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Original Research

Assessment of Solar Energy Potential for Solar Cooking - a Case of Daassenech, Ethiopia

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Abstract

The main aim of this paper is to explore the available solar energy potential for the purpose of designing and experimental analysis of small-scale low-cost solar cookers in the Daassenech area. Solar energy evaluation is done based on sunshine data collected from the Ethiopian national metrology agency and other four satellite-based data are analyzed from different freely accessible international databases. The averages of the five solar radiation data sources are used to estimate the solar energy potential of the area. From the estimated solar energy potential of the study area, the maximum global solar radiation is obtained in the month of February (6.563 KW/m2/day) and minimum in the month of July (5.578 KW/m2/day) and the overall annual average daily solar radiation of the area is 6.134 KW/m2/day. Finally, based on the estimated solar energy potential, a small-scale low-cost solar cooker has been designed and tested. Experimental values of the first figure of merits are 0.1349, 0.1238, and 0.1453 for conventional BSC, improved BSC with and without thermal storage, respectively. The second figure of merits of all solar cookers' average values are calculated as 0.524, 0.97, and 1.0964 for conventional box solar cookers, improved solar cookers with thermal energy storage, and ISC without any TES respectively.

Keywords: Solar radiation, solar energy potential, solar cooker, solar thermal system

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1. INTRODUCTION

Detail data about solar radiation is the main input in designing of photovoltaic and solar collector thermal systems, even in building designing and agroindustry processes solar radiation data is very important (Dlamini et al., 2017). Unfortunately, in developing countries like Ethiopia there are not as much as enough technological instruments to conduct detail meteorology related measurements including solar radiation. So, to overcome this problem, different analytical models have been assessed and developed to estimate solar radiation in different parts of the world by using geographical data and simple meteorological data by using air Temperature such as in Swaziland by using sunshine hour such as in USA (Allen, 1997), Nigeria (Umoh, 2013) etc. In fully organized meteorological agencies all meteorological parameters such as atmospheric temperature and pressure, relative humidity, number of sunshine hours, wind speed, cloud cover, and rainfall can be available. But in developing countries some of meteorological parameters may not be available for specific locations.

As an initial point in solar energy estimation, one should have knowledge about extraterrestrial solar radiation; it depends on solar constant, geographical location, solar hour angle and day of the year. Solar constant is solar insolation outside the earth atmosphere. After many revised measurements NASA was indicated the value of the solar constant to be 1353 W/m^2, recently well-known frequently used value of solar constant is 1367 W/m^2. Since the earth's orbit is elliptical, the earth–sun distance varies during a year, Therefore, the extraterrestrial radiation, I_o, also varies by the inverse square law (Goswami, 2015).

$$I_o = I_{sc}(D_O/D)^2$$

$$(D_O/D)^2 = 1.00011 + 0.034221cosX + 0.00128sinX + 0.000719cos2X + 0.000077sin2X$$

Where, D_O/D is the ratio between distances from sun to extraterrestrial and sun to earth.

I_{sc} is the solar constant,

$X = 360(n-1)/365$, n is day number.

Then it is approximated without significant accuracy loss to: (Goswami, 2015)

$$I_N = I_{sc}\left[1 + 0.034\, cos\left(\frac{360n}{365.25}\right)^0\right] \quad \text{.....1}$$

Extraterrestrial radiation incident on horizontal surface is the product of extraterrestrial radiation incident normal to horizontal surface and zenith angle.

$I_o = I_{sc}\left[1 + 0.034\cos\left(\frac{360n}{365.25}\right)^o\right](\cos\emptyset\cos\delta\cos\omega + \sin\emptyset\sin\delta)$ ……..…….... 2

By integrating the above equation in terms of solar time angle, daily extraterrestrial solar radiation outside the atmosphere (Ho) can be derived that is known as Klein relationship:

$Ho = \frac{24\,x3600\,Isc}{365}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]\left(\cos\emptyset\cos\delta\sin\omega s + \frac{\pi\omega s}{180}\sin\emptyset\sin\delta\right)$……...3

3.2.Fundamental angles of sun with earth

Fundamental angles of sun are hour angle, latitude, and declination. Other angles like solar incidence, azimuth etc. must be related to these fundamental angular quantities (Goswami, 2015).

Declination (δ): The declination (δ) for each day of the year can be found from the equation of Cooper (1969) as cited by Duffie (2006):

$\delta = 23.45\sin(\frac{360}{365}(284 + n))$ ……*4*

Where, n is number of the day between (1 to 365)

Equation Spencer (1971) as cited by Duffie (2006):

$\delta = \left(\frac{180}{\pi}\right)(0.006918 - 0.399912\cos B + 0.070257\sin B - 0.006758\cos 2B + 0.000907\sin 2B - 0.002697\cos 3B + 0.00148\sin 3B)$ …… *5*

The value of B given by, $B = (n-1)\frac{360}{365}$

But for engineering calculation, simple equation with sufficient accuracy can be chosen. The maximum rate of change of declination is about 0.4° per day. [3]

Sunset hour angle (ω_s) is a solar hour angle at zenith angle of 90° that is corresponding to a sunset solar time. By substituting $\omega = \omega_s = 90^o$ into equation of $(\cos\emptyset\cos\delta\cos\omega + \sin\emptyset\sin\delta)$,

$$\cos\omega_s = -\tan\varphi\tan\delta \quad \text{…… 6}$$

Solar time: - is a reckoning of the passage of time with reference to the position of the Sun in the sky, which has the fundamental unit of a day.

$$Solar\ time - standard\ time = 4(L_{st} - L_{loc}) + E$$

Where, $E = 229.2\,(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B)$

$B = (n-1)\frac{360}{365}$ Where, n is the number of the given day in the year.

In Ethiopia, estimation of solar energy based on sunshine data has been used frequently in different researches for solar radiation energy estimation and for designing purpose of solar systems.

(Bekele et al., 2013; Venkatachalam et al., 2019; Bayou & Assefa, 1989; BEZABIH, 2021; Drake & Mulugetta, 1996; Mahmud et al., 2014; Worke et al., 2020; Milikias,2020)

Neway A. (1996) estimated solar radiation energy on a horizontal surface, for nine meteorological stations in Ethiopia. He computed solar radiation by using sunshine data based on Ångström relations and compared with their corresponding global solar radiation on a horizontal surface value; he also obtained Regression coefficients and determined correlation equations to predict the global solar radiation. He explained based on the results, Ångström relations are valid for Ethiopian locations, and the correlation equations can be used to predict the monthly mean daily global solar radiation in the locations considered in the study (Argaw, 1996).

Solar energy can be practical as a thermal energy or electric energy source. Solar thermal energy has been applying for heating, cooking, or drying purposes. Solar electric energy is used by generating electric power from sun light by using PV panels, which is called photovoltaic (PV) energy. A solar cooker is a cooking device that makes utilize of only sunlight as an energy supply to cook food, heat up water, purify water and sterilize health instruments. By using solar cooker time, cost and effort that spend to collect firewood to traditional biomass oven can save. Disease causing indoor air pollution, forest deforestation and other related problems can be reduced.

The history of solar cookers started early from 18th century. Some of those documented histories, A German Physicist, named Tschirnhausen (1651–1708), carried out experiments on solar cookers (Soni & Chourasia, 2014). By the year 1767, Swiss scientist Nicholas de Saussure (1740-1799) built a black insulated solar cooker by using greenhouse effect of glass boxes placed inside one another then blackened surface in it (TIDE, 1998). Now days there are countless modification and so many styles of solar cookers. Many researchers have taken theoretical and experimental performance investigations for the different solar cookers for possible uses, such modifications focused on sun tracking system (Yettou et al., 2012), outer-inner reflectors, different insulating materials, a modified absorber plate (Melkamu Bayabl & Balasuadhakar, 2019; Terres et al., 2014; (Harmim et al., 2010), a modified utensil, and a storage system. Generally solar cookers are classified as Direct and Indirect type solar cookers.

Fortunately, the area is blessed with the high solar intensity, so using this high energy to domestic and medium level for health centers and education purpose is can also be the better mitigation application of solar energy. However, the area is a remote location, the available solar potential is not utilized due to unrevealed solar potential and no solar technologies reached to this area. So,

the main aim of this paper is to explore the available solar energy potential and designing and experimentally testing solar cooker in the selected area.

2. MATERIALS AND METHODS

3.3.Geographic locations of selected site

The study area is located at 4°49′59″ or 4.83333° N and Longitude: 36°06′00″ or 36.10° E with an elevation of 367 m above sea level. Geographical Location of Nairobi: -1°17'S, 36°49'E (To use this for solar time determination. Solar time in Daassenech (Omorate) and local time based on Nairobi location has 0.07 up to 17.9-minute differences depending on the day number of the year).

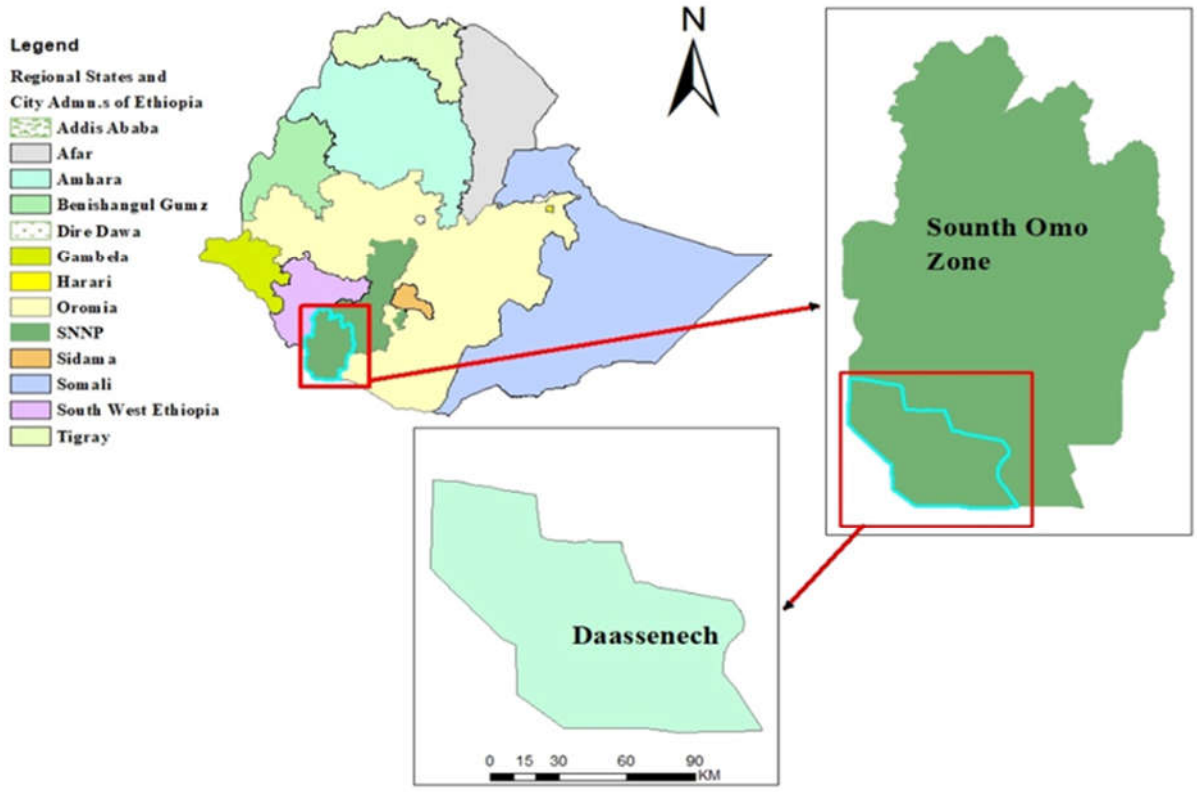


Figure 1. Location of Study area in the Country map

Solar energy data was collected from different websites and from National meteorology Agency of Ethiopia from South Nation Nationality Station (NMAE).

Website based solar radiation data were collected from:

1. Travel weather averages, https://www.weatherbase.com/weather,
2. HelioClim-1 Database, http://www.soda-is.com , data provider is MINES ParisTech -Armines (France)

3. MERRA-2 meteorological data, http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2, a provider is National Aeronautics and Space Administration (NASA)/ Goddard Space Flight Center
4. HOMER energy, http://www.homerpro.com, as a resource of National Solar Radiation Database

2.1. Solar potential examination

2.1.1. Monthly average Daily solar radiation estimation

Global monthly average daily radiation

The Angström-prescott model between sunshine duration and the amount of global solar radiation is as follows:

$$\frac{H}{Ho} = a + b\frac{n_s}{N} \quad \ldots\ldots 7$$

Where H is the daily total amount of global solar radiation at the ground surface, H_o is the daily total amount of global solar radiation outside the atmosphere, n is the sunshine duration, N is the maximum possible sunshine duration, and a and b are constants

$$a = -0.110 + 0.235\cos\varphi + 0.323\left[\frac{n_s}{N}\right],$$

$$b = 1.449 - 0.533\cos\varphi - 0.694\left[\frac{n_s}{N}\right]$$

Average days for each month are January 17, February 16, March 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14, and December 10

Diffuse monthly average daily radiation

Diffuse solar radiation is solar radiation which reaching the earths' surface after scattered in the atmosphere. Prediction of monthly average daily diffuse radiation on a horizontal surface (H_d) can be given as

$$H_d = H\left[0.931 - 0.814\left(\frac{ns}{Ns}\right)\right]$$

Beam monthly average daily radiation

Beam solar radiation is direct solar radiation which reaching the earths' surface without scattering in the atmosphere. Monthly average daily beam radiation on a horizontal surface (H_b) is the difference between global and diffuse monthly daily average radiation (H_b=H-H_d).

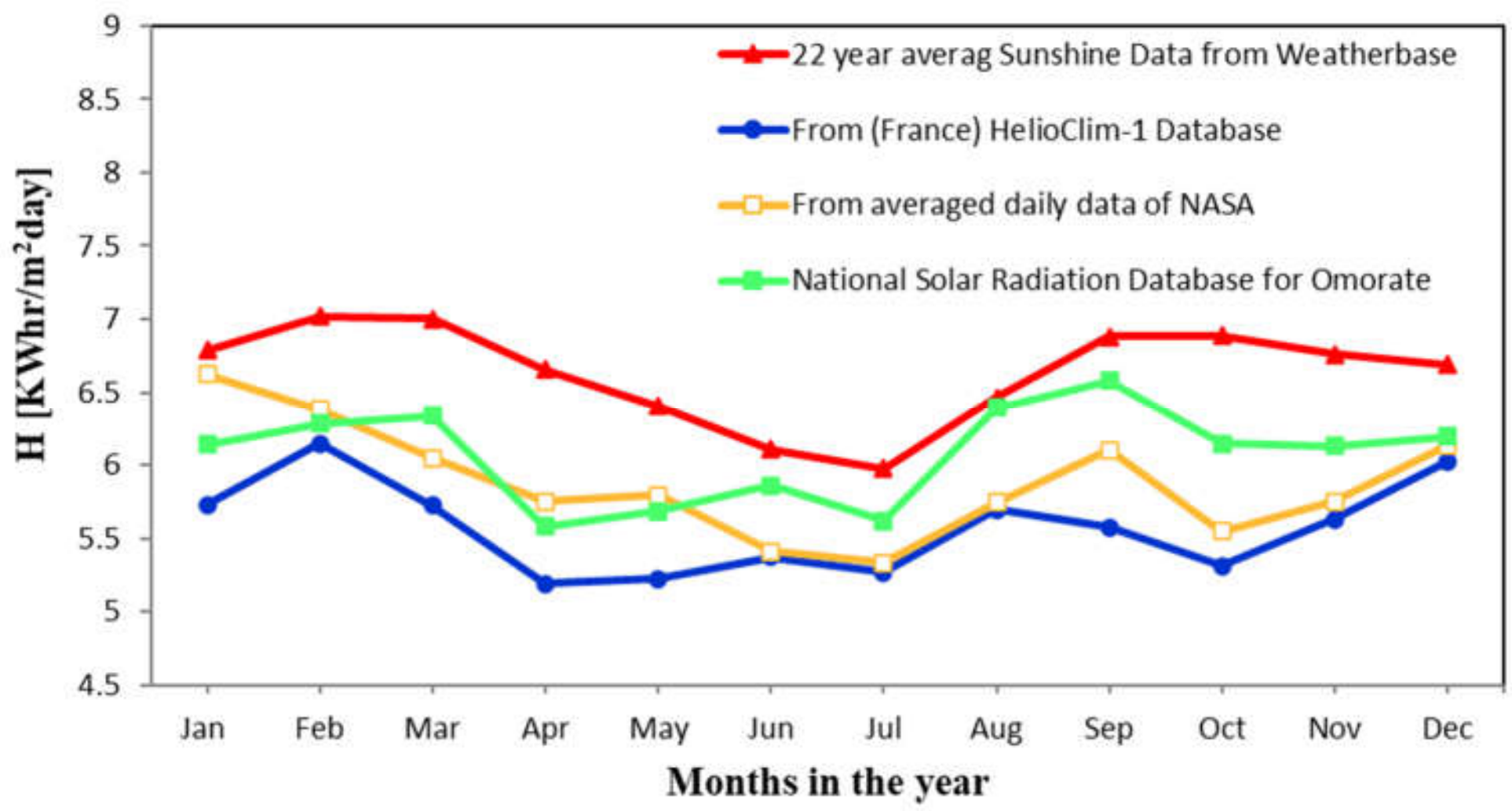


Figure 1. solar radiation obtained from different data sources

Sunshine data is used to single out the radiation components in the global solar radiation, so it should be calculated from averaged solar radiation. From averaged global solar radiation, the ratio of measured average sunshine to possible maximum sunshine (ns/N) can be calculated as follows: Let us assume, ($x = \frac{ns}{N}$) to substitute in the Ångström relations.

$$\frac{H}{Ho} = [-0.11 + 0.235\cos(\varphi) + 0.323x] + [1.449 - 0.533\cos(\varphi) - 0.694x]x$$

$$\frac{H}{Ho} = [-0.11 + 0.235\cos(\varphi)] + [0.323 + 1.449 - 0.533\cos(\varphi)]x - 0.694x^2$$

$$+ [0.323 + 1.449 - 0.533\cos(\varphi)]x + \left[0.235\cos(\varphi) - \frac{Ha}{Ho} - 0.11\right] = 0$$

$$\frac{H}{Ho} = -0.694x^2 + 1.241x + \left[0.1242 - \frac{Ha}{Ho}\right] = 0$$

In Quadratic equation form: $ax^2 + bx + c = 0$

The solution for quadratic equation: $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

2.1.2. Monthly average hourly solar radiation estimation

Global hourly solar radiation estimation

Prediction of monthly average hourly global radiation on a horizontal surface (I)

$$I = \frac{H\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 8$$

Where, $a = 0.409 + 0.5016\sin(\omega_s - 60)$ and $b = 0.6609 - 0.4767\sin(\omega_s - 60)$

Diffuse hourly solar radiation estimation

Prediction of monthly average hourly diffuse radiation on a horizontal surface (Id)

$$I_d = \frac{H_d \pi}{24} \frac{cos\omega - cos\omega s}{sin\omega s - \frac{\pi}{180}\omega s cos\omega s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 9$$

Beam hourly solar radiation estimation

Estimation of monthly average hourly beam radiation on a horizontal surface (Ib)

$$I_b = I - I_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 10$$

As it can be observed from the graphs (figure 3 and 4) February has maximum global radiation and January has highest direct beam radiation.

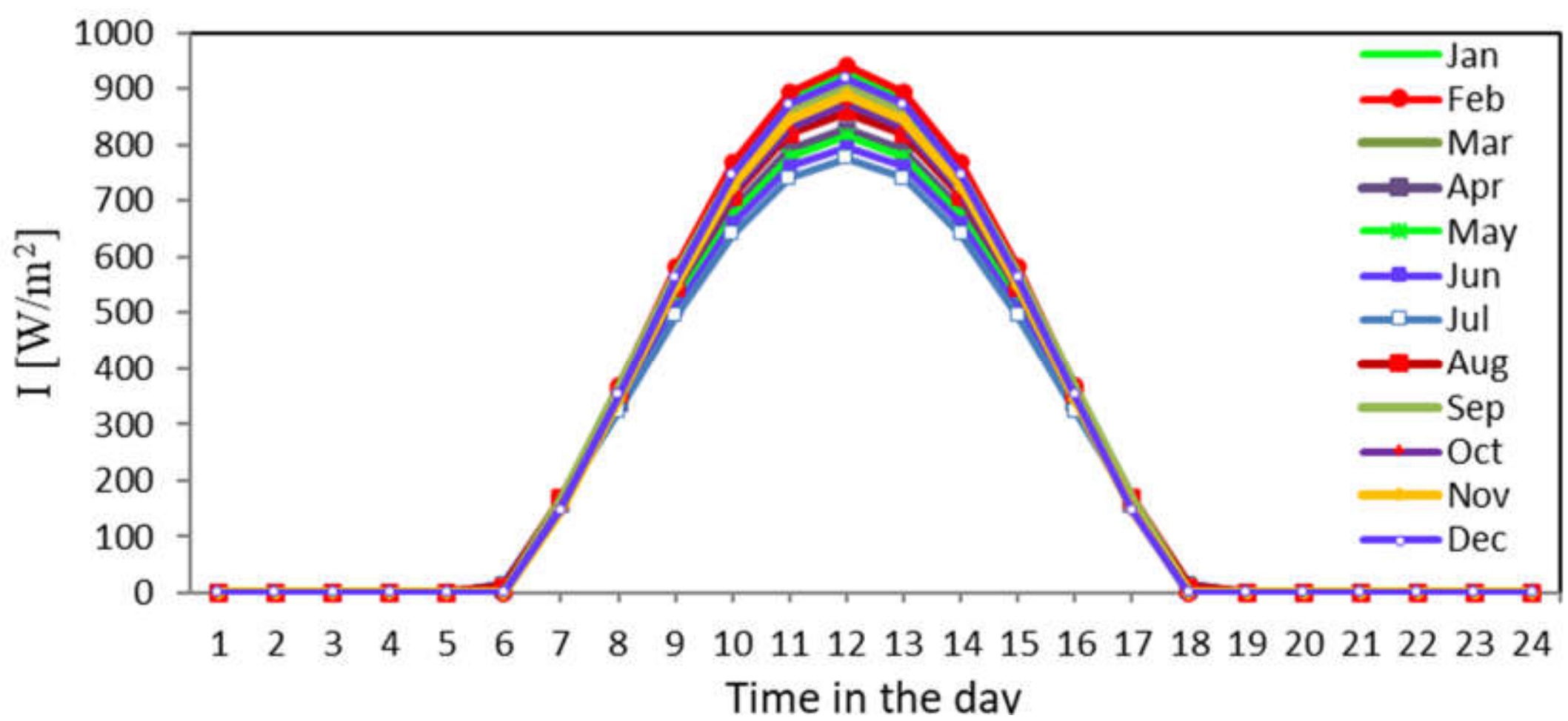


Figure 3. Monthly Average Hourly Global Radiation on Horizontal surface

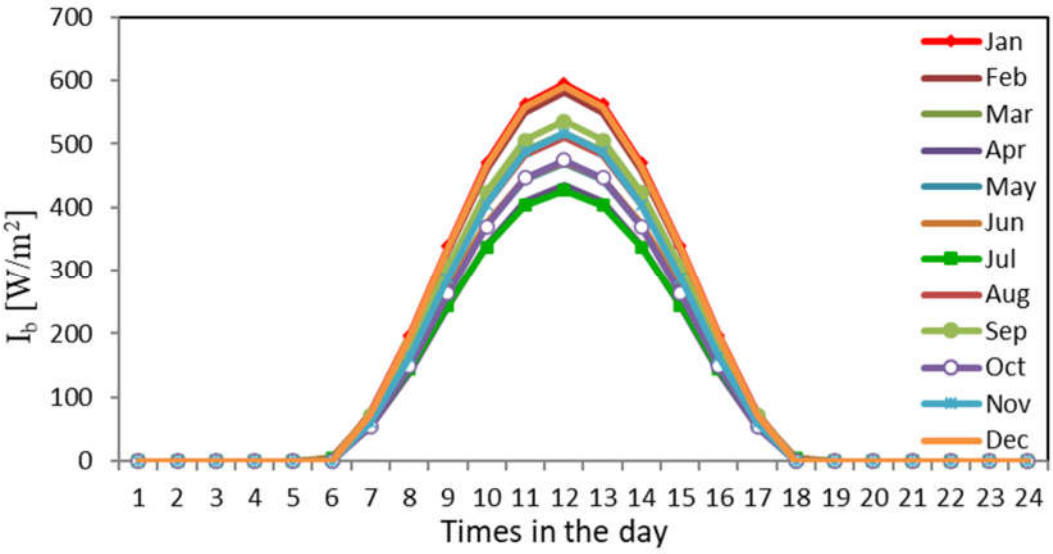


Figure 2. Monthly Average Hourly Direct Radiation on Horizontal surface

3.4.Design of box type Solar cookers

Based on the estimated solar power the absorber area is analyzed and then two different systems are designed. The conventional box type with square base and improved type with trapezoidal base but with the same absorber area are designed and constructed.

Required thermal energy,

$$Qw = Mw * Cp * \Delta T = \ 2 * 4200 * (93 - 30)KJ$$

$$Qw = 2 * 4200 * (93 - 30)J = 529.2KJ$$

Required energy rate for cooking ($\dot{Q}w$)

$$(\dot{Q}wr) = \frac{529.2 * 10^3 J}{(120 * 60)\ Sec} = 73.5\ W$$

Energy loss by evaporation ($\dot{Q}w$)

$$\dot{Q}wl = \frac{m_{\ \iota} x\ h_{fg}}{\Delta t} = \frac{\left(\frac{10}{100} * 2\right)\ Kg * 2342\ * 10^3\ \frac{\mathrm{J}}{\mathrm{Kg}}}{(120 * 60)\ \mathrm{sec}}$$

$$\dot{Q}w = 65.06\ W$$

Energy loss through insulation and glaze (7% loss) ($\dot{Q}\iota$)

$$\dot{Q}\imath = \mathrm{Ag}\left(\frac{7}{100} * I_{av}\right) = \mathrm{Ag}\left(0.07 * 600\frac{W}{m2}\right) = (42 * \mathrm{Ag})\frac{W}{m2}$$

Total power required $\dot{Q}t = 73.5 + 65.06 = 138.56\ \mathrm{W}$

Minimum aperture area of the cooker (A_g),

$$\mathrm{Ag} = \frac{\dot{Q}w}{I_{av} - 0.07I_{av}} = \frac{138.56}{600 - 42} = 0.248\ m^2$$

0.25m^2 collecting area for 2 kg load is selected based on Solar cooker full load testing standard thumb rule that is 8kg/m^2 collector area [13] The absorber area and collector area for convectional solar cooker is the equal. Therefore, collector area is 0.25m^2. As Shringi (2016) described square absorber is better than rectangular one in conventional cooker [14]. Therefore, the aperture (Glazing) area can be 0.5m x0.5m.

3. RESULTS AND DISCUSSIONS

3.1. Average Solar radiation from different sources

Solar radiation data for Daassenech (Omorate) has been collected from different sources and its average has been calculated to use as the input for designing of solar powered thermal system and PV system. Except nearby data of Jinka city from NMAE, all other solar radiation data are collected from websites and software such are RETscreen and HOMER.

Radiation data from Weatherbase is calculated from twenty-two years averaged sunshine data that was obtained from weather averages website (www.weatherbase.com)[15]. Radiation data from helioclim-1 database is obtained from HelioClim-1 Database of Daily Solar Irradiance which is derived from satellite data. HelioClim-1 database of Daily Solar Irradiance is provided by MINES ParisTech-Armines (France) and it is available in their website (www.soda-is.com)[16]. NASA surface meteorology and solar energy database is one of radiation data sources which provided also twenty-two years averaged data (July 1983- June 2005). Its cell midpoint that is near to Omorate city is Latitude 4.5 and Longitude 36.5 with cells dimension of 1°x1°. National Solar Radiation database (NSRD) is provided averaged data in different cell midpoint in latitude 4.774 and longitude 36.11831 with cell dimension of 40 km x 40 km. Both NASA surface meteorology and solar energy and National Solar Radiation database are available in HOMER software.

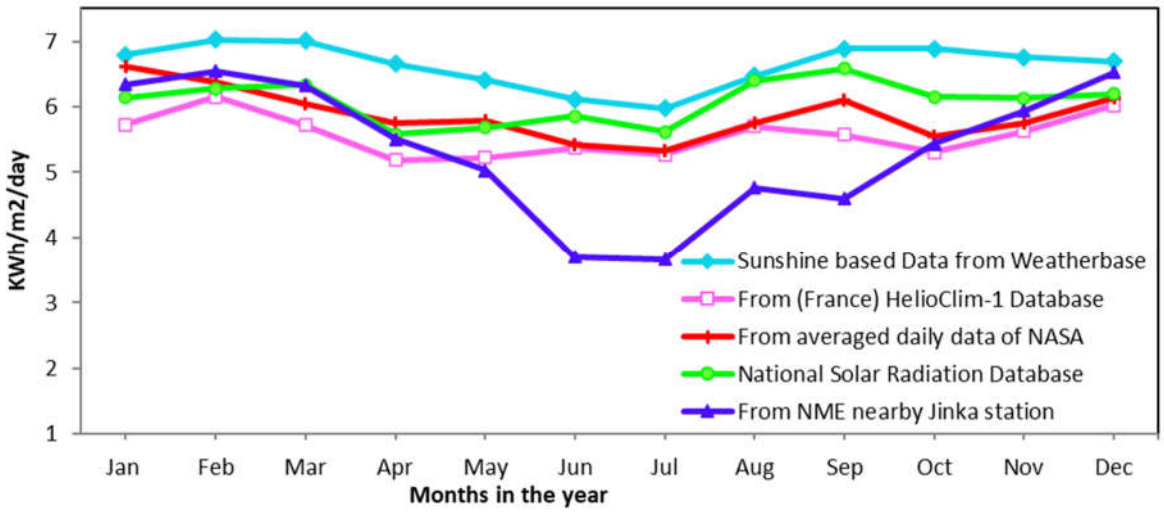


Figure 3. Comparison of calculated solar radiation with obtained from different data source

The nearby data of National Meteorological Agency (NMA) of Ethiopia from Jinka station was collected from SNNPR, Hawassa NMA branch, but it is measuring only weather condition of the city and nearby areas. Around Jinka city, it is rainy season from May up to September for four months. Except those months the weather condition of Daassenech (Omorate) and Jinka is almost near to each other. Therefore, it is possible to take an average solar radiation from different recorded data bases for the selected site except from nearby NMA sunshine based data of Jinka, then averaged result is shown in graph below.

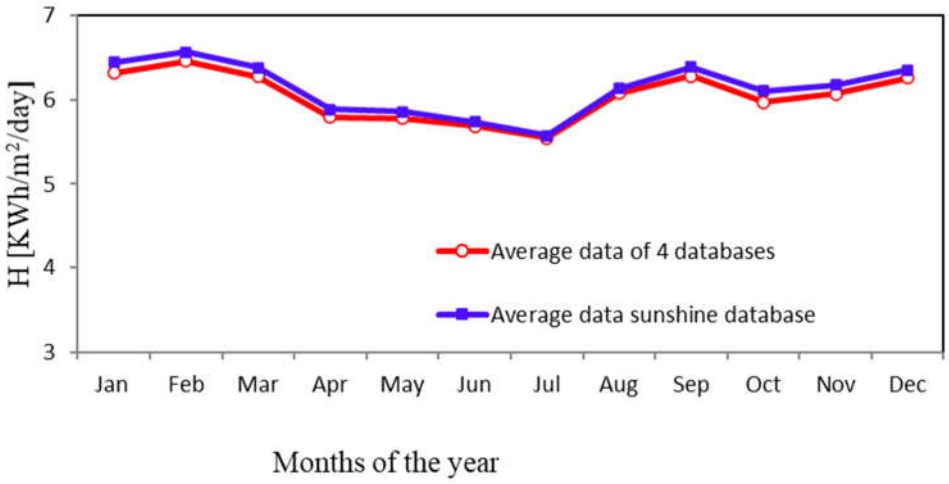


Figure 4. (Averaged) Monthly average daily solar radiation for Daassenech

The results of global and diffuse radiation components are presented below (Figure 5a-h) in graph three months in each graph.

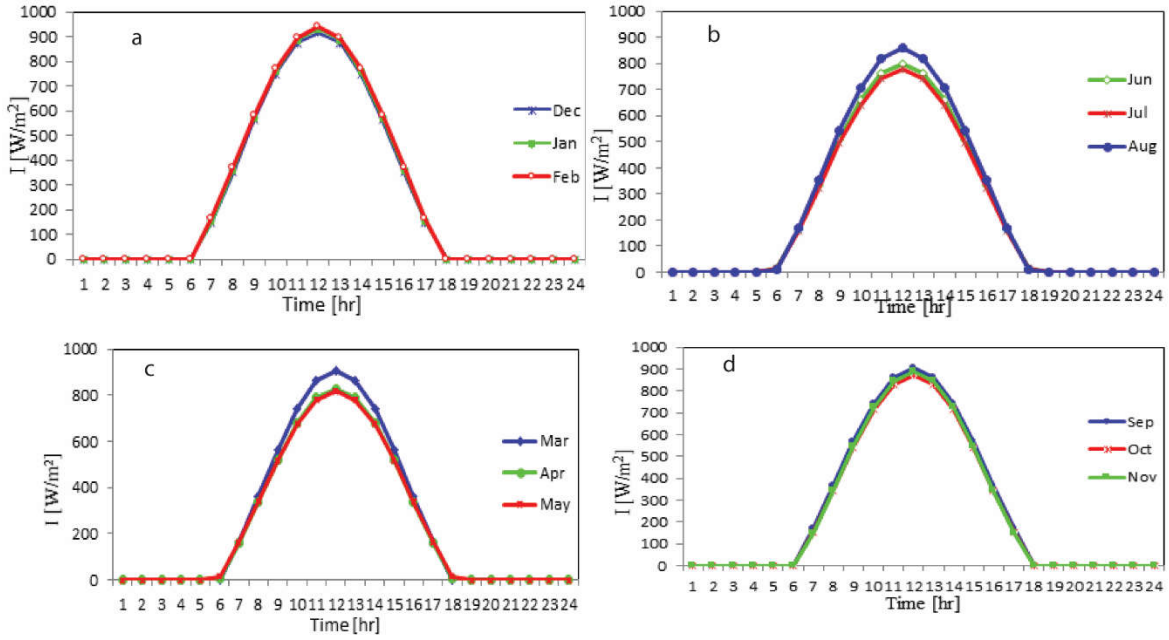
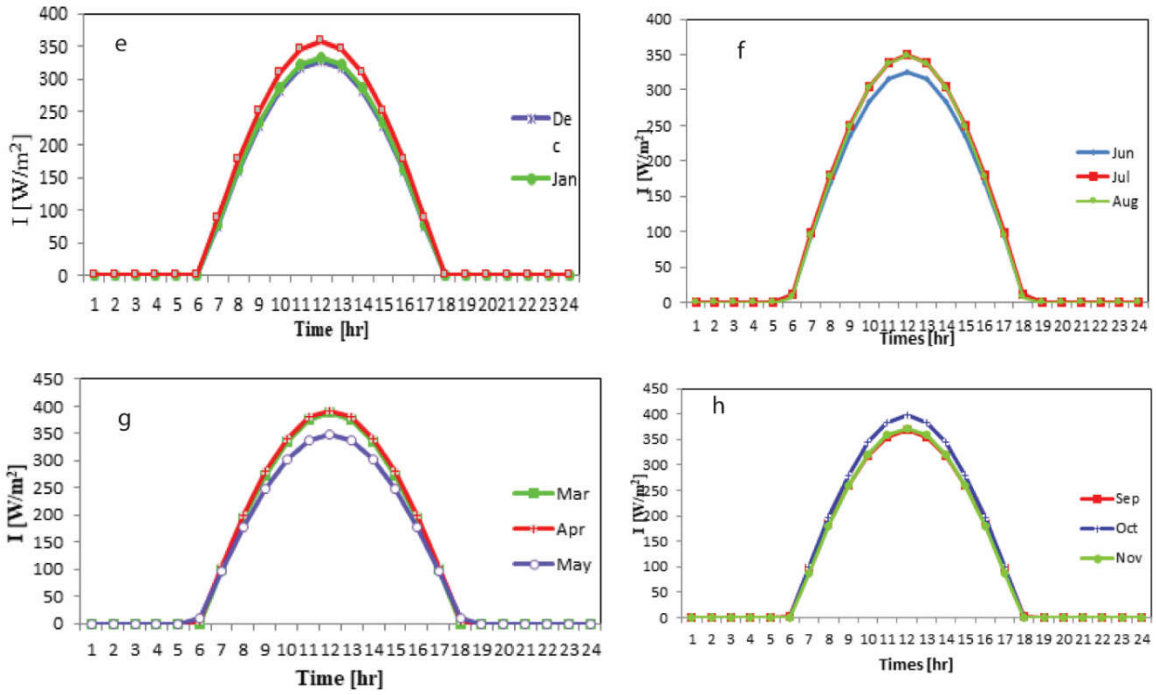


Figure 7. (a) Monthly average Hourly GSR of Winter Season (Averaged), (b) Monthly average Hourly GSR of Summer season, (c) : Monthly average Hourly GSR of Spring season. (d) Monthly average Hourly GSR of Autumn (Fall), (e) Monthly average Hourly diffuse solar radiation of Winter Season, (f) Monthly average Hourly diffuse solar radiation of Summer Season



(g) Monthly average Hourly diffuse solar radiation of Spring Season, and (h) Monthly average Hourly diffuse solar radiation of autumn (fall) Season

An average solar radiation is calculated as maximum in February (6.563 KW/m^2/day), minimum in July (5.578 KW/m^2day) and Annual Average daily solar radiation is 6.134 KW/m^2day.

Table 1. Average Solar Radiation Results of different source

Months	Sunshine based data weatherbase	Helioclim-3 satellite (France)	NASA data base	National SRD for Omorate	Average of 4 Solar data	NMA data for Jinka	Sunshine based average data
Jan	6.789054	5.730194	6.6216	6.139	6.31997	6.3500571	6.443829
Feb	7.021081	6.147429	6.3814	6.284	6.4585	6.5470284	6.562697
Mar	7.003777	5.723226	6.0490	6.339	6.27876	6.3302545	6.379182
Apr	6.655736	5.1912	5.7507	5.584	5.7954	5.5039623	5.887446
May	6.402462	5.227355	5.7976	5.688	5.77885	5.0319579	5.860035
Jun	6.106914	5.3752	5.4133	5.859	5.6886	3.6965191	5.735646
Jul	5.976383	5.266452	5.3372	5.621	5.5503	3.6586676	5.577911
Aug	6.466117	5.69729	5.7468	6.396	6.07655	4.7657556	6.131786
Sep	6.883461	5.5748	6.1037	6.579	6.2852	4.6036796	6.388194
Oct	6.887971	5.311355	5.5482	6.148	5.9739	5.4368955	6.109012
Nov	6.760407	5.6308	5.7507	6.131	6.06822	5.9481028	6.175466
Dec	6.691206	6.024774	6.1348	6.196	6.2617	6.5290217	6.351157
Annual Average daily solar radiation							**6.134 /m2/day**

3.2.Experimental testing of the thermal System

Two solar cookers designed and constructed with the same absorber area based on the estimated solar potential: conventional and improved for the selected area weather condition as shown in Figure 8. (Milikias et al., 2021).



Figure 8. Experimental setups and cooking tests

3.2.1. Experimental Temperature distribution

The data that was collected from the experiment included: ambient temperature (Ta), Plate temperatures (T_p), Water temperatures (T_w) and cooking time were measured at 20 minutes interval for 16 hours (8:00 – 24:40) for stagnation test and at 10 minutes interval for full load test for 4 hours (10:00 -14:00) by following standard recommended by the Bureau of Indian Standards (BIS, 2000). The raw data was measured by the four-channel digital k-type thermocouple and ambient temperature was measured by mercury glass thermometer, then it was entered into Excel spreadsheet and analyzed. The full load test and No-Load test (stagnation) plate temperature distribution also presented by graphs through Figure 9 and 10.

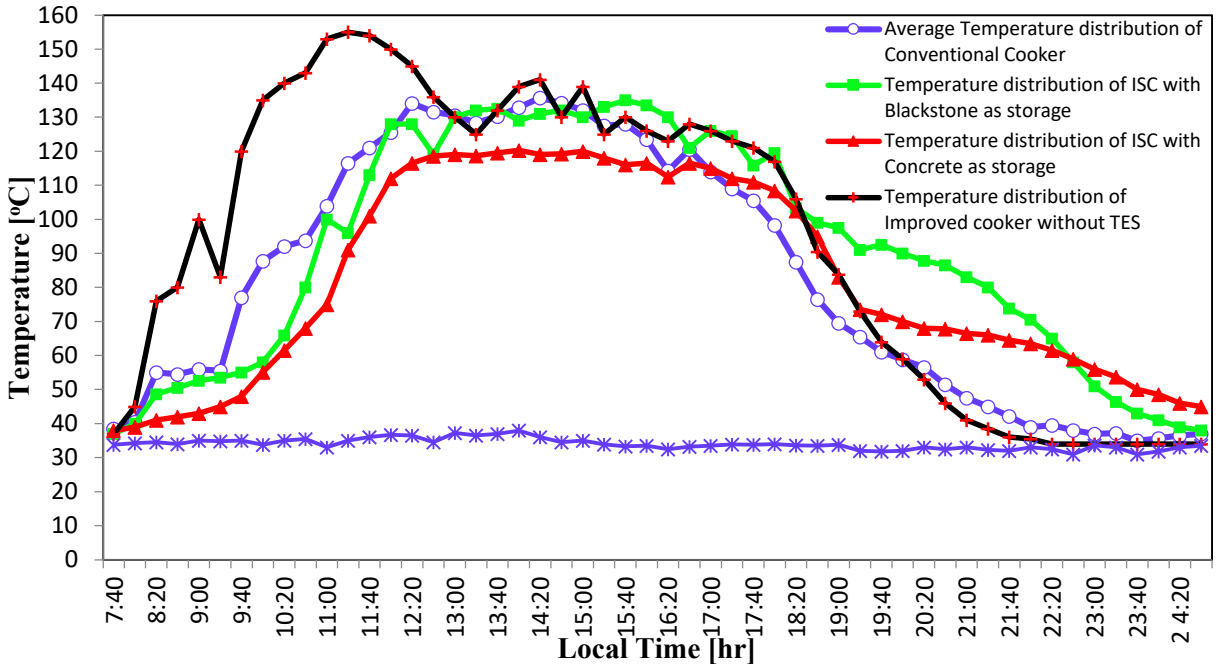


Figure 9. Comparing of plate temperature of IBSC with Average CBSC

In full load water test equal amount of water added for both cookers and stayed for 4 hours. Water testing was started in 10:00 at 38ºC for both cookers but after 10 minutes the difference has started wide between both cookers. After a hour, at 11:00, water in the conventional box solar cooker reached 53.5ºC and water in improved solar cooker reached 50ºC. This much difference is because of in improved solar cooker there was additional 6.25 kg load black stone is put as thermal energy storage. The difference of Plate temperature distributions is also increasing slowly in each of 10 minutes. So averagely water temperature in CBSC and in IBSC increased 3ºC and 2.8125ºC per each 10 minutes (0.3ºC/minute and 0.281ºC/minute), respectively.

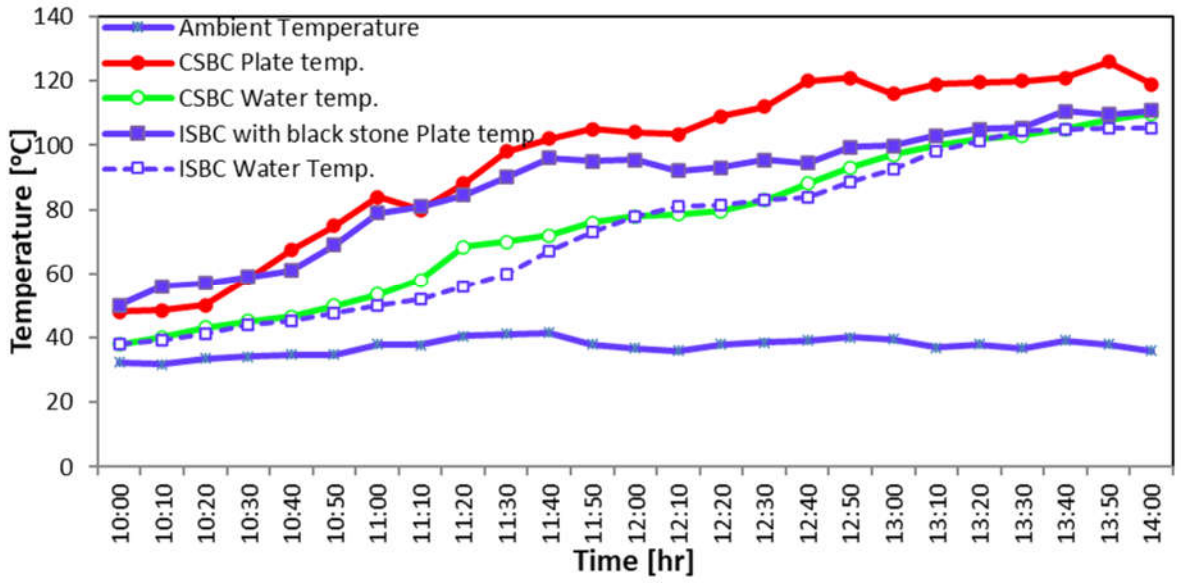


Figure 10. Comparing of full Load test temperature profile

Improved box solar cooker without any thermal energy storage has been tested, in this testing in 120 minutes above 100°c water temperature attained. Initially water was at 37°c and after 120 minutes it has become 101.5°c, so averagely it increased 5.375°c per each 10 minutes (0.5375°c/minute). IBSC with concrete as a TES is also tested to compare with Blackstone as a thermal storage.

3.2.2. Figures of merits comparison

Experimental values of first figure of merits are averaged as 0.115, 0.1349, and 0.1453 for conventional BSC, improved BSC with Blackstone, and improved BSC without any thermal storage, respectively. A high value of F1 indicates good optical efficiency and low heat loss factor.

3.2.3. Cooking tests

Cooking test is conducted at 11:00 up to 14:00 with 0.5 kg potato and one liter water added into both cooking pans, and then Shoforo with two-liter water have been cooked. The improved cooker without storage cooked the potato in 48th minute, Improved SC with black stone as TES spent 85 minutes to cook and conventional cooker stayed 110 minutes to cook the same amount of potato.

The second figure of merits of all solar cookers average values are calculated as 0.524, 0.97 and 1.0964 for conventional box solar cooker, IBSC with black stone as thermal energy storage and ISC without any TES respectively. A high value of F2 shows cooker has good heat exchange

efficiency factor F', good optical efficiency η_o, and low heat capacity of the cooker interiors and vessels compared to a full load of water. (BIS, 2000).

According to BIS (BIS, 2000) standard improved cooker with/without storage are ranked in grade A due to first figure of merits is greater than 0.12 and conventional BSC is categorized into Grade B under Daassenech (Omorate) weather condition.

4. CONCLUSIONS

Based on the results obtained from the assessments of the following conclusions are drawn.

- An average solar radiation is calculated as maximum in February (6.563 KW/m^2/day), minimum in July (5.578 KW/m^2day) and Annual Average daily solar radiation is 6.134 KW/m^2day. So, there is good enough solar energy entire the year.
- Experimental values of first figure of merits are averaged as 0.115, 0.1349, and 0.1453 for conventional BSC, improved BSC with Blackstone, and improved BSC without any thermal storage, respectively.
- The second figure of merits of all solar cookers average values are calculated as 0.524, 0.97 and 1.0964 for conventional box solar cooker, IBSC with black stone as thermal energy storage and ISC without any TES respectively.
- The available solar energy is enough to use for domestic energy needs in small scale level.
- Therefore, according to the final performance results the available solar potential can be utilized for the cooking and water heating purpose in Daassenech woreda by using improved solar cooker which is designed for Daassenech weather condition.

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