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Analysis of Wind and Solar Energy Potential in Eldoret, Kenya

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Abstract
As a developing nation, Kenya urgently needs new sources of affordable, clean and renewable energy. Wind and solar energy are potentially attractive because of their low environmental impact, availability and sustainability. This work investigated the wind and solar power production potential in Eldoret, Kenya. Wind speed and sunshine duration data over a five-year period (2004-2008) from Eldoret meteorological station (0.53°N, 35.28°E) are presented. Wind power densities, seasonal variations of speed, and estimates of power likely to be produced by small wind turbines (WT's) are included. The site investigated is found to be a class 2 wind power site with annual average wind speed of 2.5 m/s at 2 m height and power density of 80.379 W/m^2 at 20 m height. The site is, therefore, likely to be suitable for wind farms as well as small, stand-alone systems. Global solar irradiation was estimated from sunshine duration to be 21.44 $MJ.m^{-2}.day^{-1}$ (maximum) in 2008 and 16.00 $MJ.m^{-2}.day^{-1}$ (minimum) in 2007. Suggestions have been made for the effective use of small WT's in the region around Eldoret and the possibility of combining wind and solar energy for small-scale applications.
Keywords: Wind speed, wind power density, Weibull distribution, Rayleigh distribution, sunshine hours, solar irradiation, solar energy, renewable energy

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. This has led to a shift of interest to renewable energy sources such as wind and solar which is not only widely available but also environment friendly and therefore reduce carbon emissions that the world is trying to reduce. 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 been met mostly by disappointments. 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 have 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, Kenya is endowed with vast potential of sunshine all year round. This important resource can be harnessed to generate solar power for domestic applications. An important step to address the energy shortage in rural domestic setting is to combine wind and solar to supply a household with required energy continuously. This is because of intermittency of wind and sunshine both during the day and around the year. Recent studies have shown that small WT's are preferred at regions where annual wind speeds are not very high and are too crowded to build wind sites. These machines (rotor diameter < 3 metres) are set up as stand alones on rooftops and the generated power linked directly to household appliances.

Many researchers around the world have carried out studies to investigate the potential of wind energy from recorded wind speed data. Rene *et al. (*2000) presented results on estimation of wind energy available in far north Cameroon. Their results revealed that the wind power available is equal to 15 W/m^2 or higher. They recommended use of small WT's for agricultural applications. During the same year, Merzouk studied wind energy potential of Algeria. His conclusion indicated that Algeria has appreciable wind energy potential with a mean wind speed of the order of 5.6 m/s. Himri *et a.l* (2008) assessed the potential of wind power for three locations in Algeria. Their recorded wind speeds was between 4.3 m/s and 5.9 m/s and they concluded that wind farm development would be economical. Fawzi and Jowder (2009), studied wind power analysis and site matching of wind turbine generators in Kingdom of Bahrain. The maximum power densities at 10m hub height lay between 65 W/m^2 and 164 W/m^2. Aynur and Balo (2010), assessed wind power potential for turbine installation in coastal areas of turkey. They obtained highest annual wind power density as 1257 W/m^2 and the lowest calculated value as 7.01 W/m^2 . Carta *et al.(* 2009), carried out a review of wind speed probability distributions used in wind energy analysis in Canary Islands which indicated that Weibull two parmeters distribution is appropriate for wind energy studies.

Several empirical formulas have been developed for estimation of solar power from the readily available sunshine hours data. Estimation of solar energy using sunshine hours has been done by many researchers. Ododo *et al.,* (1996), correlated solar radiation with cloud cover and relative sunshine duration for three Nigerian stations. Their results revealed that cloud cover and relative sunshine duration data are quite useful in predicting total solar radiation. During the same year, Singh *et al* (1996), employed empirical relationship to estimate global solar radiation from sunshine hours at Lucknow, India. Their results revealed that sunshine hours give accurate estimation of global radiation incident on a horizontal surface with relative error rarely exceeding 5%. Nguyen and Trevor (1997) studied the relationship between global solar radiation and sunshine duration in Vietnam. They concluded that global radiation values estimated using sunshine data can be used in design and estimation of performance of solar applications. In 1998, Chegaar *et al* estimated solar radiation using sunshine hours in some Algerian and Spanish Meteorological stations. They found good agreement between the measured and computed values with those estimated from their model. This model formed the basis of estimation of solar radiation in this study.

Almorox and Hontoria (2004) studied global solar radiation estimation using sunshine duration in Spain. Their objective was to validate several expression models for the prediction of monthly average daily global radiation on horizontal surface from sunshine hours and to select the most adequate model. They recommended the use of linear equation due to its simplicity. Li *et al.,* (2008), presented an approach to estimate the annual global solar radiation on various inclined planes facing different orientations based on sunshine hours. Solar radiation and sunshine hours data recorded in 2004 in Hong Kong were used for model development. They found that the solar radiation estimated from sunshine hours was in good agreement with measured data and the peak difference was found to be less than 5.2 %. The aim of the present study is to relate energy from the wind and solar and the possibility of combining the two sources to supply the same interconnected system based on wind speed and sunshine hours data obtained from Eldoret meteorological station.

1.1 Site description

Eldoret meteorological station (0.53^{o}N, 35.28^{o}E) is located in north rift region in the republic of Kenya (East Africa). The primary energy sources in the region include hydropower from the national grid, wood fuel, petroleum and solar. Majority of the households use wood fuel which has resulted in high deforestation. The wind speed data used in this study was recorded at 2 m height above the ground. This site has a mean annual wind speeds of 2.5 m/s and power density of 80.379 W/m^2 at 20 m. Generally, wind speeds are high during the dry season when sunshine hours are also longer.

1.2. Mathematical analysis

1.2.1 Vertical variation of wind speed

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).

(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 may be used for calculation of the mean wind velocity at a certain height, if the mean wind velocity is known at the reference height.

1.2.2 Frequency distribution of wind speed

The wind speed probability density distributions and the functions representing them mathematically are the main tools used in the wind related literature. Their use includes a wide range of applications, from the techniques used to identify the parameters of the distribution functions to the use of such functions for analyzing the wind speed data and wind energy economics. Two of the commonly used functions for fitting a measured wind speed probability distribution in a given location over a certain period of time are the Weibull and Rayleigh distributions. The probability density function of the Weibull distribution is given by

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \qquad 0 < v < \alpha \tag{4}$$

where *k* is the shape parameter and *c* is the scale parameter.

By keeping the shape parameter of Weibull distribution *k*=1, *k*=2 and *k*=3.6, Weibull distributions becomes exponential, Rayleigh and normal distributions respectively. For *k*=2, the form of the Weibull PDF reduces to Rayleigh density function, leaving *c* as the only parameter of variation. Thus,

$$f(v) = \left(\frac{2v}{c^2}\right) e^{-\left(\frac{v}{c}\right)^2} \qquad 0 < v < \alpha \tag{5}$$

The single-parameter Rayleigh density function can be rewritten with the wind speed mean (v) explicitly expressed as

$$f(v) = \left(\frac{\pi}{2}\right)\left(\frac{v}{\overline{v}^2}\right) e^{-\left(\frac{\pi}{4}\right)\left(\frac{v}{\overline{v}}\right)^2} \qquad 0 < v < \alpha \tag{6}$$

The cumulative distribution function of the velocity *v* gives us the fraction of time (or probability) that the wind velocity is equal or lower than v. Thus the cumulative distribution $F(v)$ is the integral of the probability density function. Thus

$$F(v) = 1 - \exp\left\{-\left(\frac{v}{c}\right)^k\right\} \tag{7}$$

The Weibull parameters have been determined using the moment estimates method.

1.2.3 **Wind power density**

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

$$P(v) = \frac{1}{2}\rho A v^3 \tag{8}$$

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;

$$\text{WPD} = \frac{1}{2}\rho v^3 \tag{9}$$

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

$$P_W = \frac{1}{2}\rho c^3 \left(1 + \frac{3}{k}\right) \tag{10}$$

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

$$P_R = \frac{3}{\pi}\rho v^3{}_m \tag{11}$$

1.2.4 Solar radiation estimation

An empirical model originally formulated by Sivkov gives a good estimation of solar radiation (Chegaar *et al*., 1998). This model only requires the sunshine hours duration per day. The monthly average of daily global irradiation on horizontal surface is obtained using the relation given as:-

$$G = 4.18\times10^{-2}\left[K(s)^{1.11} + \frac{10500}{30}(\sinh)^{2.08}\right] \tag{12}$$

Where G is the computed daily global irradiation ($MJ.m^{-2}.day^{-1}$), s is the monthly average daily sunshine hours (hours), h is the noon solar altitude on 15th day of the month (degrees) and K is a zone parameter that depends on the climate. The values 1.11 and 2.08 are climate type correction factors for tropical regions. The constant is divided by 30 days of the month.

1.3 Results and analysis

In this study, wind speed and sunshine hours data for Eldoret, Kenya, (at 2 m above the ground) over a five year period from 2004 to 2008 were analysed. Based on these data, the wind speeds and sunshine hours data analysed were processed using MathCAD 2000 and OriginPro statistical software's. The highest monthly wind speeds occur in the months of January and December for the whole year as shown in Fig 1. June to September have little wind, as indicated by the low monthly average values.

Fig. 2 indicates that 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 i.e when wind speed doubles, the wind power increases eight times.

Table 1. presents the estimated mean global solar irradiation and the mean power for each month (2004-2008) and Fig. 3 shows the graph those results. It can be seen that the solar power and the mean power follow the same trend each year. The correlation coefficient between estimated solar power and wind power was calculated to be 0.6612. This strong relationship between wind and solar power can be effectively utilized to supply a household with needed energy requirements continuously during the dry season when hydro electric power is not reliable.

Figure 4 shows the estimated global solar irradiation for the region under study. The maximum solar irradiation was in 2008 (21.44 $MJ.m^{-2}.day^{-1}$) while the minimum was in 2007 (16 $MJ.m^{-2}.day^{-1}$)

1.4 Conclusion

Wind energy has been analysed and correlated to sunshine hours data 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 and 20 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 small WT's 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 80.38 W/m^2 (maximum) in 2005 and 55.72 W/m^2 (minimum) in 2004 at 20 m height. These values show that Uasin-Gishu region has the potential for small scale wind energy exploitation.

The results of the study also indicate that Global solar irradiation annual variation follow the same trend as that of wind power density (figure 3). When the sunshine duration is long, there is enough wind speeds. (September to April). Global solar irradiation was estimated to be 21.44 $MJ.m^{-2}.day^{-1}$ (maximum) in 2008 and 16.00 $MJ.m^{-2}.day^{-1}$ (minimum) in 2007. The correlation coefficient between global solar radiation and wind power density was computed to be 0.66162. It is therefore, possible to combine wind, hydro and solar power during the dry season when there is enough wind and long hours of sunshine. Small WT designers may use the results presented as a guide in selecting suitable Small WT's appropriate for Uasin-Gishu region.

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Table 1. Annual mean wind power density and solar power for the period 2004-2008

Year	Wind power (W/m^2)	Solar power (W/m^2)
2004	20.689	412.430
2005	30.544	430.317
2006	26.106	428.788
2007	24.947	430.188
2008	22.882	436.643

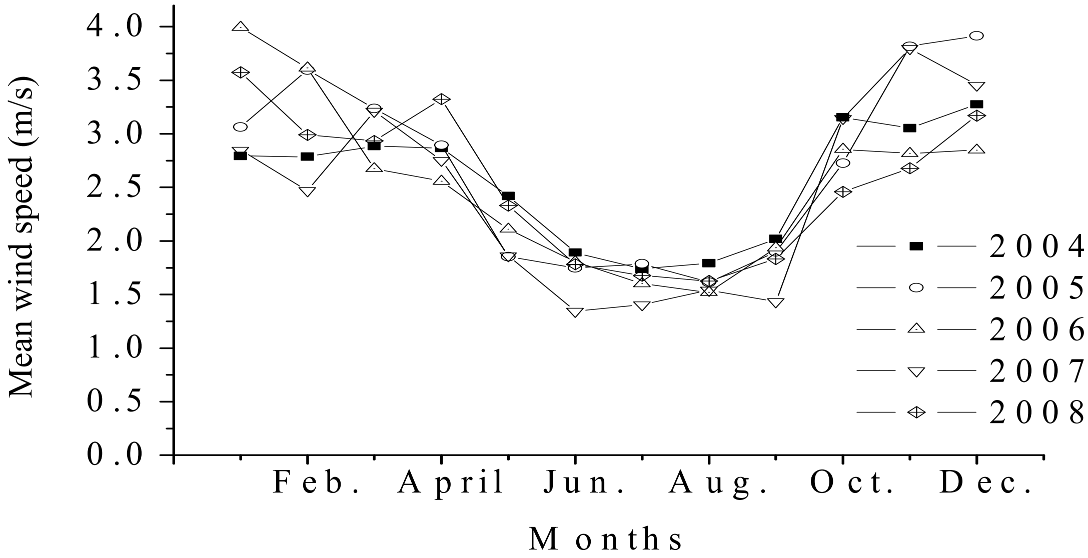

Figure 1: Monthly mean wind speeds from the year 2004 to 2008.

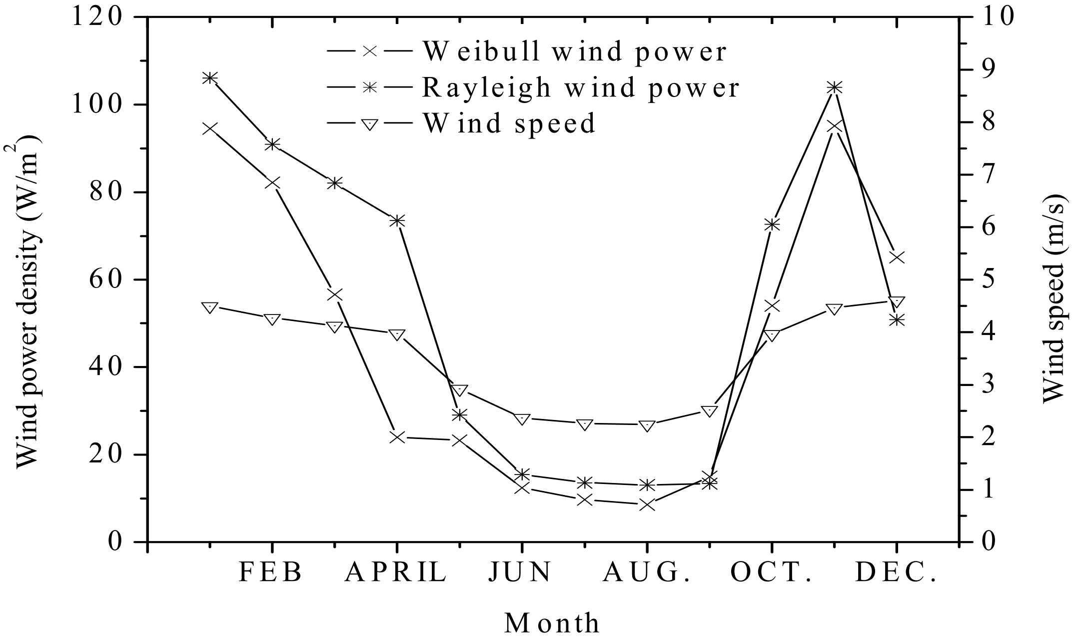

Figure 2: Wind speed, Weibull and Rayleigh wind power densities for the period 2004-2008.

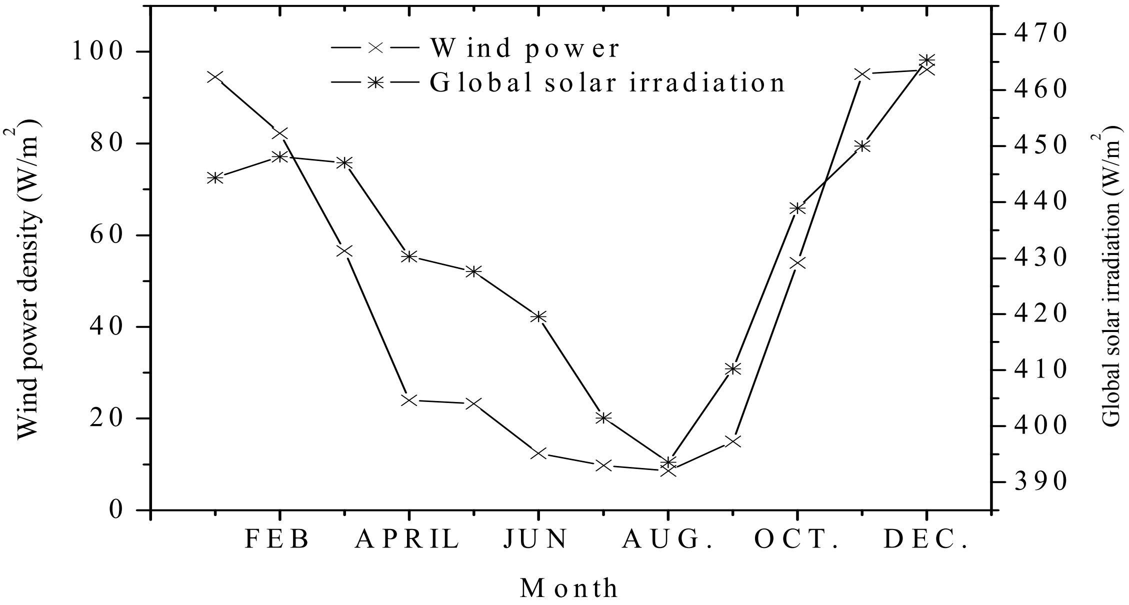

Figure 3: Relationship between wind power and solar power for the period 2004-2008.

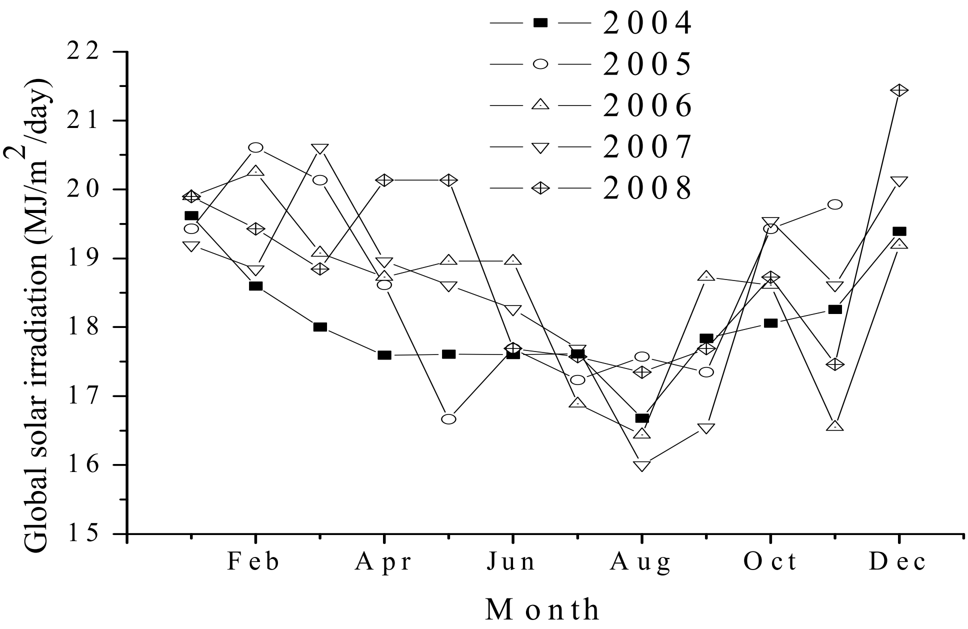

Figure 4: Global solar irradiation for each month for the period 2004-2008

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