AVAILABILITY OF DIRECT SOLAR RADIATION IN UGANDA

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Abstract

Investigation on the potential applications of concentrating solar energy systems and selection of optimum sites requires information on the geographical distribution of direct normal solar irradiance over an area of interest. Direct solar radiation data is best provided by measurements, but due to high cost of the pyreheliometers, many developing countries are without this instrument. The most common solar radiation parameter available at most Meteorological stations in Uganda is the sunshine duration measured mainly with the Campbell-Stokes sunshine recorder. The CSD1 Sunshine Duration sensors are used in a few places in Uganda. Using solar radiation models, we developed an hourly direct solar radiation distribution for Uganda from measured data of daily sunshine duration and daily global and diffuse solar radiation available. Comparison between the model and measured direct hourly solar radiation gave a MBE and RMSE of -0.112 and 0.22 kW/m^2 respectively. Hourly direct normal solar radiation intensities of the order of 500 W/m^2 can be expected as early as 0900 hours and as late as 1600 hours for locations in the eastern and northern regions of Uganda. This is between October and March. The intensities of direct solar irradiance are higher in eastern and northern regions.

Keywords: hourly direct solar irradiance, solar radiation, sunshine duration

Nomemclature

Symbol	Quantity
a_1, a_2	Empirical constants
$\overline{H}$	Monthly average daily global solar radiation
$\overline{H}_d$	Monthly average daily diffuse solar radiation
$\overline{H_o}$	Monthly average daily global to extraterrestrial solar radiation
I_b	Hourly direct solar radiation on a horizontal surface
$I_{d,h}$	Hourly diffuse irradiance on a horizontal surface
I_h	Hourly global irradiance on a horizontal surface
I_{bn}	Hourly direct normal solar irradiance
I_{sc}	Solar constant
$\overline{n}$	Monthly mean daily sunshine duration
$\overline{N}$	Maximum possible sunshine duration
φ	Latitude
δ	Declination
θ_z	Zenith angle

ω_i **and** ω_s	Hour angle and Sunset hour angle

1. Introduction

Concentrating Solar Power (CSP) technologies is currently being used in different parts of the world and they are considered an effective tool for solar energy conversion as reported by National Renewable Energy Laboratory, 2011 and Duffie and Beckman, 1991. CSP systems design mainly consists of a concentrator, a tracking mechanism to direct the concentrator towards the Sun, and an energy storage sub-system that is used to correct the mismatch between periods of availability and demand for energy. Lovseth, 1997 and Lovseth, 2000 proposed the construction and development of a solar energy cooking system with heat storage. To determine the potential use of such a system in a given area, information of the amount of direct normal solar irradiance and its spatial and temporal variability are of great importance. A good knowledge of the distribution of direct normal solar irradiance is essential in designing optimum energy storage for CSP systems and in planning for back up energy sources during bad weather periods.

Solar radiation data for a given area are best provided by measurements. The World Meteorogical Organisation recommend the use of a Pyreheliometer for measurements of direct solar radiation. However, due to the high cost of this equipment, measurements of direct solar radiation are scare. Most of the available meteorological data is the sunshine duration data recorded uisng Campell-Stokes sunshine recorder and CSD1 sunshine duration sensors. In an attempt to provide estimates of the amount of hourly direct solar irradiance and how they are distributed in a particular area, different models have been developed by researchers that estimate direct normal solar irradiance from other solar radiations parameters (Actor and Jorgen, 2009; Hove and Gotsche, 1999; Serm, 2010 and Liu and Jordan, 1960).

A substantial amount of solar radiation is received within the Equatorial region throughout the year. This makes this region a potential candidate for solar energy applications. For one to make an effective design of a concentrating solar energy system, data of hourly direct solar radiation distribution is needed. These data is of interest in modelling and assesing the performance of solar concentration systems. One way of achieving this is to present these data as maps of monthly mean hourly direct solar radiation. Locations with high intensities of hourly direct solar irradiance are required for solar industrial development. The objective of this study is develop a monthly mean hourly direct solar irradiance distribition for an Equatorial region (Uganda).

1. Materials and Methods

2.1 Overview

All the stations considered in this study are in Uganda which is located within the equatorial region and lies between latitudes 01^o 30\`S and 04$^o$ 00\`N, and longitudes 29^o 30\`E and 35$^o$ 00\`E. The perimeter and area of Uganda is 16,630km and 241,500 km^2 respectively. Most part of Uganda lies at altitudes between 900m and 1,500m, the highest point being at 5,029m and the lowest at 620m as provided by Langlands, 1974. The stations considered in this study are shown in Table 1 with their respective coordinates. They have been arranged in the order of increasing latitude.

In this study, data of global and diffuse solar radiation measurements being carried at four selected locations across the country using pyranometers starting 2003 was used. In addition, one of the station (Kampala) has a Pyreheliometer that is configured to measure hourly direct solar radiation. The Pyreheliometer data is used to validate the model. The data from six other stations were got from the Meteorogical Department that has been measuring daily sunshine durations and other climatic parameters like daily maximum and minimum temperatures, relative humidity, cloud cover, and rainfall for over 30 years. The instrument used for sunshine durations measurements at these sites is the Campbell-Stokes sunshine recorder.

Table 1: Showing different locations across the country from which solar radiation data where obtained.

	Station	Latitude	Longitude (deg. East)	Altitude (m)	Solar radiation data
1	Kabale	-1.25	29.98	1869	Sunshine duration
2	Mbarara	-0.62	30.65	1413	Global, diffuse and sunshine duration *
3	Entebbe	0.05	32.45	1155	Sunshine duration
4	Kasese	0.18	30.10	959	Sunshine duration
5	Kampala	0.32	32.58	1220	Global, diffuse, direct and sunshine duration *
6	Jinja	0.45	33.18	1175	Sunshine duration
7	Tororo	0.68	34.17	1170	Global, diffuse and sunshine duration *
8	Masindi	1.68	31.72	1147	Sunshine duration
9	Soroti	1.72	33.62	1132	Sunshine duration
10	Lira	2.28	32.93	1189	Global, diffuse and sunshine duration*

*Sunshine duration data recorded with CSD1 sunshine recorder

The Angstroms (1924) type correlation developed by Mubiru, 2006, recommended Uganda climate was used to determine the monthly mean daily global and diffuse solar radiation at locations with only sunshine duration measurement. The correlation is expressed as: $\frac{\overline{H}}{\overline{H}_o} = 0.019 + 1.295(\overline{n}/\overline{N}) - 0.548(\overline{n}/\overline{N})^2$ (eq. 1)

Values of $\overline{N}$ used in the above equation were computed from Cooper, 1969 formula given by

$$\overline{N} = (2/15)\cos^{-1}(-\tan\phi\tan\delta) \quad \text{(eq. 2)}$$

$\overline{H}_o$ were obtained from the relationship

$$\overline{H}_o = \frac{24}{\pi} I_{sc}(1 + 0.33\cos\frac{360\overline{n}}{365})(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta) \quad \text{(eq. 3)}$$

The sunset hour angle and the declination are given by the following expressions

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad \text{(eq. 4)}$$

$$\delta = 23.45\sin(360\frac{284+n}{365}) \quad \text{(eq. 5)}$$

The average day numbers of the month n used in this computation are shown in the Table 2.

Table 2: Showing the average day number of the month

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
n	17	47	75	105	135	162	198	228	258	288	318	344

Adapted from Duffie and Beckman [2]

To determine the monthly mean daily diffuse from sunshine hour's record, the correlation developed by Mubiru and Banda, 2007 of the form:

$$\frac{\overline{H}_d}{\overline{H}_o} = a_1 + a_2(\overline{n}/\overline{N}) \quad \text{(eq. 6)}$$

These coefficients for the diffuse correlations was found to be site dependent and therefore no single correlation could be used for estimating diffuse irradiation distributions at different locations in Uganda. The coefficients obtained from four stations with diffuse solar radiation measurements are shown in Table 3.

Table 3: Empirical coefficients for determining diffuse irradiance in Uganda

	Mbarara	Lira	Kampala	Tororo
a_4	0.314	0.383	0.236	0.359
a_5	-0.123	-0.136	-0.013	-0.238

In this study we have assumed closer stations with similar climatic paramaters to have the same coefficients for diffuse correlation.

2.2 Estimation hourly normal direct solar radiation

The hourly direct normal radiation can be estimated from the knowledge of hourly hemispherical radiation on a horizontal plane , and hourly diffuse radiation on horizontal plane using the relationship $I_{bn} = \frac{I_h - I_{d,h}}{\cos\theta_z}$ (eq. 7)

Values for the hourly global and diffuse can be determined using the Collares-Pereira and Rabl, 1979 conversion r_t and r_d factors for estimating average hourly insolation from average daily insolation expressed by:

$$r_t = \frac{\overline{I}_h}{\overline{H}_h} = \frac{\pi}{24}\frac{\cos\omega_i - \cos\omega_s}{\sin\omega_s - (\omega_s \frac{\pi}{180})\cos\omega_s}(a_r + b_r\cos\omega_i) \quad \text{(eq. 8)}$$

and $r_d = \frac{\overline{I}_{d,h}}{\overline{H}_d} = \frac{\pi}{24}\frac{\cos\omega_i - \cos\omega_s}{\sin\omega_s - (\omega_s \frac{\pi}{180})\cos\omega_s}$ (eq. 9)

where $a_r = 0.409 + 0.5016\sin(\omega_s - 60^o)$ and $b_r = 0.6609 - 0.4767\sin(\omega_s - 60^o)$

The hourly conversion factors, r_t and r_d are corrected to safisfy the requirement that:

$$\sum_{day} r_t \overline{H}_h = \overline{H}_h \quad \text{and} \quad \sum_{day} r_d \overline{H}_{d,h} = \overline{H}_{d,h} \quad \text{(eq.10)}$$

Interference of direct solar radiation at low solar altitudes by tall buildings, trees and other obstables, was accounted for by setting computation limits to $-82.5^o \leq \theta_z \leq 82.5^o$.

2.3 Statistical methods used for data validation

There are numerous statistical methods available in solar energy literature which deals with the assesment and comparison of solar radiation estimation models Iqbal (1983). In the present study, the statistical indicators used to evaluate the accuracy of the correlation with the measured data are the mean bias error (MBE) and the root mean square error (RMSE). The MBE test gives information on the long-term performance of a correlation. A low MBE is desired. A positive value implies an average amount of overestimation in the calculated value and vice versa. Overestimation of an individual observation can cancel underestimation in a separate observation. The MBE is given by $MBE = \frac{1}{n}\sum_{i=1}^{n}(X_{i,cal} - X_{i,meas})$ (eq. 11)

$X_{i,cal}$ being the *i*th calculated value, $X_{i,meas}$ is the *i*th measured value and *n* is the total number of observations.

The RMSE value is computed from $RMSE = \left(\frac{1}{n} \sum_{i=1}^{n} (X_{i,cal} - X_{i,meas})^2 \right)^{1/2}$ (eq. 12)

The RMSE gives information on the short-term performance of a given correlation. It allows term by term comparison of the actual deviation between the calculated and the measured values. The smaller the RMSE, the better the model's performance.

3. Results and Discusion

3.1 Monthly Sunshine Distribution in Uganda

The distribution of monthly averages of daily sunshine duration at different locations is shown in figure 1. Monthly mean daily sunshine duration varies between 4 and 9 hours. Observation indicates that Soroti, Tororo and Lira exhibit higher values of sunshine duration compared to other stations. This shows that the northern and eastern part have relatively higher insolation compared to the southern and south western part of Uganda.

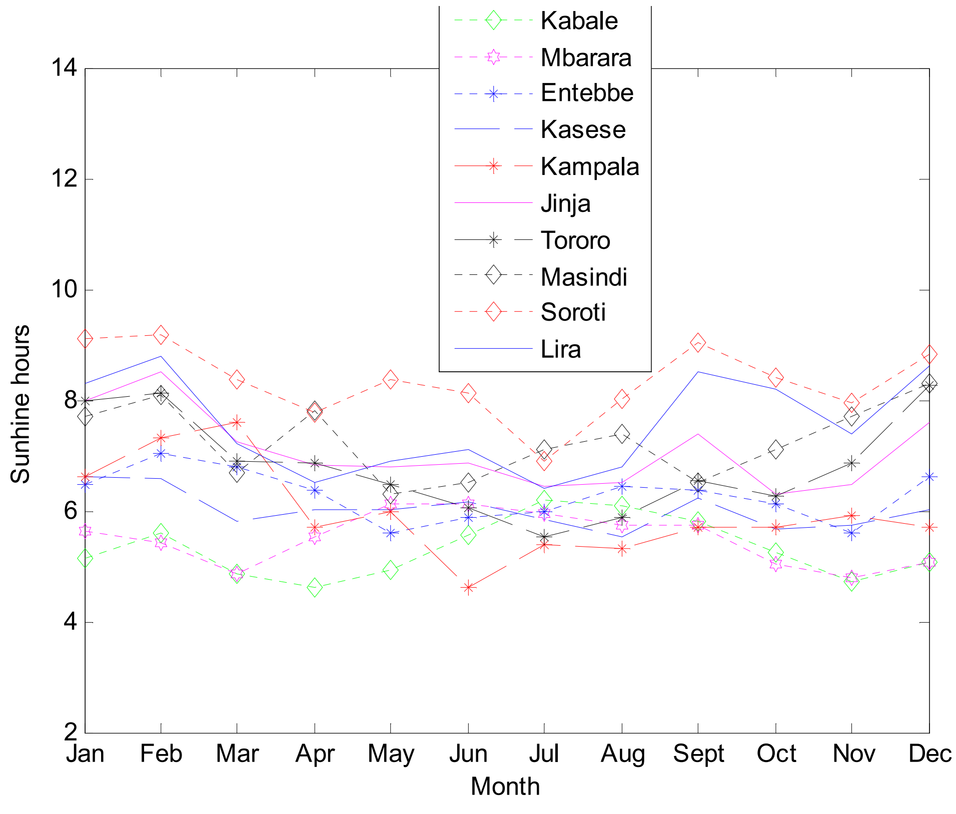

Figure 1: Distribution of monthly average daily sunshine duration across some selected stations in Uganda

3.2 Monthly average distribution of direct solar radiation

The distribution of monthly mean daily direct solar irradiance in Uganda is shown in figure 2. South-western region received less direct solar radiation compared to the eastern and northern part of Uganda. More direct solar radiation is received between December to March mainly in the northern and eastern part of Uganda. Kabale recieves the lowest intensity of direct solar radiation.

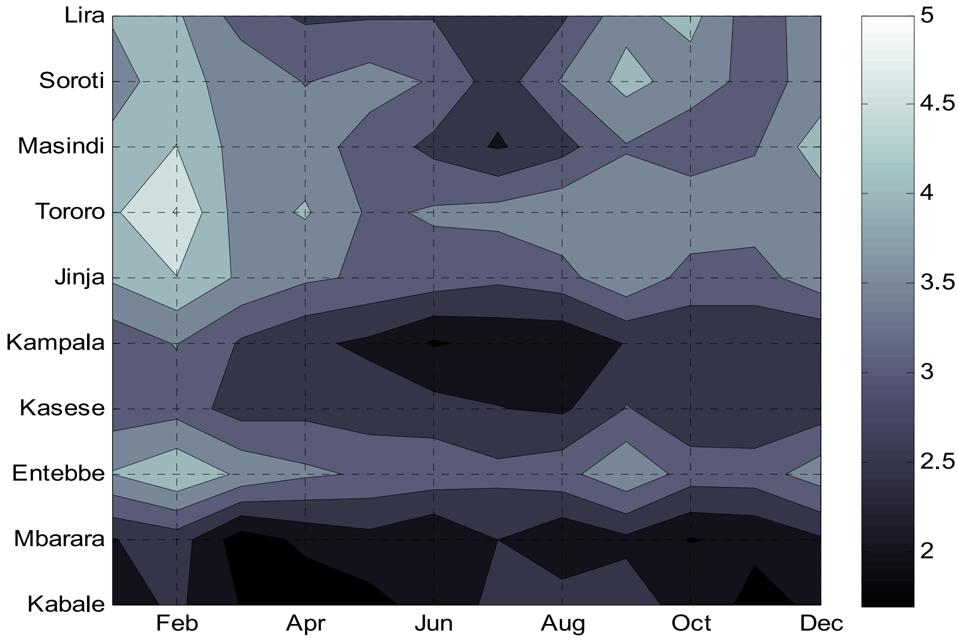

Figure 2: Estimated distribution of monthly mean daily direct solar radiation in Uganda.

3.3 Monthly average hourly distribution of direct solar radiation

Estimates of monthly mean hourly direct solar radiation obtained using Collares-Perriera and Rabl, 1979 model from sunshine hour data in Kampala were compared with clear days data measured using a Pyreheliometer through calculation of MBE and RMSE. Results gave a MBE and RMSE of -0.112 and 0.22 kW/m^2 respectively. Based on the MBE results, the model underestimates the distribution of hourly direct solar irradiance on a clear day in kampala. This is mainly because the model estimates hourly direct solar irradiance from the monthly mean daily irradiance and it does not account for days with intermittent cloud cover or heavy cloud cover for part of the day. The model results can therefore be treated as the minimum of direct solar radiation that can be expected from a given area on a clear day when used in designing of concentrating solar energy systems.

The distributions of hourly direct solar irradiance at different locations are given in figures (3-7). These figures are given in order of increasing latitudes. Direct solar irradiance of the order of 500 W/m^2 can be expected as early as 0900 hours to as late as 1600 hours for locations in the eastern and northern region, from around October to March. Direct intensity peaks of up to 700 W/m^2 and 600 W/m^2 are also observed in the eastern and northern regions between October and March. This implies that, application of active solar energy devices in these regions would require less backup energy sources during these months compared to other periods of the year. In general, eastern and northern regions of Uganda receive more radiation than southern and south-western regions.

Kabale and Mbarara received relatively low intensities of direct solar radiation which both locations experiencing a peak of about 400 W/m^2 in February. However in Kabale, more direct hourly solar radiation is experienced between July and September with a peak in August. Entebbe and Kasese received relatively more hourly solar radiation compared to Mbarara and Kabale with mean monthly hourly solar peaks at about 500 W/m^2. Tororo and Soroti received more hourly direct solar radiation compared to other stations with maximum peaks slightly above 700 W/m^2. This is typical of the north eastern part of Uganda which mainly dry with an annual rainfall as low 500 mm as reported by NEMA, 2000.

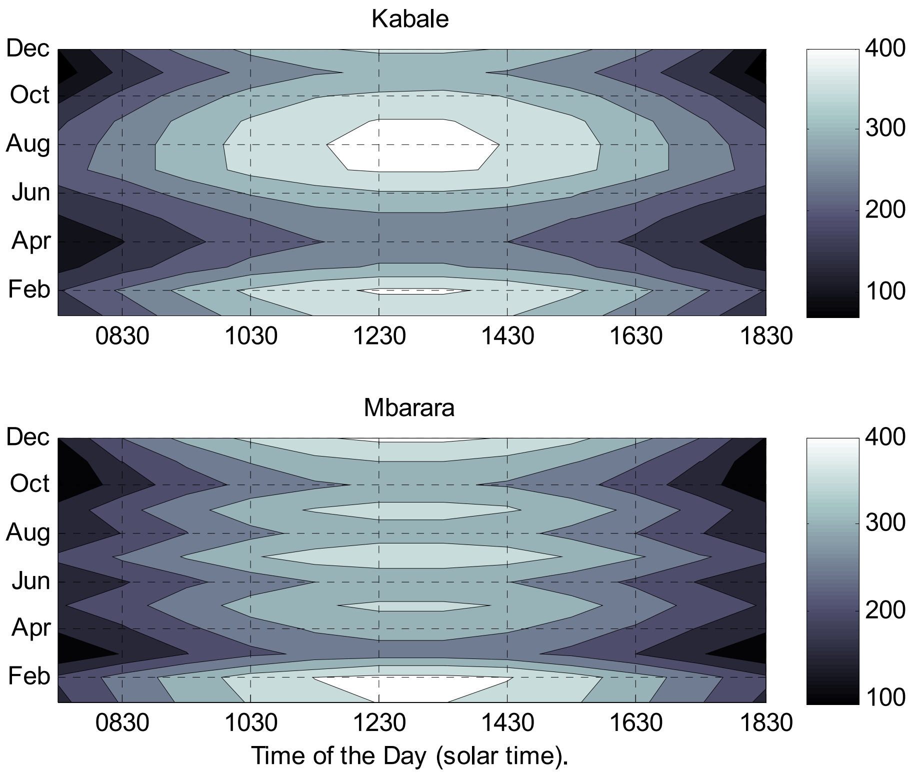

Figure 3: Monthly mean hourly distribution of direct solar irradiance in Kabale and Mbarara

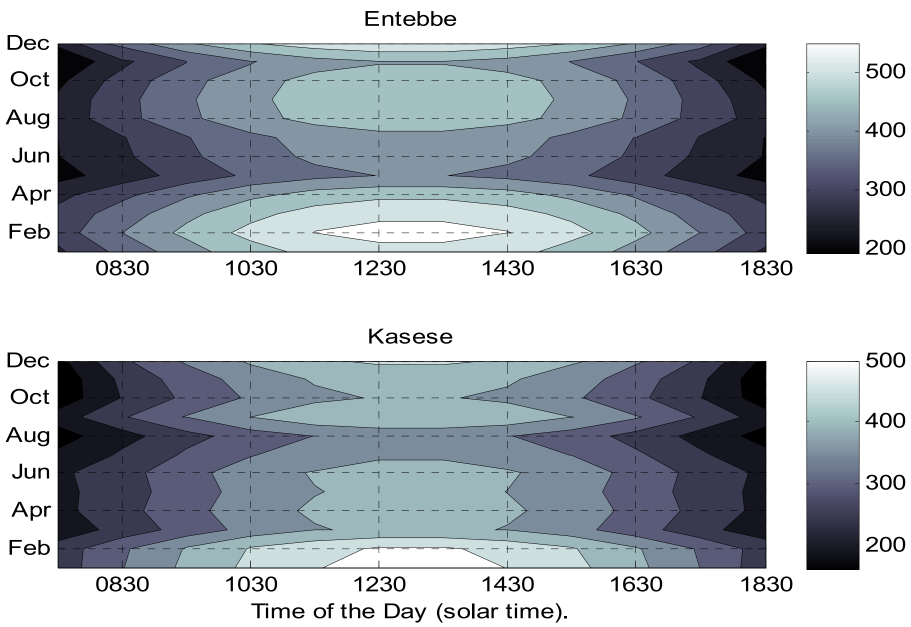

Figure 4: Monthly mean hourly distribution of direct solar irradiance in Entebbe and Kasese

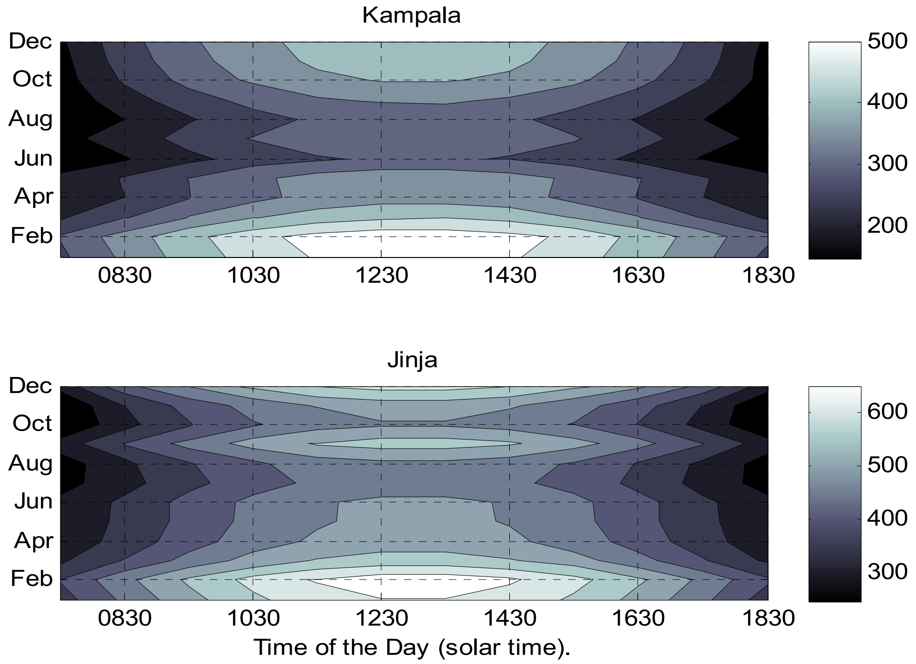

Figure 5: Monthly mean hourly distribution of direct solar irradiance in Kampala and Jinja

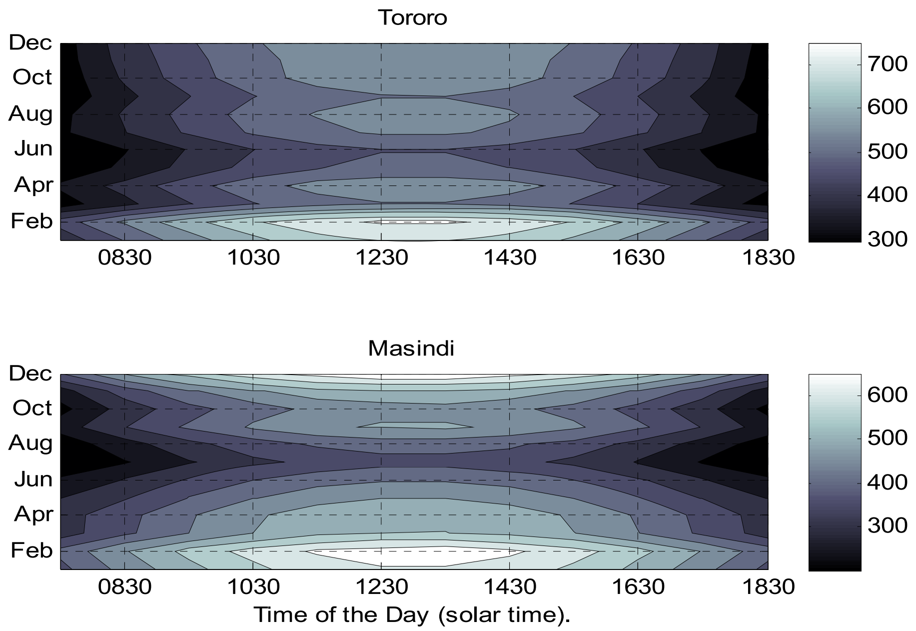

Figure 6: Monthly mean hourly distribution of direct solar irradiance in Tororo and Masindi

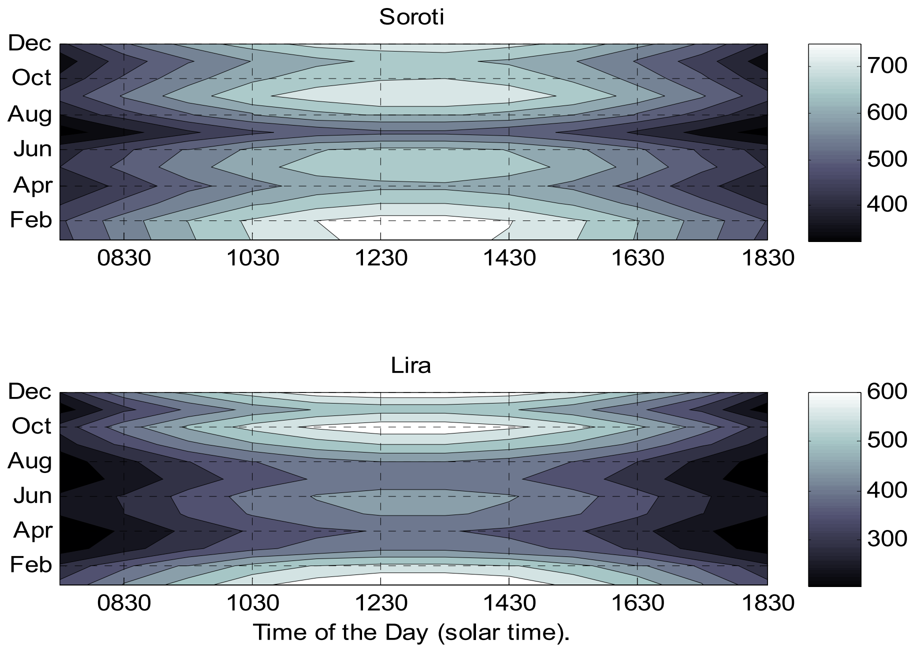

Figure 7: Monthly mean hourly distribution of direct solar irradiance in Soroti and Lira

4. Conclusion

We have developed hourly direct solar radiation charts for an African Equatorial location (Uganda). Values of monthly hourly direct irradiance estimated from this method and those obtained from measurement has a mean bias error of -0.112 kW/m^2 and a root mean square difference of 0.22 kW/m^2. Hourly direct solar irradiance estimated obtained from this method under estimate the radiation that is received on a clear day. Therefore estimates of hourly direct solar irradiance can be used as the minimum solar radiation that can be obtained on a clear day.

Location very closed to the equator received relatively lower intensity of direct hourly solar irradiance. The intensity of hourly direct solar radiation increases with latitude. More direct solar radiation intensities occurs between 1000 hours to 1600 hours implying that, concentrating solar energy devices should be designed to work effectively within this time range. More direct solar radiation is received from December to March in Uganda across most stations in Uganda.

References

Actor Chikukwa and Jorgen Lovseth, Temporal and Spatial availability of Solar Energy Resources in Zimbabwe, Proceeding of the ISES Solar World Congress 2009, pp 49-58.

Angstrom A (1924). Solar and terrestrial radiation. Q. J. R. Meteorol. Soc. 50, 121- 131.

Collares-Pereira M and Rabl A., (1979). Derivation of Method for Predicting Long-term Average Energy Delivery of Solar Collectors. Solar Energy

Cooper PI (1969). The absorption of Solar Radiation in Solar Stills. Solar Energy 12:3

Duffie J.A. and Beckman W.A., (1991). Solar Engineering of Thermal Processes, John Wiley and Sons, Inc.

Hove T and Gotsche J. Mapping global, difuse and beam solar radiation over Zimbabwe. Renewable Energy 18, pp 535-556, 1999

Iqbal M., 1983. An introduction to Solar Radiation, Academic Press Canada.

Langlands B. W., 1974. Uganda in maps. Parts II and III.

Liu, B. Y. H. and Jordan, R. C., 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy 4, 19.

Lovseth J., 1997. *Small, Multi-purpose Concentrating Solar Energy Systems for villages*. Procedings ISES 1997 Solar World Congress, Vol. 7, pp 108-117.

Lovseth J., 2000. *Small, multi-purpose concentrating solar energy system*. Proceedings of the 10th SolarPACES International Symposium on Solar Thermal Technologies "Solar Thermal 2000", Sydney, Australia, pp. 149-155.

Mubiru J., Banda E. J. K. B., Otiti T., 2004. Empirical Equations for the estimation of monthly average daily diffuse and beam solar irradiation on a horizontal surface. Discovery and Innovation Journal 16(3/4):157-164.

Mubiru, J., 2006. Development of an appropriate solar radiation model for Uganda, PhD thesis, Makerere University.

Mubiru J., Banda E.J.K.B., 2007. Performance of empirical correlations for predicting monthly mean daily diffuse solar radiation values at Kampala, Uganda. Theoretical & Applied Climatology, Vol. 88, No. 1-2, pp. 127-131.

National Renewable Energy Laboratory, in Golden, Colorado, USA. NREL Home page http://www.nrel.gov/solar, Accessed on 4th August 2011.

National Environment Management Authority, 2000/2001. State of Environment Report for Uganda.

Serm Janjai, 2010. A Method for Estimating Direct Normal Solar Radiation from Satellite Data for a Tropical Environment, Solar Energy, 84, 1685-1695