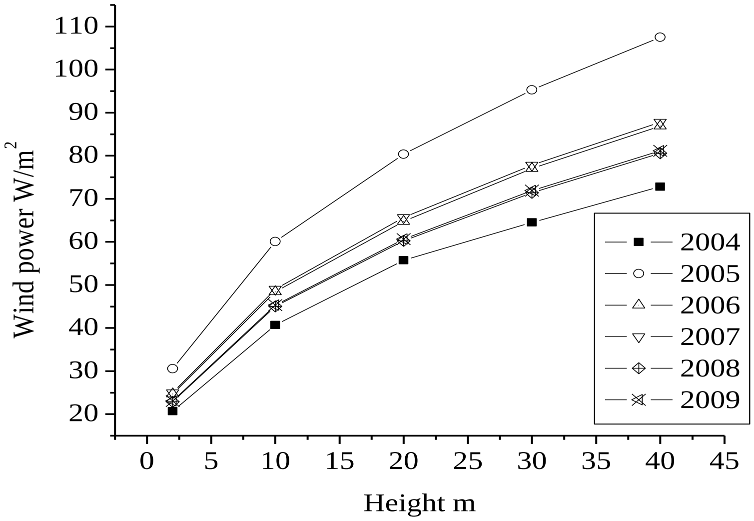

Figure 4: Wind power curves for selected HAWT's

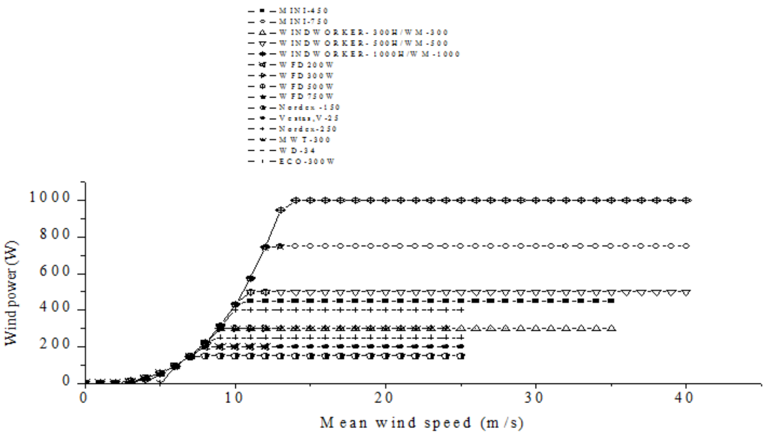

Table 1: Wind turbine data

Sr. no.	Model	P_{rated}(W)	v_{in} (m/s)	v_r (m/s)	v_c (m/s)
1	MINI-450	450	3	12	35
2	MINI-750	750	3	12	40
3	WINDWORKER-300H/WM-300	300	2.5	7	35
4	WINDWORKER-500H/WM-500	500	3	8	40
5	WINDWORKER-1000H/WM-1000	1000	3	9	40
6	WFD200W	200	2.5	9	12
7	WFD300W	300	2.5	9	12
8	WFD500W	500	3	9	12
9	WFD750W	750	3	10	13
10	ECO-300W	300/400	2.5	8	25
11	Nordex-150	150	3	10	25
12	Vestas, V-25	200	3.5	13.8	25
13	Nordex-250	250	3	13	25
14	MWT-300	300	5.5	12	24
15	WD-34	400	5	13	25

6 Conclusions

Wind speed has been analysed for a five year period (2004 to 2008). The results show that wind speeds range from a minimum of 1.34 m/s to a maximum of 3.99 m/s at 2 m height. Wind speed data at 2 m height was extrapolated using the power law (Eqn 1) to determine wind speeds at heights of 10 m, 20 m, 30 m and 40 m. The wind speeds vary from an average of 3.36 m/s to 5.5 m/s at 20 m from the data used. These speeds are enough to operate modern wind turbines which require low wind speeds for achieving wind power for domestic electrical needs and small scale water pumping among other small scale applications. Wind power densities were calculated to be 107.534 W/m^2 (maximum) in 2005 and 72.814 W/m^2 (minimum) in 2004 at 40 m height. These values show that Uasin-Gishu region has the potential for wind energy exploitation. In this study, it is recommended that the WINDWORKER-300H/WM-300 (HAWT) wind turbine with rated wind speed of 7 m/s and rated wind power of 300 Watts can be installed within buildings for domestic electrical needs. Wind energy can be combined with solar energy in isolated villages and areas which are not electrified for relatively small amount of power applications. The small wind turbine recommended in this study is fit for installation within homes on rooftops to provide the basic needs which are not commensurate to the requirements of main electrical supply.

7. References

Akpinar E. K & Akpinar S. (2005). An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics. *Energy conversion and management, 46*, 515-532.

Bw'Obaya, Nicholas M. 92002). *The Socio-Economic and Environmental Impact of Geothermal. Energy on the rural poor in Kenya.* Report. Nairobi: AFREPREN.

Carpenter P. & Locke N.(1999). Investigation of wind speeds over multiple two-dimension hills. *Wind Engineering and Industrial Aerodynamics 83*, 109-122.

Ifran U., Qamr-uz-Zamman C.& Andrew J. C.(2010). An evaluation of wind energy potential at Bandar, Pakistan. *Renewable and sustainable energy reviews 14*. 856-861.

Kamau, J. N., Kinyua, R. & Gathua, J.K.. (2010). 6 years of wind data for Marsabit, Kenya average over 14 m/s. *Renewable Energy 35*, 1298–1302.

Kenya, Ministry of energy. (2008). Feed-in-Tariffs policy on wind, biomass and small hydros. Government printer.

Madeleine G., Arno, J.B. & Wil, L.K. (2009). Estimation of Variability and Predictability of Large-scale Wind Energy in The Netherlands. *Wind Energy 12*. 241-260.

Mathenge, O. (2009, July 7). Kenya set to tap much more power from renewable energy in new plan. *Daily nation*, p.

Mayhoub A. B & Azzam A.(1997). A survey on the assessment of wind energy potential in Egypt. *Renewable energy 11*, 235-247.

Nigim K. A & Paul P. (2007). Heuristic and probabilistic wind power procedures. *Renewable energy 32*, 638-648.

Rokenes K. & Per-Age K.(2009). Wind tunnel simulation of terrain effects on a wind farm sitting. *Wind energy 12*, 391-410.

Thomas Ackermann & Lennart Sodder.(2000). Wind energy technology and current status. *Renewable and Sustainable Energy Reviews 4*, 315-374.

Yun, D. (2008). *Design Optimization of a Micro Wind Turbine using Computational Fluid Dynamics.* Unpublished Masters Thesis, University of Hong Kong.