Comparative Study on Accuracy of Selected Solar Radiation Models against Measured Data under Tropical Climate

W K. CHERUIYOT[1]*, J K. TONUI[2], & S C. LIMO[3]
[1,2,3]*University of Eldoret, Department of Physics, P.O Box 1125-30100, Eldoret, Kenya*
**Tel: +254 0726 037818, E-mail: wilkinscheruiyot@gmail.com.*

Abstract: Solar radiation is the basic source of renewable energy in the environment and its measurement is very important, but ground-based measurements are lacking in most locations across the world due to high cost and calibration difficulties of measuring instruments. However, this limitation has been addressed fairly successfully using proposed predictive models to estimate radiation in regions with no measurements. As availability of solar radiation depends on climatic conditions of a locality, any empirical model selected should be calibrated for that specific region. Four prediction models were selected and validated with radiation data measured at a location in western Kenya for the purpose of recommending the most accurate model(s) for the site. Results revealed that all proposed models have relatively good estimation, but Angstrom-Prescott and Iqbal models are the most accurate for the site having the lowest values of MAPE of 8.5% and 8.9% and RMSE of 0.252.and 0.302 respectively.

Keywords: Solar, irradiance, model, measurement, prediction.

1. Introduction

Solar radiation is the basic source of renewable energy in the environment, and has been exploited since antiquity to date. Availability of solar radiation data are beneficial in areas of agriculture, water resources, day lighting and architectural design, solar conversion devices and climate change studies (Katiyar, *et.al*., 2010; Al-Kayiem & Mohammad, 2019). In solar energy conversion and utilization devices, for example, data on solar radiation and its components at a given location are very essential for their evaluation and deployment. These data are required in order to design and size a cost effective solar collector in terms of cost and energy demand of the load at the site. Unfortunately, there are only a few public meteorological stations in Kenya that measures the solar radiation, which is a norm in many developing countries. Luckily, for locations where measured data are lacking, either spatial interpolation of measured values from the few nearby meteorological stations or empirical/ regression equations proposed by various researchers in this field can be used to estimate the solar radiation. However, spatial interpolation is restricted to a radius of 30 km from the station and estimation models need to be validated with measured data at the location, since correlation coefficients are site/climate dependent (Al-Sanea, et.al., 2004). Solar radiation travelling from the sun through the sky until it reaches the surface of the earth has been classified into three components: global, beam and diffuse irradiance, often called sunshine in layman terms (Duffie & Beckmann, 2013). These components are usually measured using instruments called radiometers (e.g. pyrheliometer and pyranometer) in units of Wm^{-2} or kWm^{-2}

and when integrated over a day, give daily irradiation which is expressed in $MJm^{-2}day^{-1}$ or $kWhm^{-2}day^{-1}$. In addition, solar radiation varies both spatially and temporarily. Thus, for a given site and regardless of type, solar radiation can be quantified with respect to time as hourly, daily, monthly or annual averages (Cucumo, *et.al*, 2007). The temporal classification is necessitated by the fact that simulation models used for predicting performance or processes in different applications of solar energy require different temporal resolution or details of the available radiation data. For instance, daily global solar radiation reaching the earth surface at hourly basis (or even sub-hourly) is very important for analysis and simulation of performance of solar energy conversion and utilization devices, e.g. a photovoltaic (PV) module (Al-Sanea, 2004), but monthly averaged solar radiation data may be sufficient for agricultural applications.

Several models with varying degrees of complexity, detail and accuracy have been developed and used in different parts of the world to generate radiation data and its components. These models are based on either empirical correlations or statistical regression between satellite and/or ground measurements and various meteorological parameters (Kais, *et.al*, 2010; Doorga, *et.al.*, 2019). The most commonly used meteorological parameters are air temperature (Gairaa & Bakelli, 2013; Bocca, *et.al.*, 2018), relative humidity (Rao, et.al., 2012; Qing & Niu, 2018), precipitation (Yu, et.al., 2019; Maleki, et.al., 2017), cloudiness cover (Paulescu & Blaga, 2016) and bright sunshine duration (Muneer, 2014). Additional input parameters used are solar altitude, aerosol concentrations and global warming factor (Hocaoglu & Serttas, 2017; Despotovic, et.al., 2016). As correlation coefficients used in the models are climate dependent, it is required to adjust the model to account for local weather conditions so that it accurately predict available solar radiation at the real site. In this paper, four models for predicting horizontal global radiation were selected and validated with the ground measured data at a site in western Kenya. These models are Angstrom-Prescott, ASHRAE, Hargreaves-Samanni and Iqbal, which are based respectively on sunshine hours, sky clearness, ambient temperature and the atmospheric transmittance. Each model has got unique merits and demerits depending on the number and availability or ease of determination of predictor variable(s), whether it takes into account the local effects such as atmospheric transmittance, and finally if it requires calibration using local measurement of solar irradiation data (Doorga, et.al., 2009).

Radiation prediction models are expected to estimate as closely as possible the monthly average daily global solar irradiation on a horizontal surface from applicable meteorological parameters. The four selected models were chosen such that the mathematical expressions were diverse and involve input parameters that are easily available or determined at the site. The models considered can be grouped into three categories: sunshine, temperature and hybrid-parameter based models (Hofmann and Seckmeyer., 2017). The Angstrom-Prescott model was developed by Angstrom but was modified by Prescott, hence the name. Prescott simplified the equation by replacing clear sky global solar irradiation with extraterrestrial solar irradiation on a horizontal surface. The Angstrom-Prescott model assumed linear relationship between sunshine duration and solar radiation, but various researchers have reported better coefficients for second order (quadratic), third order (cubic), exponential, power and logarithmic fits (Doorga, et.al., 2009). Hargreaves-Samanni's model is based on air temperature (maximum and minimum) and most appropriate when data on sunshine hours is lacking. ASHRAE clear sky model offers a simple method and is widely used as a basic tool for solar heat load calculation for air conditioning systems and building designs by engineers and architects (Maleki, et.al., 2017). Iqbal model takes into account the scattering-transmittance of the atmosphere contributed by Rayleigh, ozone, gases, water and aerosol components (Wong & Chow, 2001). In this paper, data estimated from the four selected models were compared with solar radiation data measured for a period of one year at a location in western Kenya in order to recommend one that is more accurate for the site.

2. Materials and Methods

2.1 Study location

The study was carried out at a location in western Kenya with coordinates 0.42 N and 35.03 E, hence falls within tropical zone, and as such is expected to have abundant solar radiation throughout the year. The site has an elevation of 1993 m above mean sea level, ambient temperature varies between 18 ^{o}C to 22 ^{o}C, and average rainfall ranging from 1200 mm to 2000 mm per annum.

2.2 Experimental setup

Experimental set-up used in this study is part of a PV backup power system installed at a technical training institution in western Kenya. An SPM Pyranometer is mounted as part of the instrumentation and measures global solar radiation on a horizontal plane. Data is logged at intervals of five minutes, and the data logging system uses the sensitivity specified by the manufacturer to record data in irradiance units (i.e. W/m^2). Data collection is ongoing and the data presented here are for a period of one year, beginning from July 2019 to June 2020.

2.3 Selected models

a) Angstrom-Prescott model

This model correlates the extraterrestrial, H_o and terrestrial, H_s daily horizontal global solar radiation and sunshine duration as having linear relationship (Duffie & Beckmann, 2013):

$$H_s = H_o\left[a + b\left(\frac{S}{S_o}\right)\right] \tag{1}$$

where S is daily number of hours of bright sunshine, S_a is daily number of hours of possible sunshine (day light between sunrise and sunset). The parameters a and b are regression coefficients and their values depend on the altitude of the site and atmospheric transmittance and are given by (Duffie and Beckman, 2013):

$$a = 0.110 + 0.235\cos\varphi + 0.323\left(\frac{S}{S_o}\right) \tag{2}$$

$$b = 1.449 + 0.553\cos\varphi - 0.694\left(\frac{S}{S_o}\right) \tag{3}$$

The H_o in equation (1) is given by:

$$H_o = \frac{24}{\pi} G_{sc} \left[1 + 0.33\cos\left(\frac{360n}{365}\right)\right]\left[\cos\delta\cos\varphi\sin\omega_s + \frac{\pi\omega_s}{180}\sin\varphi\sin\delta\right] \quad (4)$$

where G_{sc} is solar constant (=1367W/m^2), ω_s is the sunset angle, φ is the latitude angle of the site, δ is the sun declination angle and n is the day number of year, with n = 1 for 1st January and n = 365 for 31st December (Bandyopadhyay, et.al., 2008).

b) ASHRAE model

ASHRAE clear sky model is given by (ASHRAE, 1985; Wong & Chow, 2001; Al-Sanea, et.al., 2004):

$$H_s = G_{sc} e^{(-A/\cos\phi_z)}(\cos\phi_z + B) \quad (5)$$

where A is the atmospheric extinction coefficient, B is the diffuse sky factor, and ϕ_z is the zenith angle. The coefficient A and $\cos\phi_z$ can be calculated respectively from (Basharat and Mohd, 2014):

$$A = 360(n-81)/365 \quad (6)$$

$$\cos\phi_Z = \cos\delta\cos\varphi\cos w_s + \sin\delta\sin \quad (7)$$

c) Hargreaves-Samanni's model

Hargreaves-Samanni's temperature-based model is given by (Hargreaves & Samani, 1982):

$$H_s = K_{RS}\left(\sqrt{T_{\max} - T_{\min}}\right)H_o \quad (8)$$

where K_{RS} is empirical coefficient related to atmospheric transmittance, and T_{max} and T_{min} are respectively maximum and minimum temperatures. The K_{RS} is included to account for possible pollution at the site with values of 0.16 (used in this study) and 0.19 respectively for inland and coastal sites.

The H_o in equation (8) is given by:

$$H_o = \frac{1440}{\pi} G_{sc} E_o (\omega_s \sin\varphi\sin\delta + \cos\delta\cos\varphi\sin\omega_s) \quad (9)$$

where E_0, the eccentricity correction factor of the earth's orbit and is expressed as (Wong & Chow, 2001):

$$E_0 = 1.0 + 0.033\cos 2\pi\left(\frac{n-1}{365}\right) \quad (10)$$

d) Iqbal model

Iqbal model is based on atmospheric transmittance and is given by (Iqbal, 1983; Batlles, et. al., 2000; Wong & Chow, 2001):

$$H = \left(0.9751 G_{sc} E_o \tau_s \cos\theta_z + H_d\right)\left(\frac{1}{1-\rho_g \rho_a}\right) \tag{11}$$

where the factor 0.9751 is included to show that spectral interval considered is 0.3-3 µm, τ_s is scattering-transmittance (equal to product of Rayleigh, ozone, gas, water and aerosol scattering fractions), and H_d is diffuse component contributed by Rayleigh and aerosols scattering after passing through the atmosphere. The parameters ρ_g and ρ_a are the ground and cloudless sky albedos. Evaluation of τ_s, H_d, ρ_a and other parameters are given elaborately by Wong & Chow (2001) and Batlles, et. al. (2000).

2.4 Comparisons techniques

Several statistical indicators have been proposed and used to test and compare estimated solar radiation data from different models with measured data. Among them are mean bias error (MBE), root mean square error (RMSE), absolute percent error (MAPE), coefficient of determination (R^2), *t*-statistic method (*t*-stat), among others (Toffalis, 2015; Al-Aboosi, 2020; Doorga, et. al., 2019). The MAPE and RMSE were selected for comparison in this paper.

The RMSE represents the sample standard deviation of the differences between estimated and measured values and is given as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(H_{i,r} - H_{i,e}\right)^2} \tag{12}$$

The MAPE is a measure of relative overall fit, and has the advantage of being scale-independent (Doorga, et. al., 2019):

$$MAPE = \frac{100}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{H_{i,r} - H_{i,e}}{H_{i,r}}\right)} \tag{13}$$

where $H_{i,r}$ and $H_{i,e}$ represent the i^{th} measured and estimated values respectively, and n is the number of observations.

3. Results and Discussions

3.1 Representative experimental results

Daily solar radiation on a horizontal surface was measured and recorded on hourly basis beginning from July, 2019 and is ongoing. Figure 1 shows typical representative measured data for two days, one representing a sunny or good day (26th January, 2020) and the other one representing a cloudy or bad day (29th June, 2020). These results represent the daily solar radiation available during the dry and rainy climatic seasons experienced at the site. From the sunny sky curve, it is evident that the peak solar radiation around midday can be as high as 1200 W/m^2, with average peak solar hour (PSH) of ~6 hours between 10 am to 4 pm. Thus, it can be inferred that the site is characterized by high amount of solar radiation, which is adequate for harnessing to supply clean energy, both electricity and thermal energy.

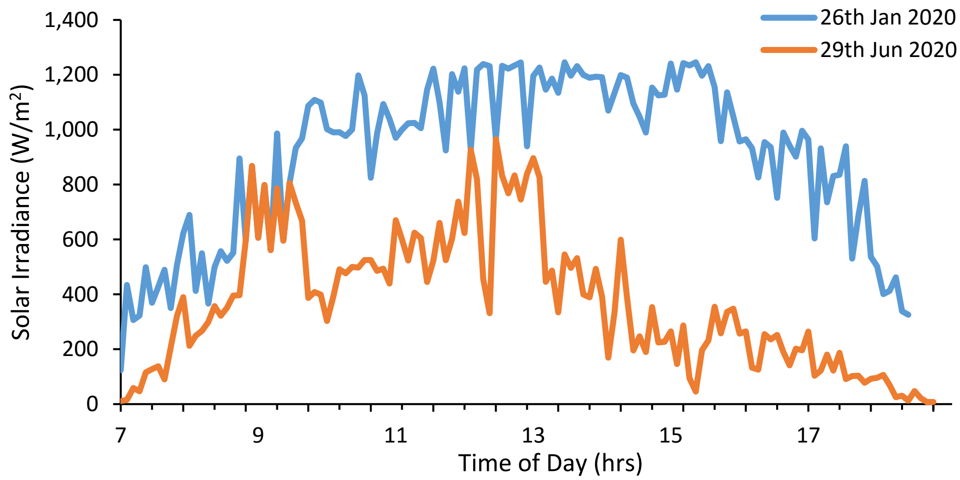

Figure 1: Typical daily solar irradiance for dry and wet seasons at the site.

Figure 2 shows the monthly average clearness index (K_T) evaluated for the site based the measured data. Clearness index is the ratio of the ground measured monthly daily average of horizontal global solar radiation, H and H_o in equation (2). It is used to partition months according to sky conditions as either cloudy (K_T < 0.3), partly cloudy (0.3 ≤ K_T ≤0.5) and sunny (K_T> 0.5) (Al-Aboosi, 2020). These results show that four months (April to July) of the year may be classified as partly cloudy and eight months (August to March) may be classified as sunny. Thus, chances of cloudy or overcast conditions at the site is low.

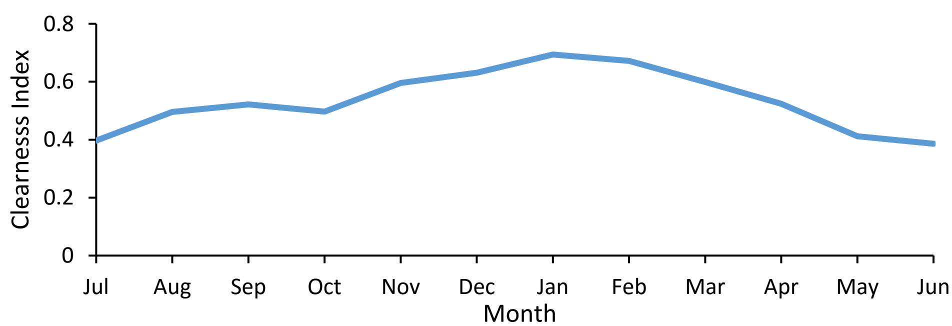

Figure 2: Monthly average clearness index.

3.2 Comparison of modelled and measured data

Figure 3 shows graphical or qualitative comparison of the monthly average of daily solar radiation between estimated data from the four models and the measured data for the one year period for the site. These results show that all the models underestimate the amount of solar radiation and hence will present undesirable consequences were these models used to estimate radiation at the site. For instance, using the estimated data to size any solar conversion device at the site will result to an oversized system, which will increase the capital cost of the system and unnecessarily prolong the payback period of the system. The Angstrom-Prescott and Iqbal models give closer estimated values to experimental values for all the months, followed respectively by ASHRAE and Hargreaves-Samanni. This means that Angstrom-Prescott and Iqbal models are more accurate for estimating the solar radiation for the site than the other two models.

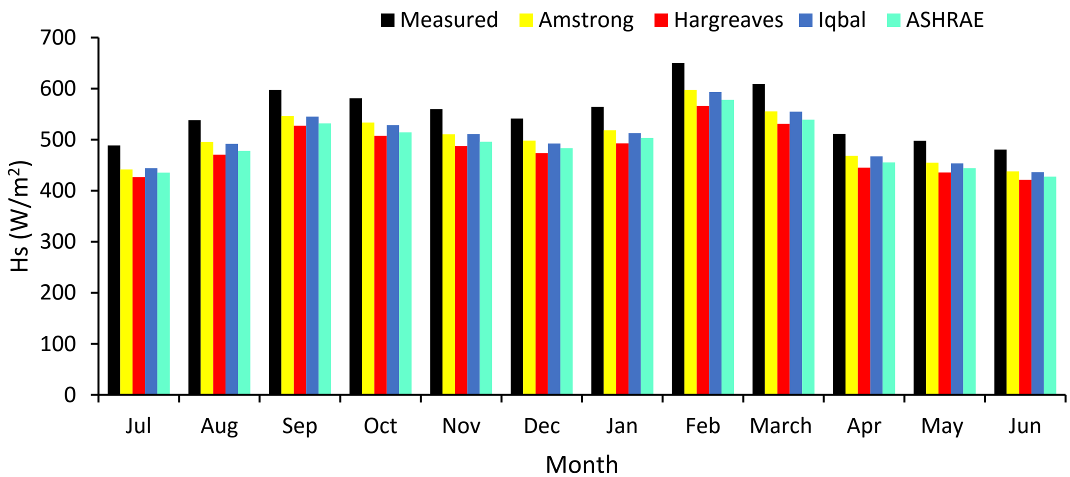

Figure 3: Comparison between estimated (by the four models) and measured values of monthly average daily global solar irradiance at the site.

3.3 Calculation of uncertainties

The accuracy and quality evaluation of models' performance were subjected to statistical tests for selecting the most precise model(s) under the climate of the site. The validation on the performance of the four models was done by comparing their estimated values of monthly average daily global solar irradiance against the measured data. Table 1 presents the performance tests of the four models selected as compared to the experimental data based upon the MAPE and RMSE statistical indicators.

Table 1: Results of testing the performance of the four models.

Month	Angstrom		ASHRAE		Hargreaves		Iqbal	
	MAPE	RMSE	MAPE	RMSE	MAPE	RMSE	MAPE	RMSE
Jul	9.6	0.111	10.9	0.21	12.7	0.114	9.1	0.165
Aug	7.9	0.231	11.2	0.112	12.6	0.123	8.6	0.462
Sep	8.6	0.562	11.0	0.145	11.8	1.035	8.8	0.165
Oct	8.2	0.321	11.5	0.732	12.7	0.601	9.1	0.633
Nov	8.8	0.145	11.4	0.561	12.9	0.532	8.7	0.126
Dec	8.0	0.124	10.7	0.085	12.5	0.096	9.0	0.125
Jan	8.1	0.217	10.8	0.365	12.7	0.325	9.1	0.187
Feb	8.1	0.521	11.1	0.119	12.9	0.356	8.7	0.822
Mar	8.8	0.317	11.5	1.023	12.8	0.723	8.9	0.124
Apr	8.4	0.117	10.9	1.823	12.9	0.117	8.6	0.562
May	8.6	0.214	10.8	0.256	12.5	0.692	8.9	0.098
Jun	8.9	0.154	11.0	0.113	12.3	0.127	9.2	0.156
Average	**8.5**	**0.252**	**11.0**	**0.462**	**12.6**	**0.403**	**8.9**	**0.302**

The MAPE test gives average monthly absolute uncertainties of 8.5%, 11.0%, 12.6% and 8.9% respectively for Angstrom-Prescott, ASHRAE, Hargreaves-Samanni, and Iqbal models. From the literature, a MAPE value of less than 10% is regarded as having a very good fit and hence provides a very good forecast (Doorga, *et. al*., 2019). Based on this criterion, Angstrom-Prescott is the best model for the site at 8.5%, followed very closely by Iqbal at 8.9% which are within the good limit. The other two models, however, are outside the good limit and in ascending order of uncertainties are ASHRAE and Heargreaves-Samanni models.

The RMSE test gives standard deviations of 0.252, 0.403, 0.462, and 0.302 respectively for Angstrom-Prescott, Hargreaves-Samanni, ASHRAE and Iqbal models. These test results again show that Angstrom-Prescott and Iqbal are the most accurate models for the site because of their lowest values of standard deviations. However, unlike MAPE test, Hargreaves-Samanni model performs better than ASHRAE model.

4. Conclusion

Availability of solar radiation plays an important role in the application of solar energy in any sector and location in the world. The scarcity of solar radiation database and the high cost of measurement equipment in most locations across the world has posed significant challenges regarding the exploitation and managing solar energy. However, a reprieve has been provided by the existence of several models that can be used to reliably estimate solar radiation data where measurements are sparse. The measured data in this study indicate that the site has high abundance of solar radiation which may be as high as 1200 Wm^{-2} on a sunny day with an average PSH of ~6 hours. Classification of clearness index of the site shows that two-thirds of the months of the year are sunny while one-third is partly cloudy, and there is no month with complete overcast. The region, therefore, has abundant solar radiation throughout the year, making it unequivocally amenable to harnessing solar energy as the prime source of energy. The MAPE test on the performance of the four models selected gave absolute uncertainties of 8.5%, 11.0%, 12.6% and 8.9% while RMSE test gave standard deviations of 0.252, 0.463, 0.403 and 0.302 respectively for Angstrom-Prescott, ASHRAE, Hargreaves-Samanni and Iqbal models. These results, therefore, show that all the four models have relatively good estimation of monthly average of daily global solar radiation. However, based on MAPE and RMSE tests, Angstrom-Prescott and Iqbal models predict the monthly average solar radiation with high accuracy than the other two models for this site. Thus, Angstrom-Prescott and Iqbal models are recommended for the site because they estimate the solar radiation data which are closer to the measured values than the ASHRAE and Hargreaves-Samanni models.

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