JREE: Vol. 8, No. 1, (Winter 2021) 69-76

Journal of Renewable Energy and Environment

Research Article

Journal Homepage: www.jree.ir

Development of a Model for Estimation of Sunshine Hour Data for Different Regions of Uganda

Muhamad Mustafa Mundu[a*], Stephen Ndubuisi Nnamchi[b], Onyinyechi Adanma Nnamchi[c]

[a] *Department of Physical Sciences, School of Engineering and Applied Sciences (SEAS), Kampala International University, P. O. Box: 20000, Kampala, Uganda.*
[b] *Department of Mechanical Engineering, School of Engineering and Applied Sciences (SEAS), Kampala International University, P. O. Box: 20000, Kampala, Uganda.*
[c] *Department of Agricultural Engineering and Bio Resources, Michael Okpara University of Agriculture, Umudike, Umuahia, Nigeria.*

P A P E R I N F O

Paper history:
Received 24 June 2020
Accepted in revised form 06 January 2021

Keywords:
Model Development,
Model Estimation,
Sunshine Hours,
Uganda

A B S T R A C T

The present study is concerned with the development, estimation and validation of sunshine hours models (SHM) in Uganda. The SHM is based on geographical (latitude) and climatological (clearness index) indices. The meteosat data (1984-2018) acquired from the National Aeronautics and Space Administration were used to compute the coefficients of the models which, yielded a coefficient of determination close to unity, signifying a good association between the sunshine hours (SH) and the associated indices. The models become distributed by introducing a longitudinal function of clearness index into the primary SHM developed. Moreover, the models were subjected to statistical validation using; mean absolute relative error (MARE), root mean square error (RMSE) and mean absolute percentage difference (APD). Consequently, the primary SHM showed strong agreement with the measured SH data in the three regions with the exception of the northern region with flawed on-station data. Also, validation of the models by; {MARE, RMSE, APD} for Eastern, Central and Western regions, yielding the following results; {0.0788,0.5441,7.8778},{0.0390,0.1453,3.9013} and {0.0124,0.0528,1.2436}, respectively. The following maximum SH; 11.16, 7.87, 9.52, 8.86 and 6.06 h were recorded for Non-regional, Northern, Eastern, Central and Western regions, respectively. Further, comparative validation with redeveloped global SHM showed that the present model stands in all the regions, whereas the global models validated only in the Eastern region. This is attributed to the synergy of geographical and climatological indices against the global models only based on climatological index. The model results show the order of regional SH distribution; eastern>northern>central>western region. These results could be employed in solar power, exploitation and agrometeorology development. This study further recommends for adoption of the present model to non-equatorial regions upon redevelopment as a meaningful extension of this work.

https://doi.org/10.30501/jree.2020.235651.1119

1. INTRODUCTION

Sunshine Hour (SH) is an indicator of solar potential of a location and plays a central role in defining global solar radiation, clearness index, and relative sunshine hours for various applications in solar technologies [1-7]. Sunshine hour has diverse applications in agriculture, hydrology, and meteorology researches with encompassing applications, in atmospheric and building thermal balance [7], evaluation of agricultural resources [7-10], and in the development of global solar radiation models [11-13]. Meteorologically, the sunshine hour is measured using recorders (Campbell-Stokes), sensors (Kipp and Zonen CSD3), pyranometer, and pyrheliometer [7, 14, 15]. The accuracy of the efficiency of these sensors and recorders is influenced by the susceptibility to genera of clouds: cumulus, altostratus, cirrostratus, cirrus, and nimbus [16]. The reliability of sunshine hour recorder depends on a regular maintenance and calibration; if neglected for a long time, it would culminate in the failure of the equipment as observed in Lira district of Uganda, which tracked a series of negative sunshine hour values for the district against the expected positive sunshine hours, when compared to the other regions in Uganda with positive values. The negative sunshine hour values observed could be attributed to the poor maintenance and calibration of the meteorological equipment in the region [5, 17, 18]. In order to avail a practical sunshine hour data for the region, the present work is geared towards developing a sunshine hour model based on both geographical and climatological indices using satellite data from [19] to generate direct sunshine hour models for the nation. However, the present work tends to convert the indirect sunshine hour models [5, 20-33] to suit the present application. Furthermore, the redeveloped sunshine model for the region will be compared with the present work through empirical validation [34-37] and statistical validation [38-41] of the sunshine hour models. For the purpose of distribution or estimation of the sunshine hours over the regions, the present work has delved into estimation of the developed sunshine hour models by substituting the clearness index component of the developed

*Corresponding Author's Email: mundu.mustafa@kiu.ac.ug (M.M. Mundu)
URL: http://www.jree.ir/article_122115.html

Please cite this article as: Mundu, M.M., Nnamchi, S.N. and Nnamchi, O.A., "Development of a model for estimation of sunshine hour data for different regions of Uganda", ***Journal of Renewable Energy and Environment (JREE)***, Vol. 8, No. 1, (2021), 69-76. (https://doi.org/10.30501/jree.2020.235651.1119).

model with a longitudinal function, which complements the latitude in the primarily developed sunshine hour model to make it sensitive to the geographical coordinates for the regions [32, 42]. Therefore, the sunshine hour model can be used to generate sunshine hour distribution for all the locations in Uganda. The previous studies in Uganda [43, 44] show that eastern Uganda experiences the highest sunshine hours with large expanse of latitude and high longitude, followed by the northern region with small expanse of latitude and wide range of longitude. However, the central region has lower sunshine hours relative to Northern and Eastern Regions, whereas the Western Region has the lowest sunshine hour at extreme latitude and low longitude compared to the rest of the region. From all indications, the dominantly hilly and mountainous terrains have high cloud cover, whereas plain or less hilly and mountainous regions have less cloud cover, which impacts on the relative sunshine hours and sunshine hour values [40, 45-47].

Systematically, the proposed sunshine hour models which are based on climatological and geographical indicators have to be subjected to validation using on-station data (measured data) in order to ascertain the validity of the developed sunshine hour models by means of statistical and comparative validations of the models adapted from the other parts of the world. Besides the statistical validation, Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Absolute Percentage Error (MAPE), Mean Absolute Error (MAE), Mean Percentage Error (MPE), Mean Absolute Relative Error (MARE), Absolute Bias Error (ABE), Absolute Mean Percentage Difference (APD) with insignificant deviations buttress the validity and application of developed sunshine hour models, whereas significant deviation suggests that the developed model is invalid and should not be implemented [48-51]. The present work will employ a more appropriate statistical tool (MARE, RMSE, and APD) and comparative validation to distinguish the present models. Therefore, the present work is poised to develop the sunshine hour models, to navigate the models in order to generate sunshine hour distribution in Uganda, and to validate the developed sunshine hour models. Consequently, these objectives will be realized through appropriate material and methods. In this regard, the navigable sunshine hour models and model validations are integrated. Subsequently, the presentation and discussion of results are given besides conclusions of findings and recommendation for further research.

2. METHODOLOGY

The sunshine hour models (combined and uncombined fifth order) were proceeded by the acquisition of a quadragenary satellite data from NASA POWER [19] for all the 122 districts in Uganda (2018) followed by the on-station data acquired from the four meteorological stations: Lira (Northern Region), Tororo (Eastern Region), Kampala (Central Region), and Mbarara (Western Region). The sunshine hour models were developed on latitude and clearness index, representing geographical and climatological indices, respectively. The acquired data were filtered and organized to suit the structure of the proposed sunshine hour models. Then, the sunshine hours data were regressed in OriginLab environment to generate the coefficients of the proposed models and the coefficient of determination (R^2) of the developed model, which unveiled the degree of association between the model variables. Additionally, the developed models were modified by introduction of longitudinal function of clearness index to make it distributed in all the regions of Uganda. Also, the models were validated statistically using MARE, RMSE, and APD and were equally compared with global sunshine hour models, ascertaining their validity and effectiveness.

2.1. Formulation of sunshine hour models

SH model is proposed to be uncombined and combined variable regression (non-mechanistic) fifth-order model in Equation (1) in order to build a strong association between SH and the indicators for the different categories: Non-Regional (NRL), Northern Region (NR), Eastern Region (ER), Central Region (CR), and Western Region (WR).

$$\begin{aligned} SH_{NR,j} = {} & a_{i,j} + a_{i+1,j}\phi_j + a_{i+2,j}k_{T,j} + a_{i+3,j}k_{T,j}\phi_j + a_{i+4,j}\phi_j^{\,2} \\ & + a_{i+5,j}k_{T,j}^{\,2} + a_{i+6,j}k_{T,j}\phi_j^{\,2} + a_{i+7,j}k_{T,j}^{\,2}\phi_j \\ & + a_{i+8,j}\phi_j^{\,3} + a_{i+9,j}k_{T,j}^{\,3} + a_{i+10,j}k_{T,j}\phi_j^{\,3} \\ & + a_{i+11,j}k_{T,j}^{\,3}\phi_j + a_{i+12,j}\phi_j^{\,4} + a_{i+13,j}k_{T,j}^{\,4} \\ & + a_{i+14,j}k_{T,j}\phi_j^{\,4} + a_{i+15,j}k_{T,j}^{\,4}\phi_j + a_{i+16,j}\phi_j^{\,5} \\ & + a_{i+17,j}k_{T,j}^{\,5} \quad (\text{hour}) \quad \exists \quad i = 0; \quad j \\ & = \{1,2,3,4,5\} \equiv \{NRL, NR, ER, CR, WR\} \end{aligned} \tag{1}$$

where a_i, i = 0, 1, 2, …, 17 are the coefficients of Equation (1), ϕ_j (°) is the latitude, and $k_{T,j}$ (−) is the clearness index.

For the purpose of representing the SH on geographical coordinates, the present work has further proposed developing clearness index (k_T) as a function of latitude and longitude in Equation (2).

$$\begin{aligned} k_{T,j} = {} & b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j + b_{l+3,j}\phi_j\lambda_j \quad \exists \ i = 0; \quad j \\ & = \{1,2,3,4,5\} \equiv \{NRL, NR, ER, CR, WR\} \end{aligned} \tag{2}$$

where b_l, l = 0, 1, 2, 3 are the coefficients of Equation (2).

Substituting Equation (2) into (1) makes SH dependent on latitude and longitude in Equation (3).

$$\begin{aligned} SH_{NR,j} = {} & a_{i,j} + a_{i+1,j}\phi_j \\ & + a_{i+2,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j + b_{l+3,j}\phi_j\lambda_j\right) \\ & + a_{i+3,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)\phi_j + a_{i+4,j}\phi_j^{\,2} \\ & + a_{i+5,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)^2 \\ & + a_{i+6,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2\,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)\phi_j^{\,2} \\ & + a_{i+7,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)^2\phi_j + a_{i+8,j}\phi_j^{\,3} \\ & + a_{i+9,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)^3 \\ & + a_{i+10,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)\phi_j^{\,3} \\ & + a_{i+11,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)^3\phi_j + a_{i+12,j}\phi_j^{\,4} \\ & + a_{i+13,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)^4 \\ & + a_{i+14,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)\phi_j^{\,4} \\ & + a_{i+15,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)^4\phi_j + a_{i+16,j}\phi_j^{\,5} \\ & + a_{i+17,j}\left(b_{l,j} + b_{l+1,j}\phi_j + b_{l+2,j}\lambda_j \right.\\ & \left. + b_{l+3,j}\phi_j\lambda_j\right)^5 \quad (\text{hr}) \\ \exists \quad & i = 0; \ l = 0; \quad j = \{1,2,3,4,5\} \equiv \{NRL, NR, ER, CR, WR\} \end{aligned} \tag{3}$$

Equation (3) for categories $\{NRL, NR, ER, CR, WR\}$ is subjected to the following constraints in Table 1. Globally, used clearness index (K_T) according to the following researchers [52-56] is algebraically given in Equation (4).

$$K_T = a(RSH)^2 + b(RSH) + c \quad (4)$$

Sequel to the redevelopment of Equation (4) with the local data to obtain coefficients a, b, c and further rearrangement of Equation (4) yielded the corresponding RSH model in Equation (5).

$$RSH = -0.171875 + (2.232143K_T - 0.61331613)^{0.5} \quad \exists \quad K_T \geq 0.275 \quad (5)$$

Expressing RSH in its components, i.e., sunshine hours and daylength, Equation (5) is expounded in Equation (6) as follows:

$$RSH = \frac{n}{N} = -0.171875 + (2.232143K_T - 0.61331613)^{0.5} \quad \exists \quad K_T \geq 0.275 \quad (6)$$

Equation (7) gives an explicit expression for sunshine hours for comparative validation.

$$\Rightarrow SH = n = N(-0.171875 + (2.232143K_T - 0.61331613)^{0.5}) \quad \exists \quad K_T \geq 0.275 \quad (7)$$

The daylength, N is defined in Equation (8) as in [57].

$$N = \frac{2}{15}\cos^{-1}(-\tan\delta\tan\phi); \ \delta = 23.45\sin\left[360\left(\frac{284+n}{365}\right)\right] \quad (8)$$

where n is the number of days from January first and δ is the declination angle.

Statistically, Equations (1) to (3) are to be validated with RMSE, MARE, and APD. The RMSE is defined in Equation (4) as follows:

$$RMSE_j = \left[\frac{1}{n}\sum_{i=1}^{n}\left(RSH_{m,j,i} - RSH_{s,j,i}\right)^2\right]^{0.5} \quad (4)$$

$\exists \quad j = \{1, 2, 3, 4, 5\} \equiv \{NRL, NR, ER, CR, WR\}$

Table 1 shows the boundaries of the sunshine hour models developed.

Table 1. Boundary conditions (constraints) in Equation (3)

Category	Operation	Latitude (degree)	Longitude (degree)
j	**j, j**		
NRL	NRL, NRL	$-0.750000 \leq \phi_{NRL} \leq 3.649997$	$29.683331 \leq \lambda_{NRL} \leq 34.94999722$
NR	NR, NR	$1.633330556 \leq \phi_{NR} \leq 3.64999$	$30.899997 \leq \lambda_{NR} \leq 34.9499972$
ER	ER, ER	$0.283333 \leq \phi_{ER} \leq 2.03333$	$33.050000 \leq \lambda_{ER} \leq 34.73333$
CR	CR, CR	$0.066667 \leq \phi_{CR} \leq 1.33333$	$29.783331 \leq \lambda_{CR} \leq 33.266667$
WR	WR, WR	$-0.750000 \leq \phi_{WR} \leq 2.183333$	$29.683331 \leq \lambda_{WR} \leq 32.00000$

The MARE is expressed in Equation (5) as follows:

$$MARE_j = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\left(SH_{m,j,i} - SH_{s,j,i}\right)}{SH_{m,j,i}}\right| \quad (5)$$

$\exists \quad j = \{1, 2, 3, 4, 5\} \equiv \{NRL, NR, ER, CR, WR\}$

The mean Absolute Percentage Difference (APD) is given in Equation (6) as follows:

$$APD_j = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\left(SH_{m,j,i} - SH_{s,j,i}\right)}{SH_{m,j,i}}\right| \times 100\% \quad (6)$$

$\exists \quad j = \{1, 2, 3, 4, 5\} \equiv \{NRL, NR, ER, CR, WR\}$

3. RESULTS AND DISCUSSION

This section presents the results and discussion of the study in Subsections 4.1 and 4.2, respectively.

3.1. Presentation of results

Firstly, the regression coefficients generated for the fifth-order model in Equation 1 which is both uncombined (K_T, ϕ) and combined ($K_T\phi$) variable sunshine hours model is represented in Table 2 for NRL, NR, ER, CR, and WR. Similarly, Table 3 gives the clearness index coefficients of Equation 2 ($K_T = f(\phi, \lambda)$) for non-regional and the different regions of Uganda. Furthermore, Table 3 provides the goodness of fit or coefficient of determination (R^2) which shows the level of association between the variables (latitude and longitude) and clearness index. The R^2 values reported for the mentioned categories tend to unity, showing a close association between the variables. All the categories have quadratic coefficients except the northern region, which shows a good association with a linear model. Lastly, Table 4 gives the results of statistical tools (RMSE, MARE, and APD) employed in the validation of the sunshine hour models in Uganda.

Table 2. Coefficients of Equation (1) for sunshine hours

Category	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
Non-regional	-238	167	1530	-1070	2.05	-3620	-3.87	2560	-0.758	3830
Northern	23.443	83.063	-0.186	-626.653	-4.178	-472.751	10.031	1807.904	0.939	1267.508
Eastern	-126.793	3618.276	-3.44584	-17558.84	74.3881	1187.509	-125.277	28128.73	-19.5588	-1348.8
Central	-7.92	206	1.27	-1530	14.9	236	-27.9	4190	-16.7	-745
Western	-0.101	2.894	0.151	-13.957	-0.048	-1.687	0.089	21.582	0.047	86.417

Category	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	R^2
Non-regional	1.53	-2700	0.0778	-1490	-0.199	1050	0.00395	0.11	0.9926

Northern	-2.736	-2341.6	-0.035	-997.856	0.277	1122.785	-0.010	143.798	0.9985
Eastern	32.953	-14854	–	–	–	–	–	–	0.9985
Central	30.8	-5080	5.85	992	-10.4	2310	-0.132	-484	0.9993
Western	-0.090	-10.465	0.0006	-80.937	–	–	–	–	0.9999

Table 3. Clearness index coefficients of Equation (2)

Category	$\mathbf{b_0}$	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{R^2}$
Non-regional	0.1752	0.0051	0.0002	0.9683
Northern	0.2054	0.0116	–	0.8638
Eastern	– 17.036	1.0165	– 0.0146	0.8765
Central	10.366	-0.6447	0.0106	0.9411
Western	11.135	-0.7101	0.0119	0.9507

Table 4. Statistical validation of sunshine hour in Uganda

Region	**MARE**	**RMSE**	**APD (%)**
Northern	–	–	–
Eastern	0.0788	0.5441	7.8778
Central	0.0390	0.1453	3.9013
Western	0.0124	0.0528	1.2436

The figures of results are presented from Figures 1–11. Figure 1 presents the non-validated sunshine hours for the northern region. This non-validation is ascribed to the poor quality of maintenance of the instrument and possibly due to accumulation of dust and vapor on the sensitive spotting surface of the instrument [7, 14, 16]. This is usually taken care of by recalibration of the instruments and regular maintenance. More so, Figures 2–4 illustrate the validation of measured and simulated sunshine hours for ER, CR, and WR, respectively. Additionally, Figures 5–9 present the estimation of sunshine hours based on the latitude (ϕ) and longitude (λ) of the locations: NRL and regional basis for NR, ER, CR, and WR, respectively. Moreover, Figures 10 and 11 give the comparative validation of the global and present sunshine hour models for eastern and central regions, respectively.

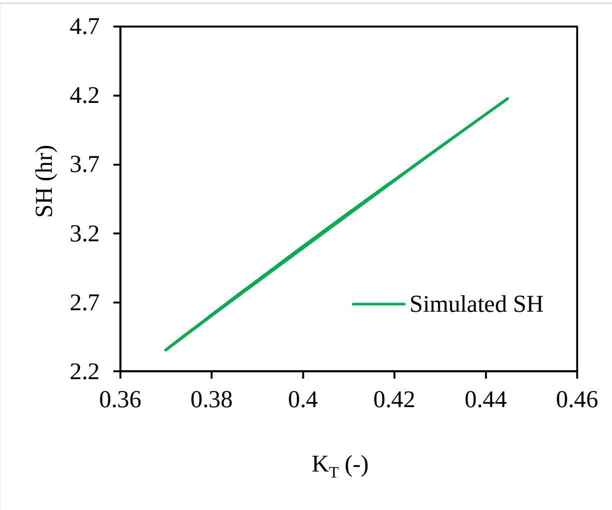

Figure 1. Non-validated sunshine hours for northern region

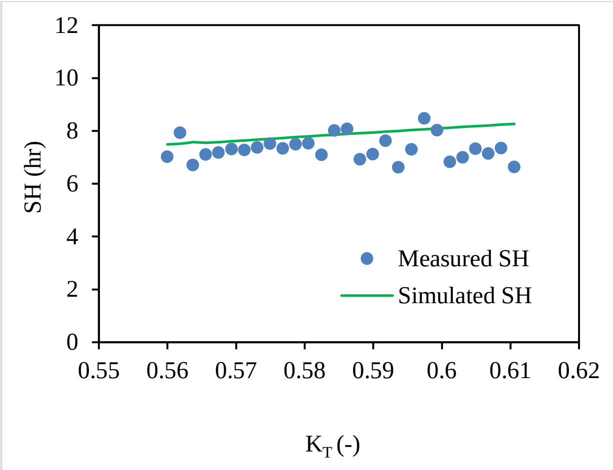

Figure 2. Validation of sunshine hours for eastern region

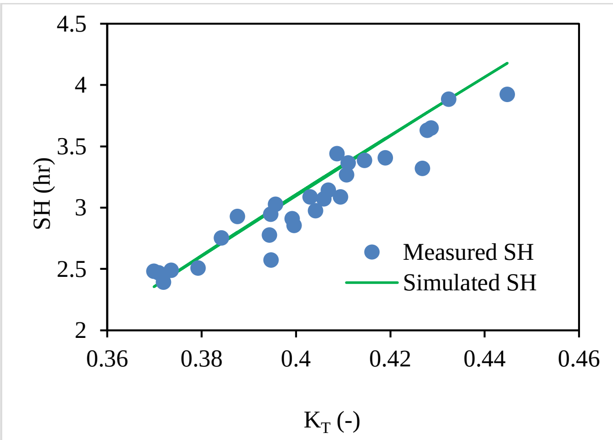

Figure 3. Validation of sunshine hours for central region

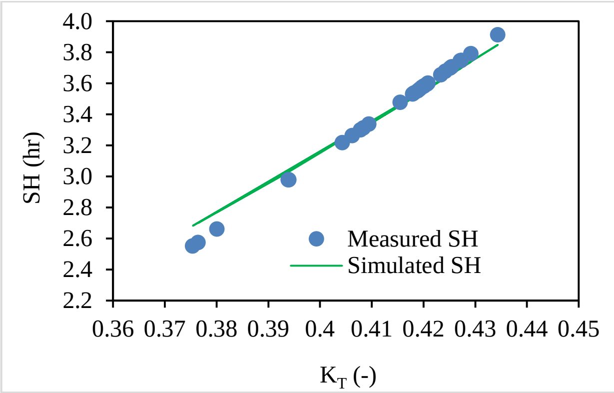

Figure 4. Validation of sunshine hours for western region

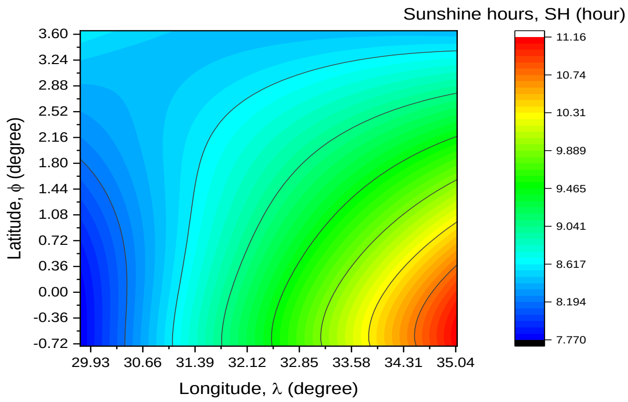

Figure 5. Non-regional estimation of sunshine hours in Uganda

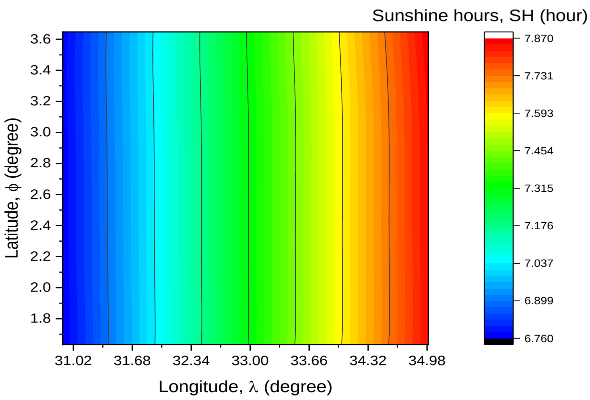

Figure 6. Regional estimation of sunshine hours for northern region

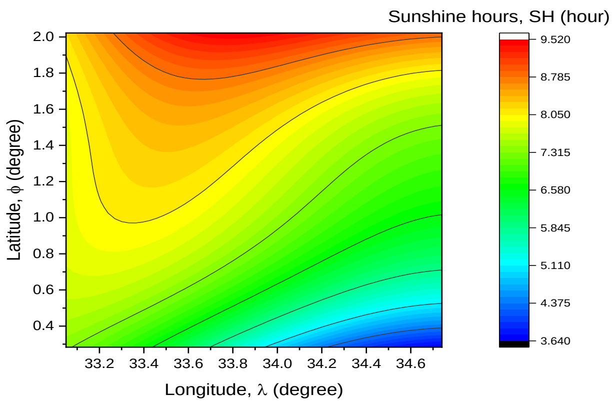

Figure 7. Regional estimation of sunshine hours for eastern region

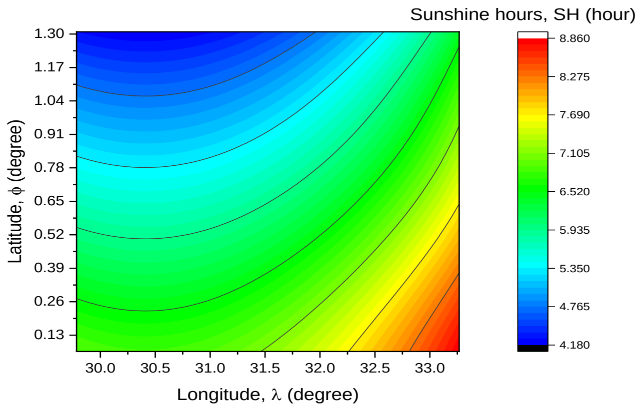

Figure 8. Regional estimation of sunshine hours for central region

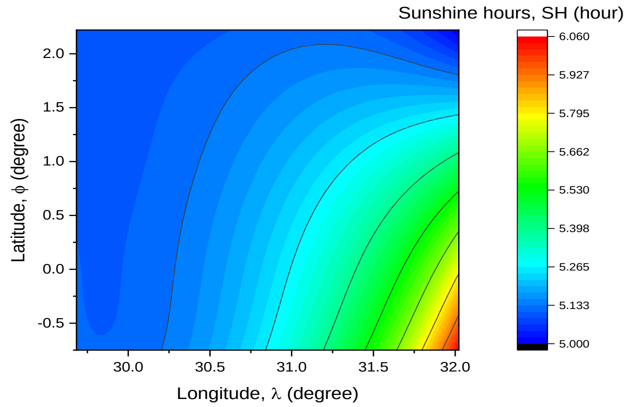

Figure 9. Regional estimation of sunshine hours for western region

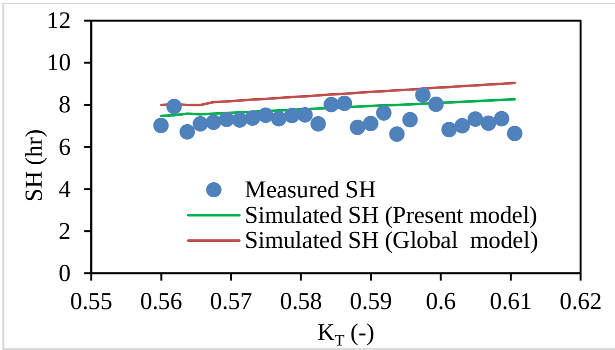

Figure 10. Comparative validation of global and present sunshine hours models for eastern region

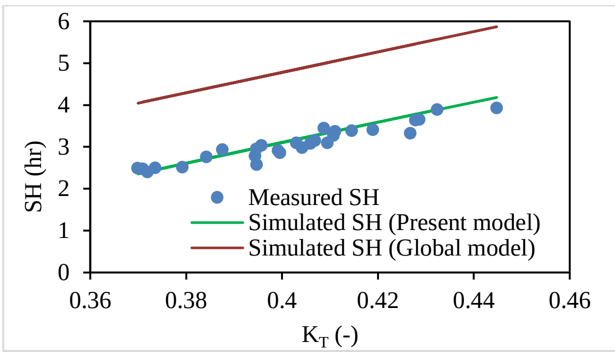

Figure 11. Comparative validation of global and present sunshine hours models for central region

3.2. Discussion

Approximately, Table 2 presents the coefficients of Equation (1) and the coefficients of determination (R^2), which are approaching unity (1). The R^2 values support that there is a strong association between the dependent variable (sunshine hours) and the independent variables (the latitude and clearness index), representing the geographic and climatological indices for the sunshine hour models.

The sunshine hour models in Table 2 are bound in Table 1, which displays the latitude and longitude of the entire Uganda and the regions. Thus, the sunshine hour models developed define the sunshine hours with certainty in as much as the constraints delineated in Table 1 are not traversed; otherwise, the model may fail if not redeveloped with data outside the boundaries.

Considering that Equation (1) cannot fulfill the main objective of this work, the clearness index is formulated as a function of longitude to engender the estimation of sunshine hour models in Equation (1) according to the following literature [32, 42].

Pertinently, Table 4 presents the statistical validation (MARE, RMSE, and APD) of sunshine hours in Uganda with minimal deviations, which is in strong agreement with the other published results [38, 40, 41]. The validation results are displayed in Figures 1–4 to substantiate the agreement between the present validations and those in the aforementioned literature.

The distribution of sunshine hours in Uganda and the corresponding regions is displayed in Figures 5–9, respectively. Generally, sunshine hours are abundant at latitudes above 3.0 and longitude below 3.15. Thus, these locations should be earmarked for installation of solar facilities in Uganda indisputably. Figure 6 portrays that the sunshine hours expand all through the longitude of the northern region with a strict restriction on the latitude (3.4–3.7). Therefore, government and developers should apply these findings without bias in the bid to exploit solar resources for maximum in this region. With the target latitude (0.7–1.8°N) and limited longitude (34.6–35.0°E), the sunshine hour is highly concentrated in the eastern region indiscriminately (as shown in Figure 7). Credibly, Tororo plant (32 000 panels; 10 MW; [58]) is within the mapped out area, whereas Soroti plant (32 680 panels; 10 MW; [58]) is slightly off the hot spot. Thus, the hot spots for enormous exploitation of solar resources is mapped out by these geographical locations. The sunshine hour is sparsely distributed in the central region from latitudes (1.2–1.4°N) and longitude (30–30.7°E); thus, government and developers should only place the solar facilities within the mapped out location; otherwise, this present work suggests that the solar facilities to be installed in locations with higher sunshine hours and power generated from such a location to be transmitted to region with low sunshine hours in order to maximize the utility of solar installations in Uganda. Notably, the largest solar installation in Uganda is located in the Gomba district in the Kabulasoke sub-county with a capacity of 68 000 solar panels (20 MW; [58]) located in the mapped out region by the study in Figure 8. Had it been that the installation at Kabulasoke is installed in northern and eastern regions, obviously, more power would have been added to the national grids. Hence, the present work has unveiled the best spots for future localization of solar facilities in order to boost solar power harvests in Uganda.

In terms of maximum sunshine hour distribution, western region (6 hours) is less favored like other regions: northern (8.0 hours), eastern (9.5 hours), and central (9.0 hours). Hence, government and developers should concentrate on solar facilities in the order of increasing sunshine hours: eastern, northern, central, and western regions for maximizing solar power exploitation. Thus, the present work is recommended for generation and transmission of solar power from the other regions (northern, eastern, and central) to the western region. However, the western region with a rifted valley is compensated by geothermal resources, which are not available in other regions. Thus, this work is encouraging for exploration and exploitation of geothermic energy to support the solar power in the sustaining power supply to the grids.

Lastly, Figure 10 shows that the redeveloped global sunshine hour models were in agreement with the present model in the eastern region, whereas it failed in the other regions due to lack of geographical indicators in the model [32, 42]. Representatively, Figure 11 portrays the aforementioned failure in the preceding paragraph. However, the present model comprehensively fitted to the observed data due to the binary indicators (latitude and clearness index). Thus, a robust sunshine hour model should be built or formulated with heterogeneous indicators by incorporating extraterrestrial and terrestrial indices.

4. CONCLUSIONS

This study successfully developed and estimated the sunshine hour models for all the regions of Uganda. Fundamentally, the developed sunshine hour models were uncombined and combined variables fifth fifth-order non-differential models, which were dependent on the clearness index and latitude. These models were distributed by substituting the clearness index with its longitudinal function into the sunshine hour lumped models. Consistently, there was a strong association between the dependent (sunshine hours) and independent variables (clearness index and latitude), as shown by the high values of coefficient of determination ($R^2 \rightarrow 1$).

Furthermore, the developed sunshine hour models were validated statistically using MARE, RMSE, and APD for eastern, central, and western regions, yielding the following results {0.0788, 0.5441, 7.8778}, {0.0390, 0.1453, 3.9013}, and {0.0124, 0.0528, 1.2436}, respectively. The following maximum sunshine hours, i.e., 11.16, 7.87, 9.52, 8.86, and 6.06 h, were recorded for non-regional, northern, eastern, central, and western regions, respectively. Comparatively, the sunshine hour models developed were in strong agreement with the measurement data in all the regions relative to the adapted and redeveloped global models which were in agreement with the eastern measured data and failed in the rest of the regions. This shows the effect of combining the geographical index (latitude) with the climatological index (clearness index) in developing robust sunshine hour models by the present study.

Moreover, the distributed sunshine hour models showed the descending order of sunshine hours in Uganda with eastern > northern > central > western region. Thus, this study suggests that localization and installation of solar power plants should be concentrated in the hotspots in the regions. In addition, the sunshine hour model could be employed in agrometeorology for the biological functioning of plants and in boosting agro-produce.

This study strongly recommends the adaption and redevelopment of the present models outside the equatorial regions as a further study.

5. ACKNOWLEDGEMENT

The authors recognize the two sources of data, NASA POWER and the Department of Physics, Makerere University, for making available the data used in the formulation and validation of the sunshine hour models in Uganda.

NOMENCLATURE

SH	Sunshine hours (hr)
K_T	Clearness index (-)
RSH	Relative sunshine hours (-)
λ	Latitude (°)
ϕ	Latitude (°)
δ	Solar declination angle (°)
SHM	Sunshine hour models
MARE	Mean absolute relative error
RMSE	Root mean square error
APD	Mean absolute percentage difference
R^2	Coefficient of determination
N	Daylength
NRL	Non-regional
NR	Northern region
ER	Eastern region
CR	Central region
WR	Western region
$a_i, i = 0\ 1, 2 \cdots, 17$	Regression coefficients
$b_l, l = 0, 1, 2, 3$	Regression coefficients

REFERENCES

1. Yang, L., Cao, Q., Yu, Y. and Liu, Y., "Comparison of daily diffuse radiation models in regions of China without solar radiation measurement", ***Energy***, Vol. 191, (2020), 116571. (https://doi.org/10.1016/j.energy.2019.116571).
2. Mundu, M.M., Nnamchi, S.N. and Ukagwu, K.J., "Algorithmized modelling, simulation and validation of clearness index in four regions of Uganda", ***Journal of Solar Energy Research***, Vol. 5, No. 2, (2020), 432-452. (https://doi.org/10.22059/jser.2020.300924.1150).
3. Jahani, B. and Mohammadi, B., "A comparison between the application of empirical and ANN methods for estimation of daily global solar radiation in Iran", ***Theoretical and Applied Climatology***, Vol. 137, No. 1-2, (2019), 1257-1269. (https://doi.org/10.1007/s00704-018-2666-3).
4. Jamil, B. and Bellos, E., "Development of empirical models for estimation of global solar radiation exergy in India", ***Journal of Cleaner Production***, Vol. 207, (2019), 1-16. (https://doi.org/10.1016/j.jclepro.2018.09.246).
5. Bakirci, K., "Models of solar radiation with hours of bright sunshine: A review", ***Renewable Sustainable Energy Reviews***, Vol. 13, No. 9, (2009), 2580-2588.(https://doi.org/10.1016/j.rser.2009.07.011).
6. Jervase, J., Al-Lawati, A. and Dorvlo, A., "Contour maps for sunshine ratio for Oman using radial basis function generated data", ***Renewable Energy***, Vol. 28, No. 3, (2003), 487-497. (https://doi.org/10.1016/s0960-1481(02)00035-6).
7. Wu, B., Liu, S., Zhu, W., Yu, M., Yan, N. and Xing, Q., "A method to estimate sunshine duration using cloud classification data from a geostationary meteorological satellite (FY-2D) over the Heihe River Basin", ***Sensors***, Vol. 16, No. 11, (2016), 1859. (https://doi.org/10.3390/s16111859).
8. Xue, L., Wang, C., Wang, C. and Shen, S., "Agricultural climatic regionalization for Longyan cultivation in Guangdong province", ***Journal of Tropical Meteorology***, Vol. 27, (2011), 403-409. (http://en.cnki.com.cn/Article_en/CJFDTotal-RDQX201103014.htm).
9. Huang, Y., Xiu, S., Zhong, S., Zheng, L. and Sun, H., "Division of banana for climatic suitability based on a decision tree", ***Journal of Tropical Meteorology***, Vol. 28, (2012), 140-144. (http://en.cnki.com.cn/Article_en/CJFDTotal-RDQX201201016.htm).
10. Mubiru, J., Banda, E., D'Ujanga, F. and Senyonga, T., "Assessing the performance of global solar radiation empirical formulations in Kampala, Uganda", ***Theoretical Applied Climatology***, Vol. 87, No. 1-4, (2007), 179-184. (https://doi.org/10.1007/s00704-005-0196-2).
11. Rabehi, A., Guermoui, M. and Lalmi, D., "Hybrid models for global solar radiation prediction: A case study", ***International Journal of Ambient Energy***, Vol. 41, No. 1, (2020), 31-40. (https://doi.org/10.1080/01430750.2018.1443498).
12. Suthar, M., Singh, G. and Saini, R., "Effects of air pollution for estimating global solar radiation in India", ***International Journal of Sustainable Energy***, Vol. 36, No. 1, (2017), 20-27. (https://doi.org/10.1080/14786451.2014.979348).
13. Adnan, S., Hayat Khan, A., Haider, S. and Mahmood, R., "Solar energy potential in Pakistan", ***Journal of Renewable Sustainable Energy***, Vol. 4, No. 3, (2012), 032701. (https://doi.org/10.1063/1.4712051).
14. Qian, H., "Study on the measurement method of direct radiation sunshine hour", Doctoral Dissertation, Master's Thesis, Nanjing University of Information Science and Technology, Nanjing, China, (2013).
15. Rijks, D. and Huxley, P., "The empirical relation between solar radiation and hours of bright sunshine near Kampala, Uganda", ***Journal of Applied Ecology***, Vol 1, No. 2, (1964), 339-345. (https://doi.org/10.2307/2401317).
16. Matuszko, D., "A comparison of sunshine duration records from the Campbell-Stokes sunshine recorder and CSD3 sunshine duration sensor", ***Theoretical and Applied Climatology***, Vol. 119, No. 3-4, (2015), 401-406. (https://doi.org/10.1007/s00704-014-1125-z).
17. Fan, J., Wang, X., Wu, L., Zhang, F., Bai, H., Lu, X. and Xiang, Y., "New combined models for estimating daily global solar radiation based on sunshine duration in humid regions: A case study in South China", ***Energy Conversion Management***, Vol. 156, (2018), 618-625. (https://doi.org/10.1016/j.enconman.2017.11.085).
18. Jahani, B., Dinpashoh, Y. and Nafchi, A.R., "Evaluation and development of empirical models for estimating daily solar radiation", ***Renewable Sustainable Energy Reviews***, Vol. 73, (2017), 878-891. (https://doi.org/10.1016/j.rser.2017.01.124).
19. NASA, "Prediction of world energy resources, power data access viewer", (2018). (Available from: https://power.larc.nasa.gov/data-access-viewer/).
20. Al-Aboosi, F.Y., "Models and hierarchical methodologies for evaluating solar energy availability under different sky conditions toward enhancing concentrating solar collectors use: Texas as a case study", ***International Journal of Energy Environmental Engineering***, Vol. 11, No. 3, (2019), 1-29. (https://doi.org/10.1007/s40095-019-00326-z).
21. Samanta, S., Patra, P.K., Banerjee, S., Narsimhaiah, L., Chandran, M.S., Kumar, P.V. and Bandyopadhyay, S., "Generation of common coefficients to estimate global solar radiation over different locations of India", ***Theoretical Applied Climatology***, Vol. 136, No. 3-4, (2019), 943-953. (https://doi.org/10.1007/s00704-018-2531-4).
22. Sahin, A.Z., Rehman, S. and Al-Sulaiman, F., "Global solar radiation and energy yield estimation from photovoltaic power plants for small loads", ***International Journal of Green Energy***, Vol. 14, No. 5, (2017), 490-498. (https://doi.org/10.1080/15435075.2016.1278374).
23. Yaniktepe, B., Kara, O. and Ozalp, C., "The global solar radiation estimation and analysis of solar energy: Case study for Osmaniye, Turkey", ***International Journal of Green Energy***, Vol. 14, No. 9, (2017), 765-773. (https://doi.org/10.1080/15435075.2017.1329148).
24. Quej, V.H., Almorox, J., Ibrakhimov, M. and Saito, L., "Empirical models for estimating daily global solar radiation in Yucatán Peninsula, Mexico", ***Energy Conversion Management***, Vol. 110, (2016), 448-456. (https://doi.org/10.1016/j.enconman.2015.12.050).
25. Namrata, K., Sharma, S. and Seksena, S., "Empirical models for the estimation of global solar radiation with sunshine hours on horizontal surface for Jharkhand (India)", ***Applied Solar Energy***, Vol. 52, No. 3, (2016), 164-172. (https://doi.org/10.3103/s0003701x16030099).
26. Kirmani, S., Jamil, M. and Rizwan, M., "Empirical correlation of estimating global solar radiation using meteorological parameters", ***International Journal of Sustainable Energy***, Vol. 34, No. 5, (2015), 327-339. (https://doi.org/10.1080/14786451.2013.826222).
27. Dumas, A., Andrisani, A., Bonnici, M., Graditi, G., Leanza, G., Madonia, M. and Trancossi, M., "A new correlation between global solar energy radiation and daily temperature variations", ***Solar Energy***, Vol. 116, (2015), 117-124. (https://doi.org/10.1016/j.solener.2015.04.002).
28. Teke, A. and Yıldırım, H.B., "Estimating the monthly global solar radiation for Eastern Mediterranean Region", ***Energy Conversion Management***, Vol. 87, (2014), 628-635. (https://doi.org/10.1016/j.enconman.2014.07.052).

29. Li, H., Ma, W., Bu, X., Lian, Y. and Wang, X., "A multiple linear regression model for estimating global solar radiation in Guangzhou, China", ***Energy Sources, Part A: Recovery, Utilization, Environmental Effects***, Vol. 35, No. 4, (2013), 321-327. (https://doi.org/10.1080/15567036.2010.499422).

30. Luis, M.A., Felipe, D.R. and Pilar N.R, "Estimation of global solar radiation by means of sunshine duration", ***Proceedings of ISES World Congress 2007***, Vol. I–Vol. V, Springer, (2008). (https://doi.org/10.1007/978-3-540-75997-3_530).

31. Sen, Z., Solar energy fundamentals and modeling techniques: Atmosphere, environment, climate change and renewable energy, Springer Science & Business Media, (2008). (https://doi.org/10.5860/choice.46-2687).

32. Matzarakis, A. and Katsoulis, V., "Sunshine duration hours over the Greek region", ***Theoretical Applied Climatology***, Vol. 83, No. 1-4, (2006), 107-120. (https://doi.org/10.1007/s00704-005-0158-8).

33. Almorox, J. and Hontoria, C., "Global solar radiation estimation using sunshine duration in Spain", ***Energy Conversion Management***, Vol. 45, No. 9-10, (2004), 1529-1535. (https://doi.org/10.1016/j.enconman.2003.08.022).

34. Samadianfard, S., Majnooni-Heris, A., Qasem, S.N., Kisi, O., Shamshirband, S. and Chau, K., "Daily global solar radiation modeling using data-driven techniques and empirical equations in a semi-arid climate", ***Engineering Applications of Computational Fluid Mechanics***, Vol. 13, No. 1, (2019), 142-157. (https://doi.org/10.1080/19942060.2018.1560364).

35. Lockart, N., Kavetski, D. and Franks, S.W., "A new stochastic model for simulating daily solar radiation from sunshine hours", ***International Journal of Climatology***, Vol. 35, No. 6, (2015), 1090-1106. (https://doi.org/10.1002/joc.4041).

36. Ineichen, P., "Validation of models that estimate the clear sky global and beam solar irradiance", ***Solar Energy***, Vol. 132, (2016), 332-344. (https://doi.org/10.1016/j.solener.2016.03.017).

37. Arslan, T., Yavuz, A.A. and Açikkalp, E., "The importance of the chosen technique to estimate diffuse solar radiation by means of regression", ***International Journal of Green Energy***, Vol. 12, No. 1, (2015), 23-27. (https://doi.org/10.1080/15435075.2014.889010).

38. Bailek, N., Bouchouicha, K., Abdel-Hadi, Y.A., El-Shimy, M., Slimani, A., Jamil, B. and Djaafari, A., "Developing a new model for predicting global solar radiation on a horizontal surface located in Southwest Region of Algeria", ***NRIAG Journal of Astronomy Geophysics***, Vol. 9, No. 1, (2020), 341-349. (https://doi.org/10.1080/20909977.2020.1746892).

39. Ramgolam, Y.K. and Soyjaudah, K.M.S., "Assessment and validation of global horizontal radiation: A case study in Mauritius", ***International Journal of Green Energy***, Vol. 16, No. 14, (2019), 1317-1328. (https://doi.org/10.1080/15435075.2019.1671407).

40. Rahimikhoob, A., "Estimating sunshine duration from other climatic data by artificial neural network for ET 0 estimation in an arid environment", ***Theoretical Applied Climatology***, Vol. 118, No. 1-2, (2014), 1-8. (https://doi.org/10.1007/s00704-013-1047-1).

41. Shamim, M.A., Remesan, R., Han, D., Ejaz, N. and Elahi, A., "An improved technique for global daily sunshine duration estimation using satellite imagery", ***Journal of Zhejiang University SCIENCE A***, Vol. 13, No. 9, (2012), 717-722. (https://doi.org/10.1631/jzus.a1100292).

42. Dolinar, M., "Spatial interpolation of sunshine duration in Slovenia", ***Meteorological Applications***, Vol. 13, No. 4, (2006), 375-384. (https://doi.org/10.1017/s1350482706002362).

43. Biira, S., "Analysis of solar radiation in Uganda", ***International Journal of Current Research***, Vol. 6, No. 8, (2014), 8110-8115. (http://www.journalcra.com/sites/default/files/issue-pdf/6062.pdf).

44. Karume, K., Banda, E., Mubiru, J. and Majaliwa, M., "Correlation between sunshine hours and climatic parameters at four locations in Uganda", ***Tanzania Journal of Science***, Vol. 33, No. 1, (2007). (https://doi.org/10.4314/tjs.v33i1.44279).

45. Kandirmaz, H., Kaba, K. and Avci, M., "Estimation of monthly sunshine duration in Turkey using artificial neural networks", ***International Journal of Photoenergy***, Vol. 2014, (2014). (https://doi.org/10.1155/2014/680596).

46. Yadav, A.K. and Chandel, S., "Solar radiation prediction using Artificial Neural Network techniques: A review", ***Renewable Sustainable Energy Reviews***, Vol. 33, (2014), 772-781. (https://doi.org/10.1016/j.rser.2013.08.055).

47. Frei, C., Willi, M., Stöckli, R. and Dürr, B., "Spatial analysis of sunshine duration in complex terrain by non-contemporaneous combination of station and satellite data", ***International Journal of Climatology***, Vol. 35, No. 15, (2015), 4771-4790. (https://doi.org/10.1002/joc.4322).

48. Ali, M.H. and Abustan, I., "A new novel index for evaluating model performance", ***Journal of Natural Resources Development***, Vol. 4, (2014), 1-9. (https://doi.org/10.5027/jnrd.v4i0.01).

49. Chai, T. and Draxler, R.R., "Root mean square error (RMSE) or mean absolute error (MAE)?–Arguments against avoiding RMSE in the literature", ***Geoscientific Model Development***, Vol. 7, No. 3, (2014), 1247-1250. (https://doi.org/10.5194/gmd-7-1247-2014).

50. Moreno, J.J.M., Pol, A.P., Abad, A.S. and Blasco, B.C., "Using the R-MAPE index as a resistant measure of forecast accuracy", ***Psicothema***, Vol. 25, No. 4, (2013), 500-506. (10.7334/psicothema2013.23).

51. Muzathik, A., Nik, W., Ibrahim, M., Samo, K., Sopian, K. and Alghoul, M., "Daily global solar radiation estimate based on sunshine hours", ***International Journal of Mechanical and Materials Engineering***, Vol. 6, No. 1, (2011), 75-80. (https://www.researchgate.net/publication/259479118_Daily_global_solar_radiation_estimate_based_on_sunshine_hours).

52. Anis, M.S., Jamil, B., Ansari, M.A. and Bellos, E., "Generalized models for estimation of global solar radiation based on sunshine duration and detailed comparison with the existing: A case study for India", ***Sustainable Energy Technologies Assessments***, Vol. 31, (2019), 179-198. (https://doi.org/10.1016/j.seta.2018.12.009).

53. Onyango, A.O. and Ongoma, V., "Estimation of mean monthly global solar radiation using sunshine hours for Nairobi City, Kenya", ***Journal of Renewable Sustainable Energy***, Vol. 7, No. 5, (2015), 053105. (https://doi.org/10.1063/1.4930530).

54. Che, H., Shi, G., Zhang, X., Zhao, J. and Li, Y., "Analysis of sky conditions using 40 year records of solar radiation data in China", ***Theoretical Applied Cimatology***, Vol. 89, No. 1-2, (2007), 83-94. (https://doi.org/10.1007/s00704-006-0258-0).

55. Jin, Z., Yezheng, W. and Gang, Y., "General formula for estimation of monthly average daily global solar radiation in China", ***Energy Conversion Management***, Vol. 46, No. 2, (2005), 257-268. (https://doi.org/10.1016/j.enconman.2004.02.020).

56. Akinoğlu, B. and Ecevit, A., "Construction of a quadratic model using modified Ångstrom coefficients to estimate global solar radiation", ***Solar Energy***, Vol. 45, No. 2, (1990), 85-92. (https://doi.org/10.1016/0038-092x(90)90032-8).

57. Duffie, J.A., Beckman, W.A. and Blair, N., Solar engineering of thermal processes, photovoltaics and wind, John Wiley & Sons, (2020). (https://doi.org/10.1002/9781119540328).

58. ERA, "Electricity supply industry performance report for the year 2018", (2019). (Available from: https://www.era.or.ug/index.php/resource-centre/publications/reports.