American Journal of Science, Engineering and Technology
2016; 1(2): 42-48
http://www.sciencepublishinggroup.com/j/ajset
doi: 10.11648/j.ajset.20160102.14

Feasibility Study of Solar Photovoltaic (PV) Energy Systems for Rural Villages of Ethiopian Somali Region (A Case Study of Jigjiga Zone)

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To cite this article:
Natei Ermias Benti, Getachew Tadesse. Feasibility Study of Solar Photovoltaic (PV) Energy Systems for Rural Villages of Ethiopian Somali Region (A Case Study of Jigjiga Zone). *American Journal of Science, Engineering and Technology.* Vol. 1, No. 2, 2016, pp. 42-48.
doi: 10.11648/j.ajset.20160102.14

Received: November 10, 2016; **Accepted:** December 9, 2016; **Published:** January 5, 2017

Abstract: Study was conducted to assess feasibility of solar PV power system for Jigjiga Zone. The data required for this work (sunshine hours) was obtained from the National Meteorological Service Agency (NMSA) and analyzed using MATLAB software. The study revealed that the area has abundant solar energy potential (6.5 KWh/m^2/day). Electric load for the basic needs of thecommunity, such as, for lighting, radio and televisionhave been estimated. As a result, based on the storage system, solar PV system is found as having a cost of energy about $12.09/kWh

Keywords: Solar Energy, Solar PV, Sunshine Hours, MATLAB, Load Estimation

1. Introduction

Most of the remote rural areas of Ethiopia are not yet electrified. Electrifying these remote areas by extending grid system to these rural communities is difficult and costly. As the current international trend in rural electrification is to utilize renewable energy resources; solar, wind, biomass, and micro hydro power systems can be seen as alternatives. Among these, solar energy system is thought to be ideal solution for rural electrification due to abundant solar radiation availability nearby the rural community in Ethiopia.[5], [3], [1]

Ethiopia lies in the sunny belt between northern latitudes of 3^0 and 15^0, and thus the potential benefits of renewable energy resources such as solar energy system can be considerable. As mentioned in [9] the total annual solar radiation reaching the territory is of the order of over 200 million tone oil equivalent (toe) per year, over thirteen fold the total annual energy consumption in the country. In terms of geographical distribution, solar radiation that reaches the surface increases as one travels from west to east: the insolation period is approximately 2200 hours of bright sunshine per year in the west increasing to over 3300 hours per year in the eastern semi-arid regions. [10]

So far, these vast renewable energy resources are not exploited sufficiently in the country, primarily due to the lack of scientific and methodological know-how as regards planning, site selection, and technical implementation. A further constraint prohibiting their utilization is that the real potential of these resources is not well-known, partly because of the lack of research emphasis in developing these technologies, and partly because of the insufficient resource data base. [4]

The aim of this paper is to study the feasibility of solar PV energy system for electrification of rural area of Somali region which not electrified via national grid system. The people in this village use kerosene for lamp, diesel for water pumping and grinding machines, fire wood for cooking and dry cells for radio and tape recorders. Desertification of the land is getting worse and worse due to deforestation and backward agriculture. Thus, in this research paper feasibility study of solar PV energy systems for electrification for a selected village found in Somali Region is analyzed.

2. Materials and Methods

A feasibility study of solar PV power system which comprises of PV arrays with battery banks and power conditioning units has been discussed. Before the Study was conducted to assess feasibility of solar PV power system for Jigjiga Zone of the Ethiopian Somali Regional State, Residential area energy consumption and solar energy potentials of the area under study had been studied.

2.1. Energy Demand

Looking back to lifestyle of a typical remote area in Ethiopia, night time light is provided by "Kuraz", a small lamp that burns kerosene. The kerosene large enough for long time, has to be brought from the faraway city for this purpose. It gives a very dim light with an eye irritant dangerous smoke. Residential area electrification provides significant improvement from "Kuraz". It brings about health and comfortable social gathering as bright light good for eye is provided and irritant smokes from kerosene burning is avoided. Also, it creates an opportunity for convenient reading and informal night classes for adults improving the literacy rate. The table below shows the residential electricity load.

Table 1. *Electricity load.*

No	Appliance	Watt (W)	Dailyuse/hour	Daily Energy (Wh/day)
1	Lamp 1 (Living room)	11	4	44
2	Lamp 2 (Kitchen room)	11	2	22
3	Lamp 3 (Bed room)	11	5	55
4	Radio / Caste player	3	4	12
5	21" color Television	60	2	120
	Total	96	17	253

2.2. Solar Radiation Estimations

To determine the PV electricity generation potential for a particular site, it is important to assess the average total solar radiation received over the year. Unfortunately in most developing countries there is no properly recorded radiation data. What usually available is sunshine duration data.

Ethiopia is one of the developing countries which have no properly recorded solar radiation data and, like many other countries, what is available is sunshine duration data. However, given a knowledge of the number of sunshine hours and local atmospheric conditions, sunshine duration data can be used to estimate monthly average solar radiation, with the help of empirical equation 1 [2].

$$\bar{H} = \bar{H}_o\left(a + b\left(\frac{\bar{n}_s}{\bar{N}_s}\right)\right) \quad (1)$$

Where: $\bar{H}$ = Monthly averaged daily solar radiation on a horizontal surface (MJ/m^2)

$\bar{H}_o$= Monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m^2)

$\bar{n}_s$= Monthly average daily hours of bright sunshine

$\bar{N}_s$ = Monthly average of the maximum possible daily hours of bright sunshine &

a and b are regression coefficients

The monthly averaged daily diffuse radiation ($\bar{H}_d$) is calculated from the monthlyaverage daily global radiation ($\bar{H}$) using [2]

$$\bar{H}_d = \bar{H}(1.391 - 3.560\left(\frac{\bar{H}}{\bar{H}_o}\right) + 4.189(\frac{\bar{H}}{\bar{H}_o})^2 - 2.137(\frac{\bar{H}}{\bar{H}_o})^3 \quad (2)$$

Equation (2) is functional when the sunset hour angle for the average day of the month is less than 81.4^0. If the sunset hour angle is greater than 81.40 then equation (2) can be written as

$$\bar{H}_d = \bar{H}(1.311 - 3.022\left(\frac{\bar{H}}{\bar{H}_o}\right) + 3.42(\frac{\bar{H}}{\bar{H}_o})^2 - 1.82(\frac{\bar{H}}{\bar{H}_o})^3 \quad (3)$$

The monthly averaged daily beam radiation $\bar{\boldsymbol{H}}_b$ is calculated from the monthlyaverage daily global radiation ($\bar{\boldsymbol{H}}$) and monthly average daily diffuse radiation ($\bar{\boldsymbol{H}}_d$) as

$$\bar{H}_b = \bar{H} - \bar{H}_d \quad (4)$$

3. Results and Discussion

3.1. Solar Energy Assessment

By using equations, (1 - 4), the solar radiation of the village around Jigjiga is estimated and the result is given in Appendix A. Column 2 (n_d) and 6 (n_s) are measured values at meteorological station. The others are calculated values.

In figure 1 the monthly average daily Global, Diffuse and Beam radiation for the entire year is depicted. The maximum monthly average daily Global solar radiation occurred during the month of March (7 KWh/m^2/day) whereas the minimum occurred in May (5.9 KWh/m^2/day). Between June-October there was almost uniform radiation. The result shows that the monthly average daily global solar radiation values for Jigjiga lay between 5.9 KWh/m^2/day (May) and 7.0 KWh/m^2/day (March).

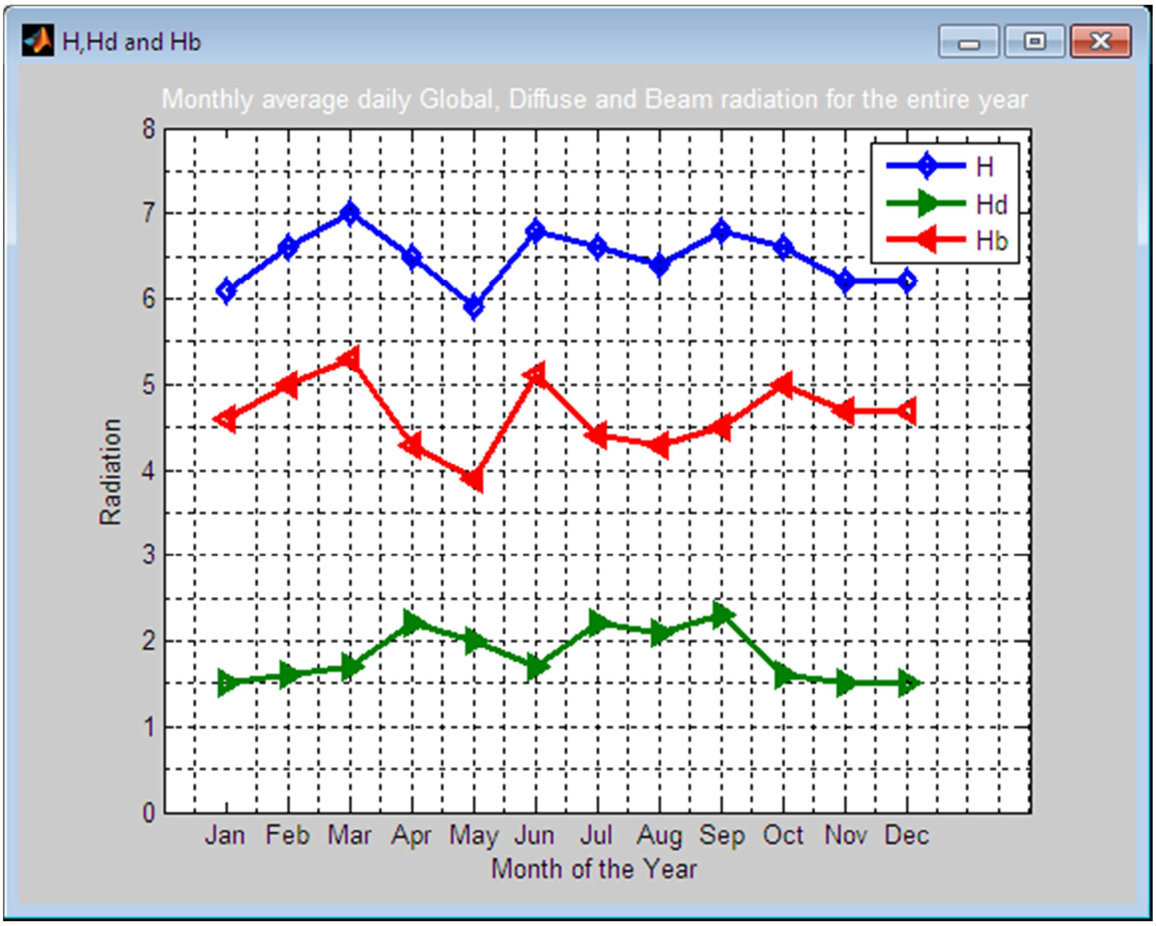

Figure 1. *Monthly average daily Global, Diffuse and Beam radiations for the entire year.*

3.2. Analysis of Photovoltaic (PV) Power

The following steps were taken to calculate radiation on the plane of the PV array:

- Hourly global and diffuse irradiances on a surface for all hours of an "average day" having the same daily global radiation as the monthly average were calculated;
- Hourly values of global irradiance on the tilted (or tracking) surface for all hours of the day were calculated; and then
- Sum the hourly tilted values were used to obtain the average daily irradiance in the plane of the PV array.

3.2.1. Hourly Irradiance in the Plane of the PV Array

Hourly irradiance in the plane of PV array (I_t) can be calculated as [6]:

$$I_t = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right) + I\rho \left(\frac{1-\cos\beta}{2}\right) \qquad (5)$$

Where: ρ = diffuse reflectance of the ground, β = slope of the PV array (for this study 10^0), R_b = ratio of beam radiation on the PV array to that on the horizontal, θ = Angle of incident on an inclined surface,θ_z= Angle of incident on a horizontal surface, Φ = latitude of the site (9.35^0)

The diffuse reflectance of the ground (ρ) (also called ground albedo) is set to 0.2 if the average monthly temperature is greater than 0°C, 0.7 if it is less than –5°C, with a linear interpolation for temperatures between these values.

Using equation(5) hourly irradiance in the plane of PV array (I_t) for each month can be determined and the result is given in Table (Appendix E).

3.2.2. Daily Total Tilted Irradiances ($\bar{H}_t$)

Once tilted irradiances for all hours of the day are computed, the daily total $\bar{H}_t$is obtained by summing values for individual hours.

Table 2. *Monthly average daily tilted irradiance.*

Month	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oc.	Nov.	Dec.	Av.
$\bar{H}_t$(KWh/m^2/d)	6.6	6.7	7.1	6.4	6.7	6.9	6.8	6.6	7.0	6.7	6.2	5.7	6.6

Figure 2 shows that the monthly average daily tilted solar irradiance in the plane of PV array. The maximum monthly average daily Global solar radiation on the plane of PV array occurred in March and September. The minimum occurred in December (5.7 KWh/m^2/day). Between May-August there was almost uniform radiation.

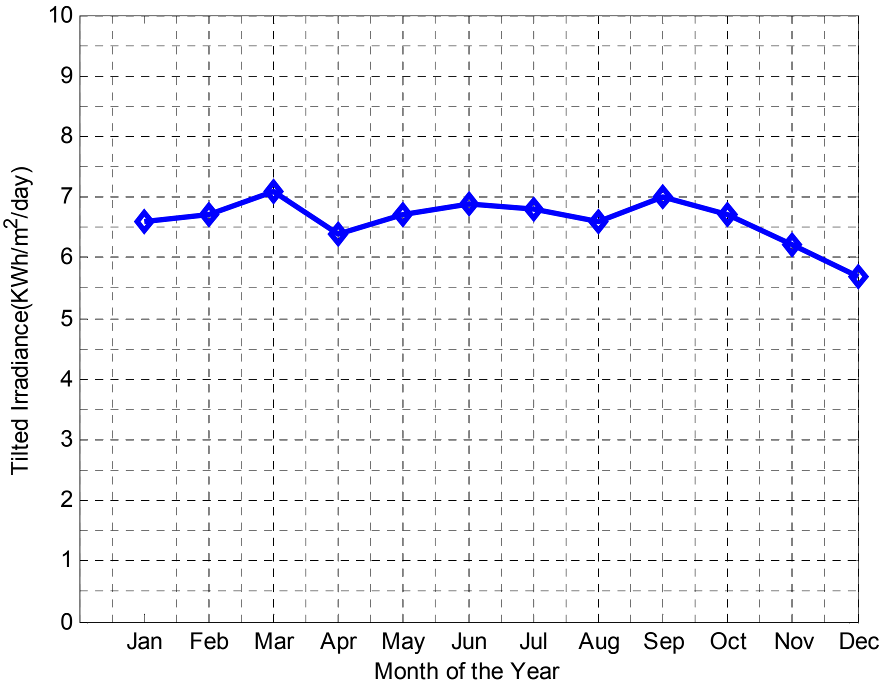

Figure 2. *Monthly mean daily solar irradiance on the plane of PV array.*

3.3. Energy of the PV Array

The power delivered by the PV array (E_P) can be calculated as [6]:

$$E_P=A_P\eta_P\bar{H}_t \quad (6)$$

Where: A_P = module area ($1m^2$)&η_P= Efficiency of PV Module (for this study 12%)

The array energy available to the load and the battery (E_A) can be obtained by the following relations [6]:

$$E_A = E_P(1-\lambda_P)(1-\lambda_c) \quad (7)$$

Where: $\boldsymbol{\lambda_P}$ =Miscellaneous loss like dust cover on the PV array commonly taken as 4%

$\boldsymbol{\lambda_c}$ =Power conditioning losses commonly taken as 10%

Using equation (6) and (7), daily averaged power delivered by the PV array (E_P) and daily average total energy available from the PV array (E_A) were determined (Appendix F and G, respectively). The result is shown in the following figure.

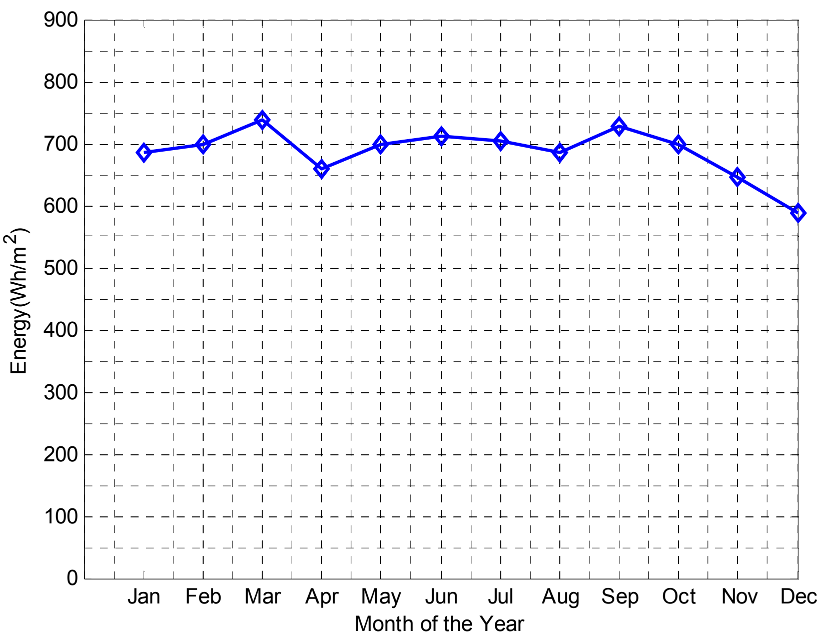

Figure 3. *Monthly average daily energy available to the load.*

Figure 3 shows that major maximum monthly average daily energy available to the load that occurred during the months ofMarch (737.5Wh/m^2) and September (728.8 Wh/m^2). The minimum monthly average daily energy available to the load occurred during the month December (588.2Wh/m^2).

3.4. Sizing of the Solar Panels

a) Area of the Solar Panel

The PV panel of the solar home system must be sized with the annual minimum of daily available PV electric energy (E_h). In this study, it occurs in the month of December (with a value of 588.2Wh/m^2) as determined in Appendix G. Thus, the net energy to the load from the panel per unit area is given by: [6].

$$E_{net} = E_h \eta_b \eta_c = 467.4 \text{ Wh/m}^2 \text{ day} \quad (8)$$

Where: η_b = efficiency of battery (Assuming to be 90%)&η_c = efficiency of charge controller (Assuming to be 90%)

The maximum daily energy consumption of each household is 253 Wh/day. Hence the required PV panel area will be

$$A_p = \frac{DailyEnergyDemand}{E_{net}} = \frac{253\frac{Wh}{day}}{467.4\frac{Wh}{m2day}} = 0.54m^2 \quad (9)$$

The energy delivered by this size of the PV panel can be calculated as follows:

$$E_p = E_h * A_p = 588.2 * 0.54 \text{ m}^2 = 318.4 \text{ Wh/day} \quad (10)$$

In order to select PV panel in the market, the panel has to be specified in peak watts, which is the power obtained with irradiation of 1000W/m^2 at the cell temperature of 25°C. The monthly global irradiance ranges from 5.9 KWh/day in May to 7.0 KWh/day in March. Hence, the effective hours with peak radiation (1000W/m^2) for the minimum case is 5.9 hours. As the temperature of the PV panel is not constant, a given correction factor (f_t) is taken as 0.89 [2]. From this, the peak power for a given PV panel from the daily available electrical energy of the panel can be obtained as follows:

$$\mathbf{P_p} = \left(\frac{\mathbf{E_p}}{\mathbf{EH*f_t}}\right) = \frac{\mathbf{318.4\frac{Wh}{day}}}{\mathbf{5.9*0.89}} = \mathbf{60W_p} \quad (11)$$

The standard size of solar module 30 W_p AEE Solar PV Modules (AE-37G) was considered; to fit the size two Modules are required for the household. The cost data was collected from importer of solar PV system and the average cost of the PV panel per peak watt was found to be Birr 68 [7]. Hence, the total cost price of modules (30 W_p) are Birr 4080.

b) Battery

The minimum energy that can be stored by the battery for the households is given by:

$$E_b = \frac{E_u}{\eta_b} = 281.1 \text{ Wh/day} \sim 0.2811 \text{ KWh/day}$$

Where: $E_{u=}$Energy demand of the household (253 Wh//day), E_b = Energy that can be stored by the battery&η_b = efficiency of battery (Assuming to be 90%)

Assuming that the working voltage for direct current is 12V, then, the net capacity that the battery can store in Ah/day will be

$$C_{bn} = \frac{E_b}{V_{cc}} = 23.43\text{Ah/day}$$

The net capacity of the battery depends on the depth of the discharge of the battery (DDP), and the depth of discharge determines the life cycle of the battery. Deep cycle lead acid battery can store 30% to 80% depth taking an assumption of DDP = 30% then the total commercial capacity of the of the battery is calculated as

$$C_b = \frac{C_{bn}}{DDP} = 78.1Ah$$

This value is correct, if only if there aren't cloudy days. Considering cloudy days, let us assume the battery have energy demand of two days.

$$C_b = 34.26 \text{ Ah*2} = 156.2 \text{ Ah.}$$

Hence, the capacity of the battery for the each household is taken as 156.2 Ah. Considering the battery type of Battery (65Ah) deep cycle, hence 3 of such kind of batteries are required for the household. The unit price of Battery (65 Ah) deep cycle is Birr 974.95 [7]. Since 3 such batteries are needed, and then the total cost of the battery is Birr 2924.85.

c) Charge controller

The power output required per household if all appliances are functional at the same time is 253W and the voltage required for the solar home system is usually 12V. So, the charge controller must work at a maximum current of

$$I_T = \frac{Poweroutput}{V_{cc}} = \frac{253\,W}{12V} = 21.1\,A$$

d) Electrical Accessories

Installation of PV panel requires the following accessory parts:

- Wire from solar panel – charge controller;
- Wire from charge controller – battery;
- Wire from charge regulator - charges: Lights, radio, etc;
- Key of charges control;
- Switches and Radio connections.

4. Cost Analysis Solar Photovoltaic Power Generation

4.1. Cost Evaluation of Solar Photovoltaic Power Generation

It is believed in rural households of Ethiopia electric energy demand is limited to lighting and radio/cassette player at minimum and addition of color television at maximum.

Table 3. *Cost break down of solar PV system.*

No	Description	Quantity	Unit rice [Birr]	Total Price [Birr]
1	Module (65Wp)	2	68/W_p	4080.00
2	Battery (65 Ah) deep cycle	3	974.95	2924.85
3	Charge Regulator	1	742.00	742.00
4	DC-AC inverter for 21" color TV	1	750.00	750.00
5	DC lamps (11w)	3	96.76	290.28
6	Cabling, Switch, Holder, plug, Divider and PV panel support structure cost			300.00
	Total			9068.50

The total cost of the solar PV for Solar Home System (SHS) for each household of the village is Birr 9068.50.

4.2. Financial Evaluation of PV Power System

The monthly energy cost which hast to be beard by the user is calculated from the annual cost of the investment and annual operating cost which is mainly maintenance cost. Similarly, the unit energy cost can be calculated by dividing the total annual cost by the energy generated per annum.

The annual payment

To evaluate the system, an assumption of 10% interest rate and 25 years life span are taken into consideration. The initial capital cost (C) of the PV system for a single household is Birr 4080 (Table 3). Then, the annual payment will be [7]:

$$C_A = \frac{\frac{C_I}{(1+i)^n-1}}{i(1+i)^n} + C_m = \frac{\frac{9068.5\text{ Birr}}{(1+0.1)^{25}-1}}{0.1(1+0.1)^{25}} + 116.994 = 1116.05\text{ Birr}$$

Where: C_A = Annual payment, C_I = Capital cost, C_m = maintenance cost, n = life span (assuming 25 years)& i = interest rate (Assuming 10%)

$$C_m = \frac{TotalBatteriescostforasinglehousehold}{lifespan} = \frac{2924.85}{25} = 116.994\text{ Birr}$$

Monthly Payment of the Systems

$$Monthly\ payment(\mathrm{MP}) = \frac{C_A}{12} = \frac{1116.05\ \mathrm{B}irr}{12} = 93.05\,\mathrm{B}irr$$

The unit energy cost will be:

$$P_e = \frac{C_A}{365 * E_d} = \frac{1116.05\,\mathrm{B}irr}{365day * 253Wh/day} = 12.09\,\mathrm{B}irr/KWh$$

Where: E_d = daily energy consumption (single household = 253 Wh/day).

5. Conclusion and Recommendation

5.1. Conclusion

There is no accurately recorded solar radiation database in the country, instead only sunshine hour data was available. Therefore, empirical formulas which are able to incorporate the available sunshine hour data and provide the required solar radiation data were used to determine the potential of the site. The analysis of the solar energy resources data has been carried out by MATLAB software. The results confirmed the availability of huge utilizable solar energy at the site (6.5 KWh/m^2/day). Electric load for the basic needs of thecommunity, such as, for lighting, radio and televisionhave been estimated.

The results revealed thatsolar PV system is found as having a cost of energy about $12.09/kWh, which is high compared to the currentglobal electricity tariff and the tariff in the country (<5 cents/kWh). However, considering theshortage of electricity in the country (<20% coverage) and absence of electricity usage in ruralareas (<2% coverage), this cost should not be taken as a decisive factor.

5.2. Recommendations

The following recommendations are made out of this paper;

- Ethiopia has a huge potential of renewable energy resources which can be used for rural electrification through the off-grid system. There are, however, many challenges like low purchasing power of the rural community, unfavourable conditions towards the utilization of renewable energies, absence of awareness how to use these resources, etc. Thus, the author of this work recommends that the government, non-governmental organizations and the private sectors should make combined efforts to overcome these challenges by using more flexible approaches to improve the current poor status of rural electrification in Ethiopia.
- As far as the environmental aspects are concerned, this kind of energy systems have to be wide spread in order to cover the energy demands of rural communities, and in that way to help reduce the green house gases and the pollution of the environment.

- Similar solar energy potential assessment can be conducted for other sites in the country.

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