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Performance Evaluation and Comparison of Models for Predicting Global Solar Radiation in Ethiopia: A Case Study of Two sites

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Abstract

Accurate estimation of the global solar radiation on a horizontal surface at a place is essential to design and check the performance of solar energy devices. This study focused on evaluating monthly average daily global solar radiation (DGSR) and monthly average global solar radiation (GSR), as well as comparing the six models used in the estimations, over Lalibela and Sirinka in Northern Ethiopia. The best models were selected according to the values of statistical performance evaluation. For Lalibela the best model to estimate DGSR was LO-model with values of MBE=-0.092 KWh/m2day, RMSE= 0.402 KWh/m2day, MPE=-1,969 % and for Sirinka- GM model with values of MBE=-0.575 KWh/m2day, RMSE= 0.643 KWh/m2day, MPE=-9.764 %. The best estimator of monthly average GSR over Lalibela was AP model with values of MBE=0.159 KWh/m2day, RMSE= 0.245 KWh/m2day, MPE=2.802 % and for Sirinka- LO model with values of MBE=-0.007 KWh/m2day, RMSE= 0.522 KWh/m2day, MPE=0.033 %. At Lallibela site, the estimated monthly average DGSR range from 4.38 KWh/m2 (in August) to 7.16 KWh/m2 (in March) and the monthly average GSR estimated is 4.96 KWh/m2 (in July) and 6.69 KWh/m2 (in March). The estimated monthly mean DGSR range from a 3.80 KW/m2 (in January) to a 5.97 KW/m2 (in May) while the predicted monthly mean GSR varies from a 4.48 KW/m2 (in January) to a 6.75 KW/m2 (in May) for Sirinka site. Most importantly, results show that estimation of DGSR and GSR not only takes into account meteorological data but also includes the latitudinal difference between the sites (GM model) and values of Nnh (LO model). The overall results suggest that the sunshine based empirical models had better performance compared with the temperature based empirical models for both study sites. Finally, Lalibela site has a higher global solar radiation potential than Sirinka.

Keywords- Sunshine hours, temperature, latitude, potential.

Introduction

Ethiopia is situated very close to the equator (between 30° and 15° degrees North) and share enough amount of solar energy potential which is collected and put to use in the form of both thermal as well as electrical energy. The daily average total solar radiation over Ethiopia ranges from 5 to 8 KWh/m2 per day. The minimum average solar radiation for most of the country is about 5.3 kWh/m2 per day [1]. Such and other solar radiation data for a site are cornerstones of design, use, and choice of technology that can harvest the particular energy potential of the site. However, in most developing countries including Ethiopia, there are no properly recorded solar radiation data for most of the prospect sites. This is for technologies available for measuring the data are not only costly and complicated but also often result in instrumental hazards [2], [3]. These led to the development of several methods to estimate GSR, namely, a neural network [4]-[6], empirical models [4], [7]-[8], stochastic algorithm [4], [9], and satellite-based methods [4, 10]. Despite the current development in new methods and technologies, the empirical method utilizing meteorological data is preferred because of the cost and technical constraint imposed on new methods and technologies [7], [8], [11],12].

In the past, a few studies have implemented using sunshine based, temperature-based, both sunshine and temperature based, equations to estimate the GSR on a horizontal surface in some selected sites of Ethiopia [13], [14] - [20], Kenya [21], [22], Egypt [23]-[25], Nigeria [26]-[28], and in other countries throughout the world. So far, there are no studies which aim to estimate both monthly average DGSR and monthly average GSR using six empirical models at Lalibela and Sirinka, in Ethiopia. Therefore, the objectives of this work were estimating monthly average DGSR and monthly average GSR over Lalibela and Sirinka sites, in Ethiopia, and comparing the appropriateness of the six empirical models used.

The models compared with values of NASA as illustrated in table: 2 to table: 5, by using statistical techniques such as: MBE, RMSE, MPE, t-test, NSE and IA. According to statistical tests, GM model and LO model were more right to estimate the monthly average DGSR at Sirinka and Lalibela sites, sequentially than the rest of the models. LO model - at Sirinka site and AP model – at Lalibela site best models to about monthly average GSR as shown in table: 6. A very poor agreement was obtained from AN model and G models for both study places.

Materials and Methods

Study Sites and data collection

Weather data (sunshine hours, minimum temperature, and maximum temperature) were collected from Kombolcha Meteorological agency and analyzed for the two sites (Sirinka and Lalibela) in Ethiopia to select the right model for estimation of monthly average DGSR as well as monthly average GSR of each site. Sirinka is found in Habru district (woreda) and is located 508 Km from Addis Ababa on the main road to Mekele. Lalibela is one of the country's most famous and serene settings, beloved by tourists and Ethiopian orthodox Christians alike for its concentration of rock-hewn churches and located in North Wollo Zone of Amhara region, which is at 645 km from Addis Ababa. The distance between Sirinka and Lalibela is 137 Km.

Table: 1 Geographical location of the sites.			
Site	Latitude		
(degree)	Longitude		
(degree)	Altitude		
(m)			
Sirinka	11.75	39.60	1850
Lalibela	12.03	39.04	2444

Solar Radiation Models

Sun shine based model

The global solar radiation is mainly related to meteorological factors such as the duration of sunshine, extent of cloud cover, ambient temperature and so on [20]. For many developing countries like Ethiopia, solar radiation measurements are not easily available due to the high equipment cost, maintenance and calibration requirements of the measuring equipment. Therefore, there are very few meteorological stations that measure global solar radiation in Ethiopia [3].

Sunshine duration fraction models in 1924, a linear equation relating the clearness index and the sunshine duration fraction was proposed by Angstrom [28], [29] as shown below:

$$\frac{H}{H_c} = a + b\left(\frac{n}{N}\right)$$

Where (H)/H_c - the clearness index, H - the daily global solar radiation, H_(c)- the clear day global solar radiation, n/N - the sunshine duration fraction, n - the daily sunshine duration, N - the maximum daily sunshine duration, a and b are empirical coefficients.

Angstrom- Prescott model (AP)

Angstrom [30], [31] derived a simple linear relationship between the ratio of average daily R_s and the corresponding value on a completely clear day at a given location and the ratio of average daily sunshine duration to the maximum possible sunshine duration, which is the most widely, used correlation for estimating daily R_s[32]. Prescott [33] modified the method and proposed the following equation:

$$R_s = \left[a + b\left(\frac{n}{N}\right)\right] * R_a \qquad (2)$$

Where R_s - (MJ m^{-2} d^{-1}), R_a - (MJ m^{-2} d^{-1}), n - sunshine duration (hr), N- maximum possible sunshine duration (hr) and a and b are empirical coefficients and assumed [22], [29] as;

$$a = -0.11 + 0.235 * \cos(\varphi) + 0.323 * \left(\frac{n}{N}\right) \qquad (3)$$

and

$$b = 1.449 - 0.553 * \cos(\varphi) - 0.694 * \left(\frac{n}{n}\right) \qquad (4)$$

R_a is also provided as [34], [35];

$$R_a = \left(\frac{1440}{\pi}\right) G_{sc} d_r \begin{bmatrix} \cos(\varphi)\cos(\delta)\sin(\omega_s) \\ +\omega_s \sin(\varphi)\sin(\delta) \end{bmatrix} \qquad (5)$$

Where: G_{SC} is the solar constant (1367 W/m^2 or 0.082 MJ.m^{-2}) and d_r is the eccentricity correction factor of the earth's orbit which can be calculated using,

$$d_r = 1 + 0.033 \,\mathrm{Cos}\left[2\pi\left(\frac{\mathrm{Julianday}}{365}\right)\right] \qquad (6)$$

The variables φ, δ and ω_s, in the above equations, can be also calculated using their respective relations. φ (Latitude of the site) and, Solar declination (δ) are provided as;

$$\varphi = \mathrm{latitude}\left(\frac{\pi}{180}\right) \text{ and}$$

$$\delta = \left[\frac{23.45\pi}{180}\right] \sin\left[2\pi\left(\frac{284 + Julianday}{365}\right)\right] \text{ respectively.}$$

The other variable ω_s is mean sunrise hour angle calculable using the following expression;

$$\omega_s = \cos^{-1}[-\tan\varphi \ \tan\delta]. \qquad (7)$$

Finally, N, the maximum possible sunshine duration can be calculated using:

$$N = \frac{2\omega_s}{15} = \frac{2}{15}\cos^{-1}[-\tan\varphi \ \tan\delta] \qquad (8)$$

Louche model (LO)

Louche et al. [30], [37] have modified the AP model through the use of the ratio of (n/Nnh) instead of (n/N) and the equation is presented as follows:

$$R_s = \left[a + b\left(\frac{n}{N_{nh}}\right)\right] * R_a$$

$$\frac{1}{N_{nh}} = \frac{0.8706}{N} + 0.0003$$

Where a and b are the empirical coefficients.

Glover McCulloch model (GM)

Glover and McCulloch [30], [38] suggested the following model, which took into account the effect of latitude of the site as an additional input and was valid for < 60°:

R_s=[a*cos()+b*(n/N)]*R_a (10)

Where a and b are the empirical coefficients.

Temperature based Models

Hargreaves and Samani Model (HS)

Hargreaves and Samani [40] were the first to propose a procedure to estimate the global solar radiation by using the difference between monthly average of daily maximum and daily minimum air temperature and extraterrestrial irradiation. It is a single-parameter model and can be expressed in the form [41], [42]:

H/H_o =a*(ΔT)^0.5 (11)

Where ΔT - the difference between the monthly average of daily maximum and minimum air temperature (Tmax - Tmin). The coefficient a isregression constant. Later, Hargreaves [44] recommended using a = 0.16 for interior regions and a = 0.19 for coastal regions.

Garcia Model (G)

Garcia proposed a single-parameter model for estimating global solar radiation in 1994. Garcia model is an adaptation of AP model with a slight modification that makes it temperature-based type expressed in the form:

$$\frac{H}{H_o} = a + b * \left(\frac{\Delta T}{N}\right) \qquad (12)$$

Where (a, b) are regression constants to be determined and Δ the difference between maximum and minimum temperature values [41], [44].

Allen Model (A)

This model is special type of Hargreaves and Samani. If the coefficient "a" is equal to zero, then the relationship of Hargreaves turns to simple equation based on air temperature differences and is given as [45].

$$\frac{H}{H_o} = b * (\Delta T)^{0.5} \qquad (13)$$

Where b- empirical coefficient.

Performance Evaluation of models

The accuracy or validation of the estimated values was statistically tested by computing the MBE, RMSE, MPE, t-test, NSE and the IA. The expressions for the MBE, RMSE and MPE as stated according to El-Sebaii and Trabea [46] are given as follows;

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(H_{i,cal} - H_{i,mea}\right)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(H_{i,cal} - H_{i,mea}\right)^2\right]^{1/2}$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_{i,cal} - H_{i,mea}}{H_{i,mea}}\right) * 100$$

The t-test defined by student [2], [47] in one of the tests for mean values, the random variable t with n-1 degrees of freedom may be written as follows.

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}\right]^{1/2}$$

The Nash-Sutcliffe equation (NSE) and the Index of Agreement (IA) are given as [2];

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(H_{i,mea} - H_{i,cal}\right)^2}{\sum\left(H_{i,mea} - \bar{H}_{mea}\right)^2}$$

$$IA = 1 - \frac{\sum_{i=1}^{n}\left(H_{i,cal} - H_{i,mea}\right)^2}{\sum_{i=1}^{n}\left(\left|H_{i,cal} - \bar{H}_{mea}\right| + \left|H_{i,mea} - \bar{H}_{mea}\right|\right)^2}$$

In equation (14) - (19); H i,mea - measured and Hi,cal - calculated values of monthly averaged global solar radiation and n- the total number of observations, also H mea - the mean measured global radiation.

Chen et al. [2], [48] have recommended that a zero value for MBE is ideal and a low RMSE and MPE are desirable. The smaller the value of the MBE, MPE and RMSE the better is the model's performance, a positive MPE and MBE values provide the averages amount of overestimation in the calculated values, while the negative values gives underestimation. The percentage error between -10% and +10% is considered acceptable [2], [49]. The smaller the value of t-test the better is the performance. High value of NSE and IA are desirable. The MBE and the RMSE are in MJm-2day-1, while MPE, NSE and IA are in percentage (%), the t-test is non dimensional.

Discussion and Results

In this study, six empirical-based models (three sunshine and three temperatures) were evaluated and compared. The monthly mean DGSR and monthly mean GSR estimated on a horizontal surface for two study sites (Lalibela and Sirinka) in Ethiopia during the three years (2014-20160. These models compared with values of NASA by using statistical techniques such as MBE (KWh/m2day), RMSE (KWh/m2 day), MPE (%) , t-test (non-dimensional), NSE(%), and IA (%). The results of the study illustrated in the table: 2 to table: 6 as well as in figure: 1 to figure: 4 for both study sites

Monthly average daily values of NASA (spatial resolution from NASA/

Month	AP-d (KW/m²)	LO-d (KW/m²)	GM-d (KW/m²)	HS-d (KW/m²)	G-d (KW/m²)	AN-d (KW/m²)	NASA-d (KW/m²)
January	5.84	5.6	5.41	4.89	6.94	8.57	5.47
February	6.33	6.08	5.87	5.5	7.55	9.63	5.67
March	7.34	7.16	6.77	5.9	9.17	10.33	6.44
April	7.36	7.08	6.8	5.77	9.38	10.38	6.86
May	5.75	5.57	5.43	5.67	8.43	9.93	6.1
June	5.74	5.49	5.36	5.49	7.59	9.31	5.59
July	4.7	4.47	4.4	5.01	7.5	8.77	5.02
August	4.6	4.38	4.29	4.8	7.56	8.42	4.96
September	5.54	5.29	5.18	5.11	7.58	8.86	5.66
October	5.91	5.66	5.5	5.38	8.08	9.45	5.77
November	5.79	5.55	5.37	4.99	7.15	8.75	5.59
December	5.57	5.35	5.16	4.72	6.68	8.27	5.65

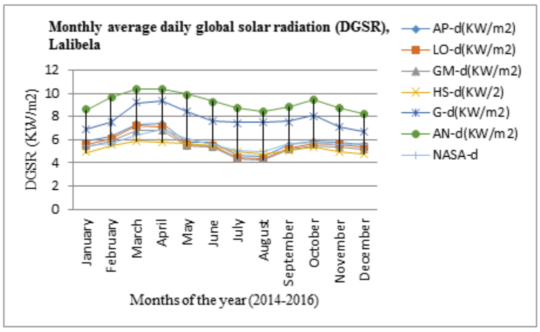

Figure: 1 Monthly average daily global solar radiation at Lalibela, Ethiopia (2014-2016).

POWER database for all sky condition) and the estimated monthly average DGSR for each model shown in table: 2 and Figure: 1, for Lalibela, Ethiopia. According to statistical performance evaluation, there is an agreement between the monthly average DGSR and the monthly average values of NASA. The best agreement was found for the LO model. Next to the LO model, the best model was AP and GM models to estimate monthly average DGSR. The AP and GM models were applicable equally for this site in the study period (2014 – 2016). As indicated in table: 2 and in figure: 1, the least monthly average DGSR on a horizontal surface occurred in August (4.38 KW/m2), July (4.47 KW/m2) and September (5.29 KW/m2) in order. The largest monthly average daily global solar radiation was found in March (7.16 KW/m2), April (7.08 KW/m2), and February (6.08 KW/m2) for Lalibela, Ethiopia

Table 3: Monthly average global solar radiation, Lalibela, Ethiopia from 2014-2016

Month	AP-m (KW/m²)	LO-m (KW/m²)	GM-m (KW/m²)	HS-m (KW/m²)	G-m (KW/m²)	AN-m (KW/m²)	NASA-m (KW/m²)
January	5.93	5.48	5.5	4.89	6.98	8.49	5.35
February	6.33	5.84	5.87	5.48	7.64	9.5	6.09
March	6.69	6.16	6.23	5.9	8.4	10.24	6.64
April	6.68	6.13	6.24	5.94	8.5	10.3	6.68
May	6.39	5.86	5.97	5.68	8.54	9.86	6.26
June	5.66	5.15	5.33	5.51	7.91	9.55	5.75
July	4.96	4.54	4.64	5.03	7.6	8.72	4.96
August	5.01	4.59	4.68	4.83	7.4	8.38	5.02
September	6	5.51	5.61	5.04	7.81	8.34	5.58
October	6.36	5.86	5.92	5.41	8.36	9.39	6.2
November	6.01	5.55	5.58	5	7.27	8.68	5.77
December	5.69	5.26	5.28	4.71	6.74	8.18	5.51

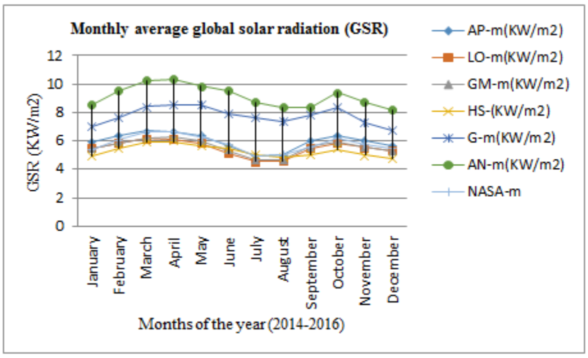

Figure: 2 Monthly average global solar radiation at Lalibela, Ethiopia (2014-2016).

According to statistical performance evaluation; the AP model, GM model, and LO models (agreed with values of NASA in order) were the best models to estimate the monthly average GSR at Lalibela, Ethiopia. The monthly average GSR at this site was least in July (4.96 KW/m2), August (5.01 KW/m2), and June (5.66 KW/m2) in order. The largest monthly average GSR occurred in March (6.69 KW/m2), April (6.68 KW/m2) and May (6.39 KW/m2) for this study site show that table: 3 and figure: 2.

Table 4: Monthly average daily global solar radiation, Sirinka, Ethiopia from 2014-2016.

Month	AP-d (KW/m²)	LO-d (KW/m²)	GM-d (KW/m²)	HS-d (KW/m²)	G-d (KW/m²)	AN-d (KW/m²)	NASA-d (KW/m²)
January	4.39	4.07	3.8	4.42	7.06	7.63	5.37
February	5.6	5.28	4.84	5.22	8.19	9.01	5.94
March	6.41	5.94	5.54	5.86	9.1	10.1	6.51
April	6.79	6.3	5.89	5.97	9.05	10.31	6.47
May	6.88	6.39	5.97	6.16	9.34	10.64	6.16
June	6.49	6.01	5.65	6.48	10.36	11.18	5.6
July	6.17	5.71	5.41	6.36	10.36	10.98	5.09
August	5.6	5.54	5.25	5.91	9.59	10.2	5.35
September	6.16	5.69	5.4	5.76	9.46	9.94	5.6
October	6.32	5.85	5.48	5.65	9.01	9.74	6.09
November	5.47	5.08	4.73	5.04	8.08	8.7	5.78
December	5.44	5.06	4.7	4.63	7.7	7.99	5.6

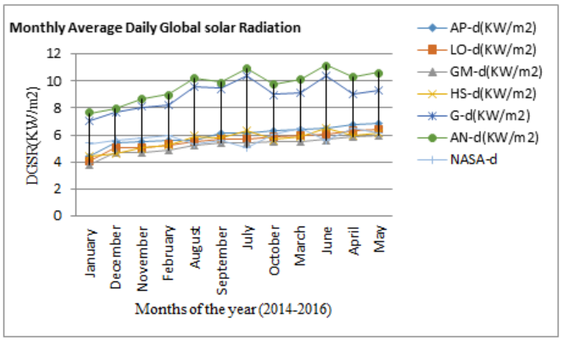

Figure: 3 Monthly average daily global solar radiation Sirinka, Ethiopia (2014-2016).

According to statistical techniques evaluation, the GM model was the best model to predict the monthly mean DGSR on a horizontal surface at Sirinka, Ethiopia. Next to the GM model, the best models were the Hargreaves -Samani Model (HS), LO model, and the AP model respectively in the study period of 2014-2016. The least monthly average DGSR on a horizontal surface was found in January (4.48 KW/m2), December (5.12 KW/m2), and November (5.4 KW/m2) in order. The largest monthly average DGSR occurred in May (6.75 KW/m2), April (6.34 KW/m2), and June (6.32 4.48 KW/m2) in order as illustrated in the table: 4 and figure: 3

Table-5: Monthly average global solar radiation, Lalibela, Ethiopia from 2014-2016.

Month	AP-m (KW/m²)	LO-m (KW/m²)	GM-m (KW/m²)	HS-m (KW/m²)	G-m (Kw/m²)	AN-m (KW/m²)	NASA-m (KW/m²)
January	4.55	4.48	4.26	4.48	7.5	7.64	5.37
February	5.99	5.54	5.22	5.26	8.49	8.98	6.09
March	6.8	6.29	5.94	5.89	9.44	10.05	6.51
April	6.84	6.34	5.94	5.79	8.95	9.87	6.47
May	7.3	6.75	6.34	6.18	9.52	10.55	6.16
June	6.85	6.32	6.02	6.5	10.53	11.08	5.71
July	6.49	5.98	5.72	6.35	10.41	10.83	5.14
August	6.32	5.83	5.58	5.93	9.67	10.11	5.34
September	6.36	5.87	5.6	5.79	9.54	9.88	5.67
October	6.54	6.05	5.7	5.67	9.18	9.68	6.16
November	5.84	5.4	5.1	5.06	8.38	8.64	5.84
December	5.53	5.12	4.82	4.67	7.57	7.97	5.6

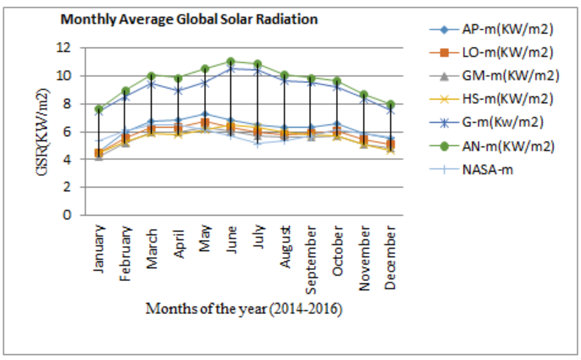

Figure: 4 Monthly average global solar radiation Sirinka, Ethiopia (2014-2016)

The acquired results in a table: 5 and figure: 4 show the comparison of monthly average GSR with monthly average values of NASA at Sirinka. According to statistical performance evaluations, the best models to estimate monthly average GSR on a horizontal surface were the LO, the HS, and the GM models sequentially. The least monthly average GSR was found in January (3.8 KW/m2), December (4.7 KW/m2), and November (4.73KW/ m2) in order. The largest monthly average global solar radiation on a horizontal surface was found in May (5.97 KW/m2), April (5.89 KW/m2), and June (5.65 KW/m2) sequentially at this study site.

Generally, the best models for estimation of DGSR at Lalibela, Ethiopia were the LO model, the AP model, and GM model sequentially in the study period of (2014-2016). However, the AP model and GM model equally applicable for this study site. For Sirinka, Ethiopia the best models to predict monthly average DGSR, were the GM model, the HS model, and LO models in order. The best estimator models of monthly average GSR were the AP model, the GM model, and LO model at the Lalibela site in order. For the Sirinka site the best models to predict monthly average GSR were the LO model, the HS model, and GM model in order.

Table 6: The minimum and maximum results of DGSR and GSR with best models, for Lalibela and Sirinka

sites	Minimum DGSR(KW/m²)		Best model	Maximum DGSR(KW/m²)		Best model	Minimum GSR(KW/m²)		Best model	Maximum GSR(KW/m²)		Best model
	Month	Value		Month	Value		Month	Value		Month	Value	
Lalibela	August	4.38	LO	March	7.16	LO	July	4.96	AP	March	6.69	AP
Sirinka	January	3.80	GM	May	5.97	GM	January	4.48	LO	May	6.75	LO

In this paper, a set of statistical performance evaluation methods such as: MBE (KWh/m2day), RMSE (KWh/m2 day), MPE (%), t-test (non-dimensional), NSE(%), and IA (%) used to assess the model performance for prediction of monthly average DGSR and monthly average GSR. Each method has its own strength and weakness to decide the performance of models. By assessing the overall these statistical techniques the best model selected for both study sites (Lalibela and Sirinka). Therefore, the most accurate model in estimating monthly average DGSR and monthly average GSR at Lalibela were LO with values of statistical tests (MBE=-0.092 KWh/m2day, RMSE= 0.402 KWh/m2 day, MPE=-1.969%, t-test = 0.779, NSE=38.1 and IA= 90.5%) and AP (MBE=0.159 KWh/m2day, RMSE = 0.245 KWh/m2 day, MPE = 2.802%, t-test =2.855 NSE= 80 % and IA = 95.1%) sequentially. For Sirinka- the most accurate model in predicting the monthly average DGSR and monthly average GSR was the

GM and LO with statistical performance values of ((MBE=-0.575 KWh/m2day, RMSE=0.643KWh/m2 day, MPE=9.764%, t-test = 6.596, NSE=70.9 % and IA= 66.4 %) and MBE=-0.007KWh/m2day, RMSE = 0.522 KWh/m2 day, MPE = 0.033 %, t-test =0.046, NSE= 0 % and IA = 80.1%) in order.

Conclusion

In this study, solar radiation models were reviewed for the choice of the most right model based on the available measured meteorological data (sunshine hours, minimum temperature, and maximum temperature), the value of Nnh, and latitude of the study place. These models were evaluated and compared based on the statistical error tests such as MBE, MPE, RMSE, t-test, NSE, and IA. According to these statistical error evaluations, the most suitable sunshine and temperature-based empirical models were compared for both locations (Sirinka and Lalibela). Finally, the following conclusions can be drawn from this study:

(i) In this study, the latitude of the site can play a role in the estimation of global solar radiation in addition to meteorological data. Thus, the GM model was the best model to estimate the monthly average DGSR at Sirinka.

(ii) The value of Nnh also essential to estimate GSR. Therefore, the LO model was the best model to estimate the monthly average DGSR for the Lalibela site as well as the monthly average GSR for Sirinka.

(iii) The AP model more suitable to estimate monthly average GSR for Lalibela from those proposed models.

(iv) The better global solar radiation was found at the Lalibela site than the Sirinka site.

The most accurate and proper empirical models mentioned in this paper will allow the solar energy researcher as well as other researchers to use them. It concludes that the empirical models recommended for this work are applicable in anyplace with a similar geographical location throughout Ethiopia. Overall, sunshine based empirical models were found more suitable for estimating monthly average DGSR as well as monthly average GSR at both study sites.

Acknowledgment

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Conflict of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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