



Assessment of Solar Resource Potential for Photovoltaic Applications in East Gojjam Zone, Ethiopia

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Abstract. The primary challenge in choosing the right electrification approach across the globe is understanding the local energy resource potential. In this paper, the result of solar resource potential assessment of East Gojjam (EG) Zone, Ethiopia is presented. The solar insolation, an important parameter in designing and planning solar photovoltaic systems, at four meteorological stations of EG (viz. Debre Markos, Debrewerq, Mota and Yetnora) is estimated from sunshine hour and extraterrestrial radiation. The hour of bright sunshine data which covered eleven years has been collected from National Meteorological Agency Bahir Dar Branch. This data is prepared and used to estimate the solar insolation using a well-known linear Ångström-Prescott (A-P) model. The site-specific A-P model is adopted by using regression coefficients, 'a' and 'b', which are obtained from well-known empirical formulas. The empirical formulas were validated using the measured data from other sites in the region. The annual mean daily solar insolation (kWh/m²/day) for Debre Markos, Debrewerq, Mota, and Yetnora is estimated to be 5.47, 7.05, 6.11, and 6.16, respectively. According to the monthly solar insolation profile, EG receives the highest and lowest solar insolation in April at Debrewerq and July at Debre Markos, respectively. The solar insolation profile at Debre Markos demonstrates a significant inconsistency while Debrewerq receives more uniform solar radiation throughout the year; and therefore, the later site is the most suitable for solar photovoltaic energy investments with a highest and more uniform clearness index profile throughout the year.

Keywords: Solar energy potential · East Gojjam · Sunshine hour · Solar insolation

1 Introduction

The energy supply of Ethiopia is mainly based on biomass while the rate of access to electricity services is one of the lowest in the world. Waste and biomass took a share of 91% of Ethiopia's energy supply, followed by petroleum (7%) and electric energy (2%).

Electric energy is still enjoyed only by urban households and industries [1]. Meanwhile, with an average economic growth rate of 10.8%, the economy is one of the fastest-growing in the world. Moreover, the country has planned to achieve climate-friendly economic development until 2025 [2]. Ethiopia produces about 9TWh of electricity per year, 96% of which is from hydroelectric power plants and the remaining 4% is from wind and geothermal power plants [2]. About 83% of the country's citizens are living in remote rural areas which are either inaccessible to the central electricity grid system or not covered by grid extension to date. More than 95% of rural areas do not have access to electricity [1]. The rural residents still depend on firewood for cooking and heating and imported kerosene and solar lanterns for lighting uses. As a result, with a growing population, the consumption of firewood is rising with a consequence of deforestation leading to global warming and health-related problems. About 70% of health clinics and 76% of primary schools do not have access to electricity [3] which negatively affects health and education services. Nevertheless, to support rural development, rural households and institutions need to be supplied with adequate and reliable electric power [4].

By considering the socio-economic and environmental aspects, rural electrification policies should be formulated linking the efforts of the government and private sector. Data-driven policies and regulations need to be formulated to implement rural electrification approaches. Among the rural electrification approaches are grid extension, renewable or diesel generator based mini-grids, or solar home systems [4]. The choice of electrification approach depends on available energy resource potential and the feasibility of the technology [5, 6]. Planning and formulating sustainable energy policy which supports a sustainable economy by prioritizing the use of local resources and promoting energy independence requires high-quality renewable energy (RE) resource and other geographic information data [7–23]. Without detailed knowledge of the spatial and temporal distribution of RE data, it is hardly possible to make informed decisions ranging from policymaking, investment decisions, and power sector planning.

Determination of the RE potential like solar energy of a region requires that extensive measurements of high quality be made at a large number of stations covering the major climatic zones of the region [14]. The solar energy potential of any location expressed in the form of global horizontal solar radiation (also known as solar insolation or peak sun hours) in kWh/m² is the sun's radiant energy from all directions incident on a horizontal surface on earth of unit area. It is typically expressed daily for a given month. The solar insolation is an essential parameter for sizing solar energy and irrigation systems [24, 25]. The amount of solar insolation received at any location on earth depends on the time of the day, time of the year, the local latitude, weather conditions, and the orientation of the receiving surface [13, 14, 16, 21, 22].

Four techniques can be used to estimate the solar insolation of any location across the globe. These are direct in-situ measurements using pyranometer, satellite image data processing [16, 24], derivation of solar insolation from some other measured meteorological data, and extrapolation from nearby stations. In-situ measurement, though it is more expensive than any other method [5, 13, 16, 26, 27], provides the most reliable data. However, in Ethiopia, there are only a few meteorological stations in major cities (Addis Ababa, Dire Dawa, Gonder, Bahir Dar, Jimma and Wonji) that are equipped to measure

solar radiation directly on the site [28, 37, 40]. Solar radiation data for any location in the world can be found from Surface Meteorology and Solar Energy (SSE/NASA), Solar and Wind Resource Assessment (SWERA), Photovoltaic Geographical Information System (PVGIS), SOLCAST data sets [31]. However, the data obtained from these datasets cannot be used reliably for detailed feasibility study and design as the data is interpolated or extrapolated from other regions of the world or evaluated from satellite image processing [23, 24]. Solar radiation can be obtained by conversion of readily available meteorological data such as sunshine hours, relative humidity, temperature, soil temperature, number of rainy days, altitude, latitude, total precipitable water, albedo, cloudiness, and evaporation. Authors in [11, 13, 16–19, 21, 26, 32, 33] have stated that conversion of sunshine hours into solar radiation is the most common method which has been utilized around the world where there are no solar radiation measurement facilities [14–17, 19–22, 24].

Varieties of empirical models has been developed to obtain solar radiation from other climatic parameters [13–17, 26, 33–35]. The linear Ångström-PreScott model is the most suitable and commonly utilized model to estimate solar insolation for any location from the extraterrestrial solar radiation, and the ratio of actual sunshine duration to the length of the day [17, 19, 22, 24, 28, 29, 33, 34, 36–43]. In the research work presented in [37], with the use of measured solar radiation data, it is proved that it is possible to use Ångström models to estimate solar radiation with minimal error. Authors in [38, 39] estimated the solar radiation from sunshine duration for rural areas in Southern and Northern Ethiopia by using the Ångström model. Regression coefficients of $a = 0.33$ and $b = 0.43$ are utilized for both regions. In another paper in [28], authors calculated regression coefficients from measured solar radiation and sunshine duration data for major cities and towns in Ethiopia where solar radiation measurement instruments are available, and showed different locations have different regression coefficients. Authors in [40] showed that regression constant 'a' is a cosine function of latitude while 'b' is more or less constant and proposed the use of location-specific regression constants to obtain reliable results. However, latitude, sunshine duration, and maximum day length are found important factors that determine constants 'a' and 'b' [14, 15, 19, 36, 41]. All these parameters are site-dependent [22]. However, if none of these data is available for estimation, it is possible to use values from nearby locations with similar climatological conditions [28, 32].

In this paper, monthly mean solar insolation for the four meteorological stations in East Gojjam is estimated from the relative sunshine duration and daily average extraterrestrial radiation by using regression constants, 'a' and 'b', derived from empirical formulas proposed by Samuel [16]. Sunshine duration also is known as hours of bright sunshine is the sum of all periods (in hours) during the day when the direct solar irradiance equals or exceeds 120 Wm^{-2} [19, 44]. Extraterrestrial radiation is the amount of solar radiation incident on a horizontal surface outside the earth's atmosphere; and it is obtained theoretically considering the seasonal variation of the distance between the earth and the sun [17–23, 32–34].

2 Study Area

East Gojjam Zone is one of the eleven political administrations in the Amhara Region, Ethiopia. It lies between 9.84° – 11.24° North (N) latitudes and 37.05° – 38.53° East (E)

longitudes. Figure 1(a) shows the location of East Gojjam Zone in Ethiopia. With four town administrations and sixteen rural districts, East Gojjam Zone has twenty administrative regions. The population of East Gojjam Zone is estimated to reach 3.8 million. According to government reports, only 8% of the inhabitants of East Gojjam have access to electricity [45] which is far less than the country's average electricity access of 28% [2]. The primary sources of energy in the region are fuelwood for cooking and kerosene for lighting. In East Gojjam Zone, there are only four meteorological data measurement stations located at Debre Markos (10.33°N, 37.73°E), Debrewerk (10.66°N, 38.17°E), Mota (11.08°N, 37.88°E), and Yetnora (10.17°N, 38.12°E). Black dots in Fig. 1 indicate the location of the meteorological stations in East Gojjam. These stations are administered by National Metrological Agency (NMA) Bahir Dar Branch Office. The stations gather meteorological data like temperature, rainfall, wind speed and direction, sunshine duration, etc. and none of these stations can measure solar radiation as there are no measuring instruments. The estimation of solar insolation will be done for these meteorological stations.

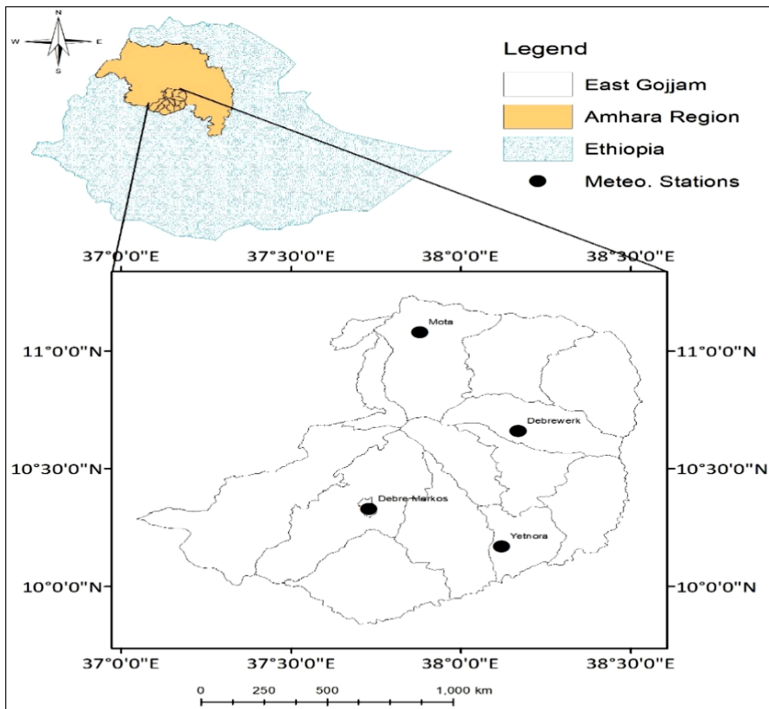


Fig. 1. Location of meteorological stations in East Gojjam Zone

3 Data and Methods

3.1 Data Collection and Preparation

The hours of bright sunshine data which covered eleven years (2008–2018) for the four meteorological stations have been obtained from National Meteorological Agency, Bahir Dar Branch. The daily hours of sunshine data are processed to obtain the monthly mean daily hours of bright sunshine for each year. The eleven years' monthly mean daily hours of bright sunshine data is processed for the second time using a simple spreadsheet to find the long term monthly average of daily hours of sunshine of the sites and the result is presented in Table 1. This data will be used subsequently to estimate the daily solar insolation and other important information for respective stations.

Table 1. Monthly average daily hours of bright sunshine for meteorological stations.

Month	Debre Markos	Debrewerq	Mota	Yetnora
Jan	8.38	10.16	9.48	10.01
Feb	9.09	9.99	10.21	9.56
Mar	7.91	10.04	8.97	9.47
Apr	7.54	10.36	9.21	8.56
May	6.57	10.28	8.99	8.28
Jun	5.16	9.60	7.01	7.39
Jul	3.13	9.07	5.50	6.29
Aug	3.70	8.58	4.76	5.64
Sep	5.36	9.90	8.46	7.14
Oct	7.98	10.25	8.29	8.94
Nov	8.51	10.20	9.30	9.60
Dec	9.35	9.93	9.73	9.95
Av.	6.89	9.84	8.33	8.40

3.2 Estimation of Solar Insolation

The monthly mean daily hours of bright sunshine data are used to estimate monthly mean daily solar insolation using the most convenient and widely used Ångström-Preseott model as given by Eq. (1) [9, 12, 14, 15, 19, 42, 43]:

$$H = H_0(a + b(S/S_0)) \quad (1)$$

where H = monthly mean daily solar insolation ($\text{kWh/m}^2/\text{day}$), S = monthly mean daily hours of bright sunshine, S_0 = monthly mean length of the day in hours which

can be obtained by using Eq. (5), ‘a’ and ‘b’ are empirical constants determined for a particular site, H_o = monthly mean daily extraterrestrial radiation (kWh/m²/day) on a horizontal surface which can be computed by [7, 12, 19, 25, 42, 43]:

$$H_o = 24G_{sc}/(1000\pi)[(1 + 0.033\cos(360d/365)) [\cos \varphi \cos \delta \sin \omega + (\pi\omega/180) \sin \varphi \sin \delta] \quad (2)$$

where G_{sc} is solar constant with a value of 1367Wm⁻², d: is the number of the day of the year starting from 1st of January as 1 and continues to December 31 as 365(366), φ (degrees): latitude of the location, δ (degrees): is sun declination angle obtained by using Eq. (4), ω (degrees): is monthly mean sunset hour angle given by [12, 25]:

$$\omega = \cos^{-1}(-\tan \varphi \cdot \tan \delta) \quad (3)$$

$$\delta = 23.45\sin (360(284 + d)/365) \quad (4)$$

The monthly mean length of the day, S_o (hours) is given by [12, 25]:

$$S_o = 2\omega/15 \quad (5)$$

Parameters d, δ , ω , S_o and H_o are estimated for the mean day of each month.

The physical significance of empirical constants ‘a’ and ‘b’ is that ‘a’ is a measure of the overall atmospheric transmission for total cloud conditions and is a function of the type and the thickness of the cloud cover, while ‘b’ is the rate of increase of H/H_o with S/S_o . Different empirical formulas have been utilized in different regions of the world to obtain ‘a’ and ‘b’ from site-specific parameters, S and S_o . Some of the most familiar expressions for ‘a’ and ‘b’ [12, 14–16, 24, 25, 32, 42] are tested with 4–9 years measured annual mean solar insolation and sunshine hour data at Gondar, Addis Ababa and Bahir Dar [28]. The results obtained using Eqs. (6) and (7) [16], were found to be better than others.

$$a = -0.27 + 1.75(S/S_o) - 1.34(S/S_o)^2 \quad (6)$$

$$b = 1.32 - 2.93(S/S_o) + 2.30(S/S_o)^2 \quad (7)$$

These expressions are adjusted until the percentage deviation of the calculated solar insolation from the measured value is less than 2% for the three test sites.

Finally, expressions presented in Eq. (8) and (9) are obtained to estimate ‘a’ and ‘b’:

$$a = -0.27 + 1.74(S/S_o) - 1.15(S/S_o)^2 \quad (8)$$

$$b = 1.32 - 2.99(S/S_o) + 2.29(S/S_o)^2 \quad (9)$$

3.3 Estimation of Clearness Index

The clearness index (K) is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1 [30]. The value 0 signifies that a total cloud cover occurs and no irradiance is to be received on the ground. Conversely, a value of 1 signifies that the maximum theoretical amount will be received on the ground i.e. clear, sunny conditions and the solar radiation reaches the earth's surface with a more direct (beam) component. Knowledge of clearness index distribution for a particular site helps in deciding whether the site is suitable for concentrating solar thermal applications or not and to estimate its thermal output [46]. The monthly mean daily clearness index K is obtained from the monthly mean daily solar insolation, H and monthly mean daily extraterrestrial solar radiation, H_0 with the following expression [23, 27, 30]:

$$K = H/H_0 \quad (10)$$

4 Results and Discussion

4.1 Monthly Mean Daily Solar Insolation for East Gojjam

The monthly mean hours of bright sunshine data are first converted into the monthly mean relative sunshine duration, S/S_0 , by dividing the observed monthly sunshine data, S , (Table 1) by the corresponding monthly mean maximum possible sunshine S_0 obtained from Eq. (5) for mid of each month. Then the monthly mean hours of bright sunshine S/S_0 for each site is used in Eq. (8), (9), (2), and (1) to obtain the monthly mean values of empirical coefficients, 'a' and 'b', extraterrestrial radiation, H_0 and solar insolation, H for all sites. H and H_0 are both in $\text{kWh/m}^2/\text{day}$. The detailed results are presented in Table 2.

The monthly mean daily hours of bright sunshine S in the region is in the range of 3.13 h at Debre Markos in July and 10.36 h at Debrewerq in April. The relative sunshine duration (S/S_0) as shown in Fig. 2 is between 0.25 at Debre Markos in July and 0.89 at Debrewerq in November and January. In general terms, the relative sunshine duration for all sites lowers from May to September and gets deeper in rainy months (June to August). Debrewerq has a more uniform profile of relative sunshine duration (between 0.69 in August and 0.89 in November and January) than any other station with an annual mean value of 0.82. In the meantime, Debre Markos has a less uniform sunshine duration (between 0.25 in July and 0.82 in December) with its annual mean value of 0.57.

As it is stated earlier, empirical coefficients 'a' and 'b' are calculated from relative sunshine duration for respective months. The monthly profile of empirical coefficients 'a' and 'b' for the four meteorological stations is shown in Fig. 3 and Fig. 4 in respective order.

As shown in Fig. 3, 'a' and 'b' are highly dependent the cloud conditions. In the rainy months of June to September, 'a' gets smaller while 'b' gets bigger. This effect is more significant for Debre Markos station while Debrewerq has more uniform 'a' and 'b' profiles.

Table 2. Monthly mean H, H_o, a, b and K for study sites

Site	Month	H _o	S/S _o	a	b	H	K
Debre Markos	Jan	8.83	0.73	0.39	0.36	5.72	0.65
	Feb	9.55	0.78	0.39	0.38	6.52	0.68
	Mar	10.23	0.66	0.38	0.34	6.20	0.61
	Apr	10.54	0.62	0.37	0.35	6.11	0.58
	May	10.45	0.53	0.33	0.38	5.51	0.53
	Jun	10.30	0.41	0.25	0.48	4.59	0.45
	Jul	10.33	0.25	0.10	0.72	2.80	0.27
	Aug	10.44	0.30	0.15	0.63	3.52	0.34
	Sep	10.30	0.44	0.28	0.44	4.87	0.47
	Oct	9.71	0.68	0.38	0.35	5.97	0.62
	Nov	8.98	0.74	0.39	0.36	5.87	0.65
	Dec	8.57	0.82	0.38	0.41	6.15	0.72
	Annual mean	9.85	0.57	0.35	0.36	5.48	0.56
Debrewerq	Jan	8.78	0.89	0.37	0.47	6.89	0.79
	Feb	9.55	0.86	0.38	0.44	7.16	0.75
	Mar	10.23	0.84	0.38	0.42	7.53	0.74
	Apr	10.54	0.85	0.38	0.43	7.83	0.74
	May	10.45	0.82	0.38	0.41	7.54	0.72
	Jun	10.30	0.76	0.39	0.37	6.91	0.67
	Jul	10.33	0.72	0.39	0.35	6.65	0.64
	Aug	10.44	0.69	0.38	0.35	6.54	0.63
	Sep	10.30	0.82	0.38	0.41	7.39	0.72
	Oct	9.71	0.87	0.36	0.49	7.83	0.81
	Nov	8.98	0.89	0.33	0.60	8.24	0.92
	Dec	8.57	0.87	0.37	0.45	6.55	0.77
	Annual mean	9.85	0.82	0.38	0.42	7.19	0.73
Mota	Jan	8.73	0.83	0.38	0.42	6.34	0.73
	Feb	9.48	0.88	0.37	0.46	7.33	0.77
	Mar	10.20	0.75	0.39	0.37	6.76	0.66
	Apr	10.55	0.75	0.39	0.37	7.00	0.66
	May	10.50	0.72	0.39	0.35	6.72	0.64

(continued)

Table 2. (continued)

Site	Month	H_o	S/S_o	a	b	H	K
	Jun	10.36	0.55	0.34	0.37	5.63	0.54
	Jul	10.38	0.44	0.27	0.45	4.86	0.47
	Aug	10.47	0.38	0.23	0.51	4.45	0.43
	Sep	10.28	0.70	0.38	0.35	6.47	0.63
	Oct	9.65	0.71	0.39	0.35	6.10	0.63
	Nov	8.88	0.81	0.38	0.40	6.30	0.71
	Dec	8.46	0.86	0.38	0.44	6.37	0.75
	Annual mean	9.83	0.70	0.38	0.35	6.15	0.63
Yetnora	Jan	8.85	0.87	0.37	0.45	6.80	0.77
	Feb	9.56	0.82	0.38	0.41	6.86	0.72
	Mar	10.24	0.79	0.39	0.39	7.12	0.69
	Apr	10.54	0.70	0.38	0.35	6.63	0.63
	May	10.44	0.66	0.38	0.34	6.33	0.61
	Jun	10.28	0.59	0.36	0.35	5.79	0.56
	Jul	10.31	0.50	0.31	0.40	5.28	0.51
	Aug	10.44	0.46	0.29	0.43	5.03	0.48
	Sep	10.30	0.59	0.36	0.35	5.83	0.57
	Oct	9.72	0.76	0.39	0.37	6.51	0.67
	Nov	9.00	0.83	0.38	0.42	6.56	0.73
	Dec	8.59	0.87	0.37	0.45	6.60	0.77
	Annual mean	9.86	0.70	0.38	0.35	6.21	0.63

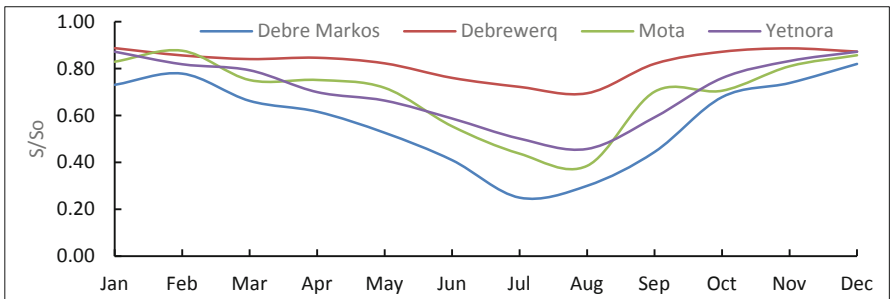


Fig. 2. Monthly profile of relative sunshine duration for meteorological stations

Using respective values of ‘a’, b, S/S_o , and extraterrestrial radiation H_o , the solar insolation profile as shown in Fig. 5 is obtained. As it is shown in the figure, the solar

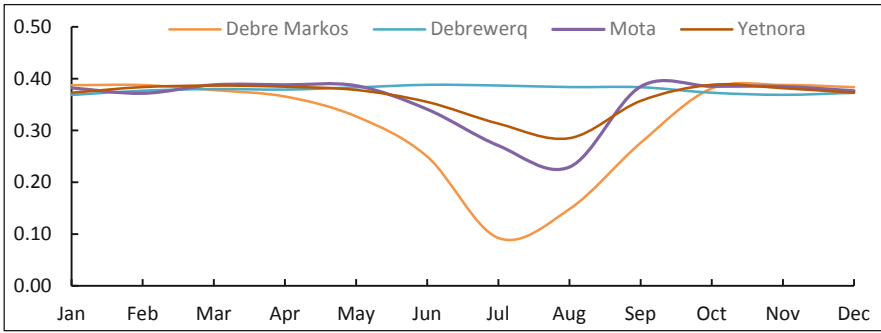


Fig. 3. Monthly profile of 'a'

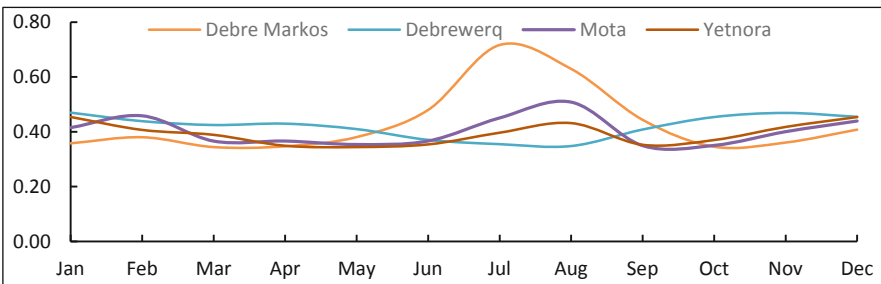


Fig. 4. Monthly profile of 'b'

insolation for the meteorological stations from October to February is close to each other. However, for the rainy months of June to September, the values are significantly different from each other. The solar insolation profile at Debre Markos site shows significant variability from month to month being the lowest in July and the highest in February while Debrewerq receives the highest and more uniform solar radiation throughout the year.

The monthly mean clearness index, K for the study sites is as shown in Fig. 6. The clearness index gets deeper in the rainy months (June to September) because of thick clouds in the sky. Debre Markos and Debrewerq demonstrate the lowest and the highest clearness indices, respectively.

4.2 Ångström-Prescott(A-P) Model for East Gojjam Zone

For each study site, the annual mean values of coefficients, 'a' and 'b' are calculated; and the A-P model was derived for each site as presented in Table 3. From Table 3, the average values of 'a' and 'b' for East Gojjam are both 0.37.

From the annual mean values of a, b, S/S₀ and H₀, the annual mean solar insolation for the meteorological stations is obtained; and the result is presented in Table 4.

As presented in Table 4, Debrewerq receives the highest annual mean daily solar insolation (7.05 kWh/m²/day) followed by Yetnora (6.16 kWh/m²/day) and Mota

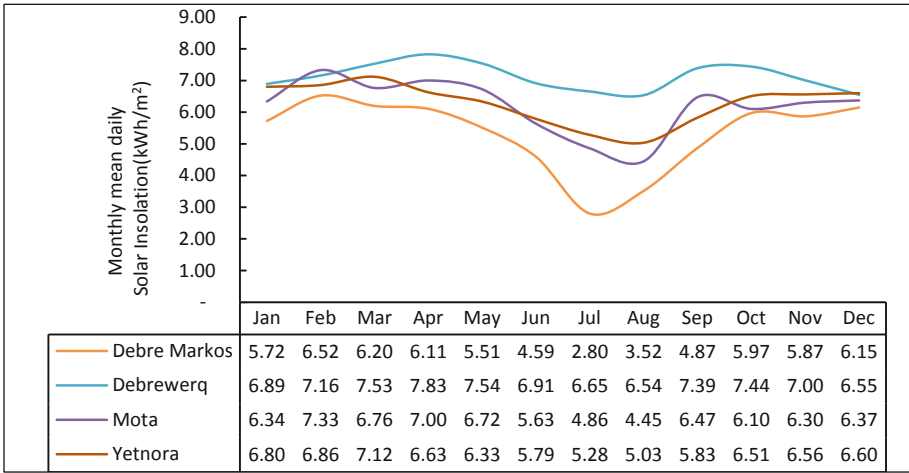


Fig. 5. Monthly mean insolation values for study sites

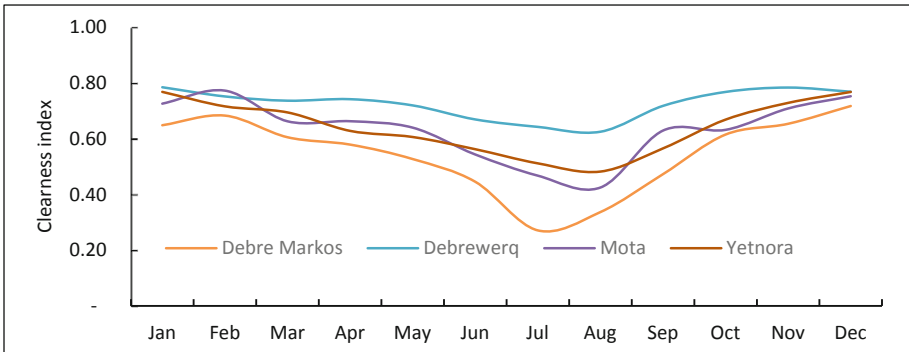


Fig. 6. Monthly mean clearness index profile of the study sites

Table 3. Angstrom-Prescott model for study sites

Site	a	b	Å-P Model
Debre Markos	0.35	0.36	$H/H_o = 0.35 + 0.36S/S_o$
Debrewerq	0.38	0.41	$H/H_o = 0.38 + 0.42 S/S_o$
Mota	0.38	0.35	$H/H_o = 0.38 + 0.35 S/S_o$
Yetnora	0.38	0.35	$H/H_o = 0.38 + 0.35 S/S_o$
Average (East Gojjam)	0.37	0.37	$H/H_o = 0.37(1 + S/S_o)$

(6.151 kWh/m²/day) in descending order. However, even though, Debre Markos and Debrewerq receive the same magnitude of extraterrestrial radiation (9.85 kWh/m²/day),

Table 4. Annual mean values of S/S_0 , a, b, H_0 and H

Site	S/S_0	a	b	H_0	H
Debre Markos	0.57	0.35	0.36	9.85	5.47
Debrewerq	0.82	0.38	0.41	9.85	7.05
Mota	0.69	0.38	0.35	9.83	6.11
Yetnora	0.70	0.38	0.35	9.86	6.16
Average	0.70	0.37	0.37	9.85	6.20

Debre Markos receives the lowest annual mean solar insolation among the four study sites because of its lowest clearness index (as shown in Fig. 4) and sunshine duration resulted from mostly cloudy days throughout the year. In general, the mean global horizontal radiation for East Gojjam Zone is 6.20 kWh/m²/day which actually tells that the region has a very good solar energy potential. Taking the results in Fig. 2 and Table 4 in mind, Debrewerq is the best site in the study area for solar energy projects with 82% of annual mean relative sunshine duration and uniform solar radiation profile throughout the year.

5 Conclusion

Knowledge of energy resource potential helps in making policies, investment decisions and power sector planning. In this paper, the result of the assessment of solar energy potential for East Gojjam Zone is presented. The solar energy potential expressed in the form of solar insolation was obtained from sun-shine hour data which was collected from NMA Bahir Dar Branch. Ångström-PreScott Model has been adopted and utilized to calculate solar insolation from extraterrestrial radiation and the ratio of hours of bright sunshine to length of the day. The adopted A-P model is $H = 0.37(1 + S/S_0)$. The solar insolation profile at Debre Markos and Debrewerq demonstrates the maximum and the minimum variability during the year, respectively. East Gojjam Zone receives the highest solar radiation (7.83 kWh/m²/day at Debrewerq) in April and the lowest solar radiation (2.82 kWh/m²/day at Debre Markos) in July with an annual mean value of 6.20 kWh/m²/day which is considered as a very good solar resource potential. Comparing meteorological stations in terms of uniformity of solar insolation profile, clearness index, and annual mean solar insolation, Debrewerq, and Debre Markos are being the best and worst sites, respectively for solar photovoltaic energy generation investments.

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