Design of Solar Photovoltaic Power Generation System for Water Pumping

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***Abstract*—In this paper photovoltaic power generating system design procedures are presented considering two submersible pumps for water supply of Robit village. The design includes Analysis of Photovoltaic (PV) Power for the village water supply including calculations on the declination angle, Solar Hour Angle and Sunset Hour Angle, Extraterrestrial Radiation, Terrestrial Radiation. and depending on the pump water demand solar panel , inverter are selected and additional installation conditions are recommended.**

Keywords—Photovoltaic; Pump; Solar Radiation; Solar Insolation

I. Introduction

Water is the primary source of life for mankind and one of the most basic necessities for rural development the rural demand of water for domestic use is increasing. At the same time, rainfall is decreasing so surface water is becoming scarce. Ground water seems to be the only alternative to this dilemma but the ground water table is also decreasing which makes traditional hand pumping and bucketing difficult.

The present day world, especially the developing countries, is experiencing a rapid growth in demand for energy use in order to improve the standard of living. For sustaining this growth, the fossil energy sources are not considered adequate. Realization of this situation has led the whole world to harness energy from other sources especially new and renewable sources of energy and to take measures of conservation due to this reason and the higher solar energy potential (Daily average monthly solar radiation on the horizontal surface is 6 kwh/m^2/day in Robit Village which is higher than the recommended feasible solar energy potential of 5.2 kwh/m^2/day for the generation of electrical energy.[10]

Robit village is located 27km from the capital of Amhara region BahirDar, with a total population of 15,946.The inhabitants in the village use hand pumps and diesel pumps for their water need. As a result of the raise in the price of fuel and the increase in the cost of maintenance the peoples in the village are suffering this huge problems. The relatively higher quantity of underground water in the village facilitates the implementation of additional pumping techniques for improving the water supply.

As it has been mentioned earlier currently the peoples in the village use diesel and hand pumps. because of the increase in the price of fuel for the diesel pumps and the decrease in the water level as well as lack of maintenance personnel's the difficulty in operation occurs. In addition, environmental pollution effects of fuels are the main issues of our world so in this study the feasibility of pumping systems with less pollution effects would be investigated.

In Ethiopia, both governmental and non-governmental development agents have been involved in order to enhance the coverage of potable water supply in different parts of the country. But, the coverage of the service in the country still lags behind and remains only less than 18 %. Even this low figure is not reliable as it presupposes a situation in which schemes that had been constructed so far are 100% functional, a presupposition that doesn't reflect the reality on the ground. The existing poor coverage of potable water supply has been mostly attributed to and/or aggravated by the lack of sustainability of the water supply systems. Meanwhile, only a few of the water supply systems in rural Ethiopia have currently attained their financial status needed to run the schemes effectively through the collection of service charges from community members. This, however, is in contrary to the claim of the current water policy of the country that requires communities to cover the operation and maintenance costs.

Sustainability of a rural water system is a function of a number of factors. It depends not only on factors controlled by the project such as training, technology, the cost of the system, and construction quality, but also on factors beyond the control of the project such as the community's poverty level and their access to technical assistance and spare parts. Moreover, Ethiopia exhibits excellent prerequisites for a nearly 100% renewable energy supply. hydropower and solar resources offer the chance of renewable energy supply in an economically, ecologically and socially sustainable way. PV-hydro potentials have been already analyzed for Ethiopia and might lead to utility-scale PV power plants. Hence in this paper the design procedure considering Robit village for solar photovoltaic power generating system in order to pump water is introduced.

I. PHOTOVOLTAIC POWER GENERATION SYSTEM DESIGN

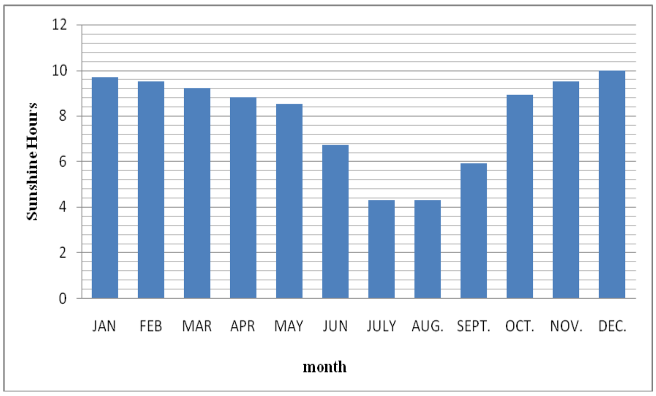

Fig-1 Average Sunshine Hour for each month of the year

A. Photovoltaic Power Generation

There are three basic ways that the solar PV can be used:

- On-grid applications: - which cover both central-grid and isolated-grid systems;
- Off-grid applications- which include both stand-alone PV systems and hybrid (PV-battery-generator set) systems; and
- Water pumping applications: - which include PV-pump system

B. Analysis of Photovoltaic (PV) Power for the Selected Site

- Declination Angle(δ)

As the earth rotates about the sun the angle between the earth's equatorial plane and the earth sun line varies between +23.45° and -23.45° throughout the year, this angle is the declination, δ.

Table 1 Representative day of the year for each month.[14]

Month	Day of the year	Representative day of the year
January	17	January 17
February	47	February 16
March	75	March 16
April	105	April 15
May	135	May 15
June	162	June 11
July	198	July 17
August	228	August 16
September	258	September 15
October	288	October 15
November	318	November 14
December	344	December 10

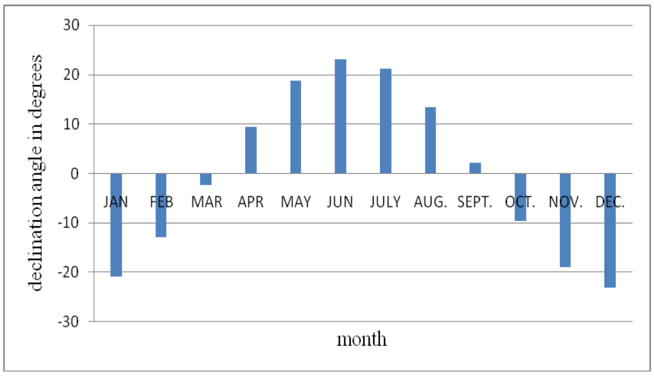

Fig-1 Declination angle for each month

The value of δ in degrees is given by Cooper's equation.

$$\delta = 23.45^0 \sin\left[360^0\left(\frac{284+n}{365}\right)\right] \qquad (1)$$

For the recommended day of each month the declination angle is calculated and shown in fig-2

- Solar Hour Angle and Sunset Hour Angle

The solar hour angle is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon.

The sunset hour angle ω_{ss} is the solar hour angle corresponding to the time when the sun sets and it is given by

$$\omega_{ss} = \cos^{-1}(-\tan\phi\tan\delta) \qquad (2)$$

Using the representative days of the year the sunset (or sunrise) hour angle is calculated and shown as,

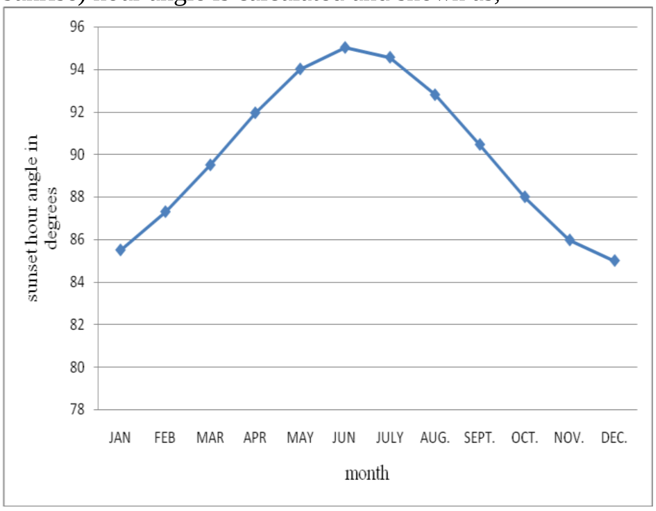

Fig-2 Sunset hour angle for each month of the year.

- Extraterrestrial Radiation $(\overline{H}_o)$

The extraterrestrial total beam solar radiation on a horizontal surface which is the amount of beam insolation that reaches the top of the earth's atmosphere, daily extraterrestrial radiation on a horizontal surface is given as,

$$\overline{H}_o = \frac{24}{\pi} I_{SC}\left(1+0.034\cos\frac{360n}{365}\right)\left(\cos\phi\cos\delta\sin\omega_{ss} + \frac{\pi\omega_{ss}}{180}\sin\phi\sin\delta\right) \qquad (3)$$

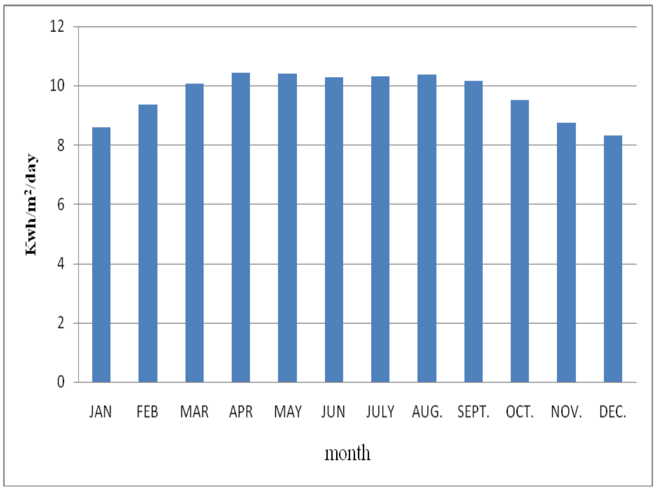

Fig-3 The monthly average daily extraterrestrial total beam solar radiation on a horizontal surface

The monthly average daily extraterrestrial total beam solar radiation on a horizontal surface for the recommended day number of each month at the same location is calculated using equation 3 and the result of the calculation are plotted using bar charts for each season of a year, shown in fig-4,

- Terrestrial solar radiation $\left(\overline{H}\right)$

The terrestrial total beam solar radiation on a horizontal surface which is the solar radiation at the surface of the earth, the minimum daily solar radiation on the horizontal surface at the ground is on July with the value 5.16Kwh/m^2/day. The terrestrial solar radiation data from NASA for Robit village is shown in fig-5. The monthly average daily terrestrial isolation received on a horizontal surface which is convenient to obtain the monthly average values of solar radiation on a tilted surface and also both the direct and diffused monthly average daily energies are also determined by beginning from the terrestrial total beam solar radiation on a horizontal surface fig.-5 shows the NASA data.

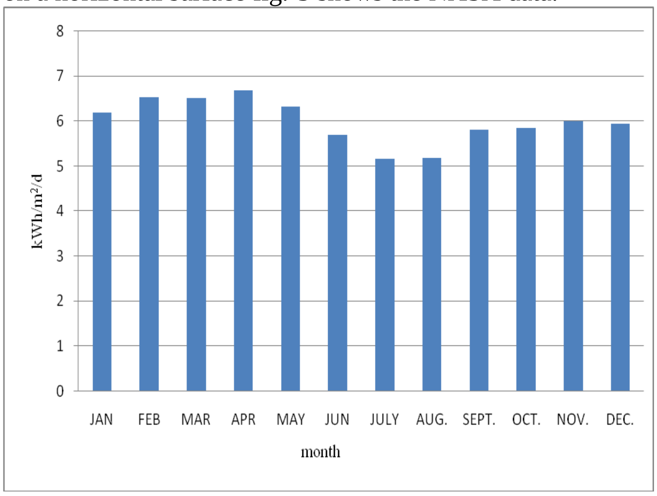

Fig-4 The terrestrial total solar radiation on a horizontal surface

- Monthly Average Daily clearness index $\left(\overline{K}_T\right)$

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index. Thus the monthly average clearness index as described by Page and others [15]: this helps to produce the monthly average hourly insolation data from the monthly average daily value.

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_o} \qquad (4)$$

The quantity $\overline{K}_T$ is given various names including the cloudiness index, the hourly percent sunshine and clearness index, its value ranges from about 0.8 under very clear conditions to nearly zero in sever overcast. In some countries such as United states, based on beam and horizontal global terrestrial insolation measurements data for a very simple correlation between $\overline{K}_T$ and beam insolation is developed. The monthly average daily clearness index value calculated using equation 4 is shown as,

- The monthly average diffuse (terrestrial) insolation on a horizontal surface $\left(\overline{H}_d\right)$

The diffuse component of the insolation is the sunlight that reaches the earth's surface after being scattered or diverted from its original path in the atmosphere.

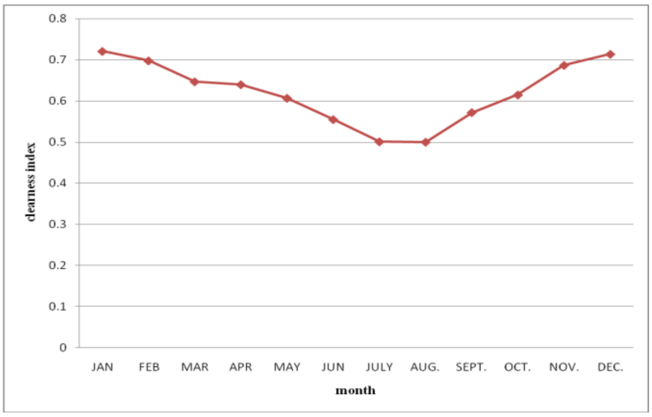

Fig-5 Monthly Average Daily clearness index

The monthly average diffuse (terrestrial) insolation on a horizontal surface $\left(\overline{H}_d\right)$ is the component of terrestrial insolation and it is given by page[15] as,

$$\frac{\overline{H}_d}{\overline{H}} = 1.00 - 1.13\overline{K}_T \qquad (5)$$

The monthly average diffuse (terrestrial) insolation on a horizontal surface which is calculated using equation 5 is shown in fig-7

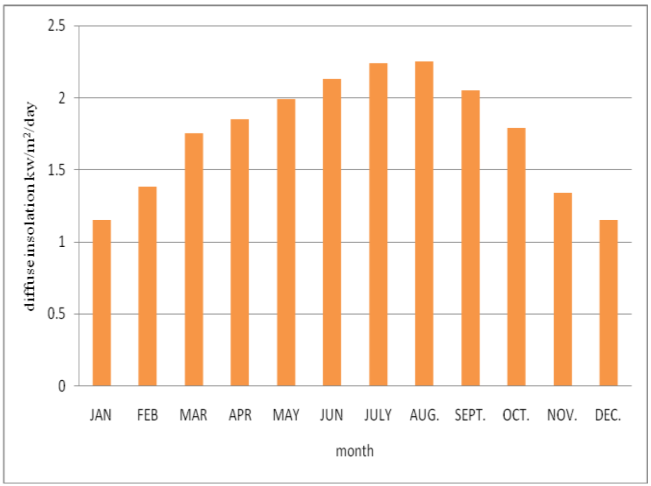

Fig-6 The monthly average diffuse (terrestrial) insolation on a horizontal surface

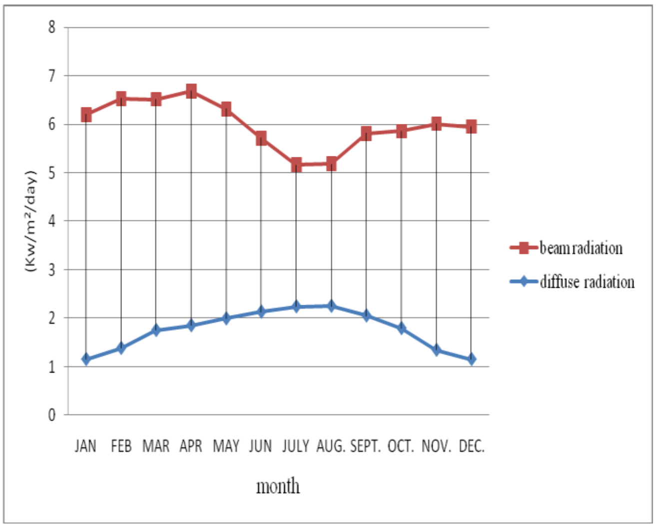

Fig-7 The monthly average diffuse and beam (terrestrial) insolation on a horizontal surface

- Calculation of Hourly Global and Diffuse Irradiance

Solar radiation can be broken down into two components:

i. **Beam radiation**, which the solar radiation propagating along the line joining the receiving surface and the sun, and

ii. **Diffuse radiation**, the solar radiation scattered by aerosols, dust, and molecules.

To determine the hourly insolation solar time must be used as the time frame the solar time is calculated as,

$$ST = ZMT + 4(\lambda_{ST} - \lambda) + ET \qquad (6)$$

The zonal time or clock time is 11a.m, the equation of time for the selected day is -6min[14].

ST=11a.m+4(38.4-37.2)min+(-6)min

ST=10:59a.m≅11 a.m.

$$\omega = (ST - 12) \times 15^0$$

$$\omega = -15^0$$

- Calculation of Hourly Irradiance in the Plane of the PV Array

For the PV array is directed towards the equator and tilted at an angle β then H_T is given by

The insolation on the tilted surface is given as,

$$H_T = H_b R_b + H_d R_d + H\rho_f R_f \qquad (7)$$

$$R_b = \frac{\cos\theta}{\sin\alpha_s},\ R_d = \cos^2,\ R_f = \sin^2\frac{\beta}{2}$$

$$\cos\theta = \cos(\phi - \beta)\cos\delta\cos\omega + \sin(\phi - \beta)$$

$$\sin\alpha_s = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$

Where:

θ=the angle between the solar and the normal to tilted surface.

R_d =the radiative configuration factor from the tilted surface to the sky

(it is the fraction of the sky "seen" by the surface and represents the fraction of the diffuse insolation that strikes the surface).

R_r =the radiation configuration factor from the tilted surface to the ground and surroundings (it is one minus the surface-to-sky configuration factor).

ρ_r =effective diffuse ground reflectance of the diffuse plus beam insolation on a horizontal surface.

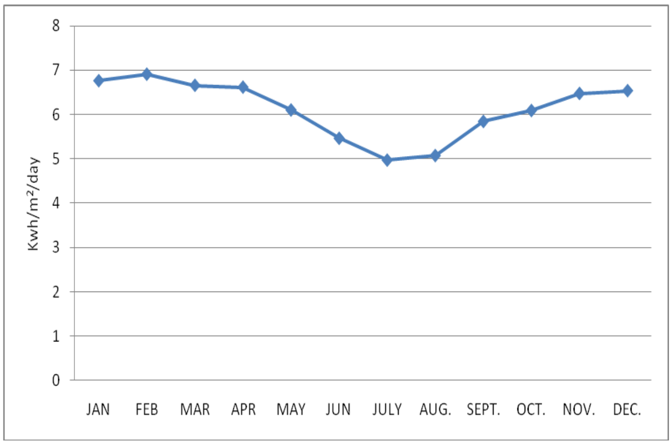

Fig-8 Insolation on the tilted surface.

The instantaneous global solar radiation on tilted surface G (kW m^{-2}) is given by Liu and Jordan's relationship.[15].

$$G = \left(\frac{\pi}{24}\right) H_T \left(\frac{\cos\omega - \cos\omega_{ss}}{\sin\omega_{ss} - \omega_{ss}\cos\omega_{ss}}\right) \qquad (8)$$

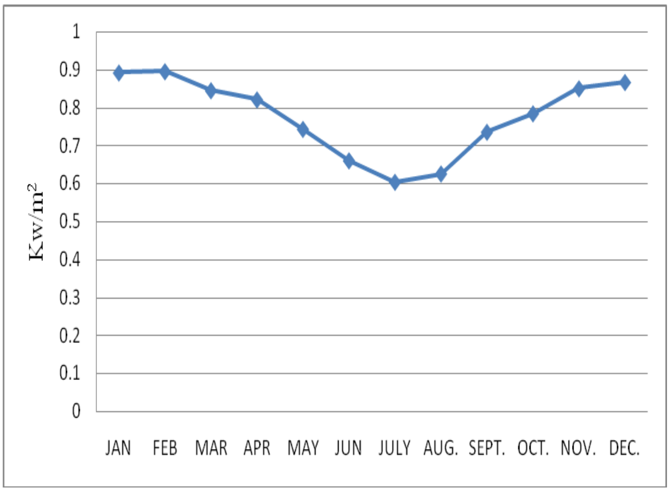

Fig-9 The instantaneous global solar radiation on tilted surface

So the Monthly mean daily solar irradiance in the plane of PV array in (Wh/m^2) is calculated for each month and described in the chart below,

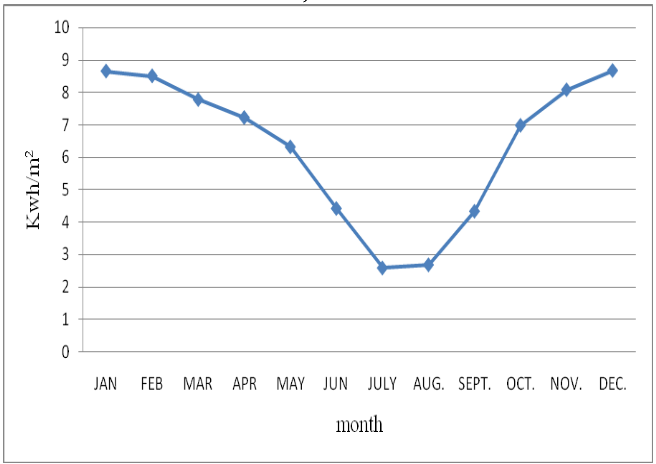

Fig-10 Monthly mean daily solar irradiance in the plane of PV array

- Calculation of Average Efficiency of PV Module

The average module temperature (T_C) can be obtained from the mean monthly ambient temperature (T_a) through Evans' formula.[16]

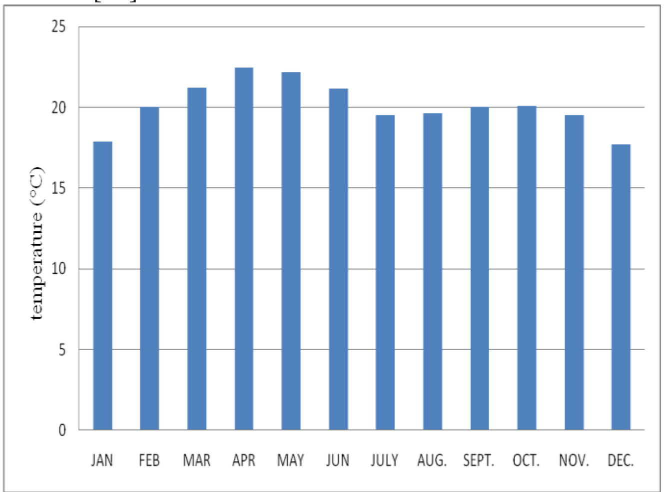

Fig-11 Monthly average ambient temperature

$$T_c - T_a = \left(219 + 832\overline{K}_T\right)\frac{NOCT - 20}{800} \qquad (9)$$

Table-2 PV module characteristics for Standard Technology

PV module	$\eta_r\,(\%)$	NOCT (°C)	$\beta_P\left(\%/{}^0C\right)$
Mono silicon	13.0	45	0.40
Poly silicon	11.0	45	0.40
a-SI (amorphous silic.)	5.0	50	0.11
cdTe(cadmium telluride)	7.0	46	0.24
CIS (copper indium diselenide)	7.5	47	0.46

The average module temperature (T_c) is plotted as,

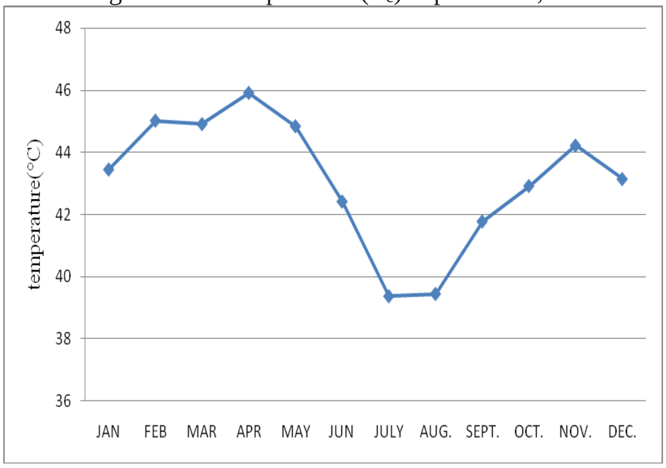

Fig-12 Average module temperature

The array is characterized by its average efficiency, η_p which is a function of average module temperature T_c

$$\eta_p = \eta_r\left[1 - \beta_p\left(T_c - T_f\right)\right] \qquad (10)$$

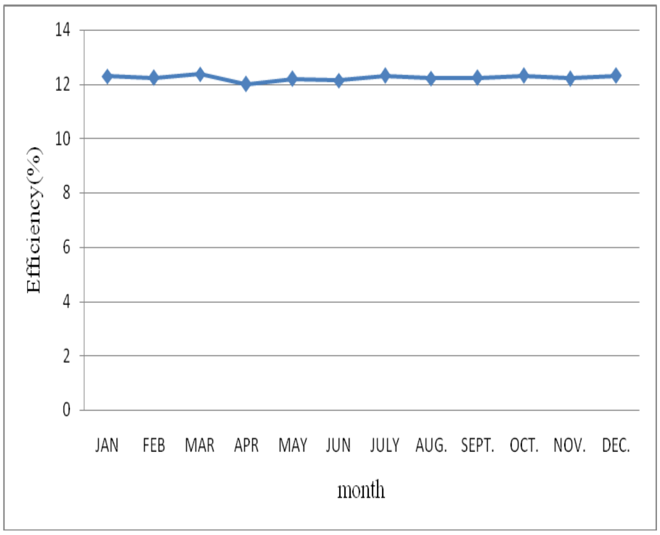

Fig-13 Variation of average module efficiency with time.

Energy of the PV Array

The power delivered by the PV array $\left(E_P\right)$ can be calculated as:

$$E_p = A_p \eta_p \overline{H}_t \qquad (11)$$

The results of the equation are provided in the form of bar chart as,

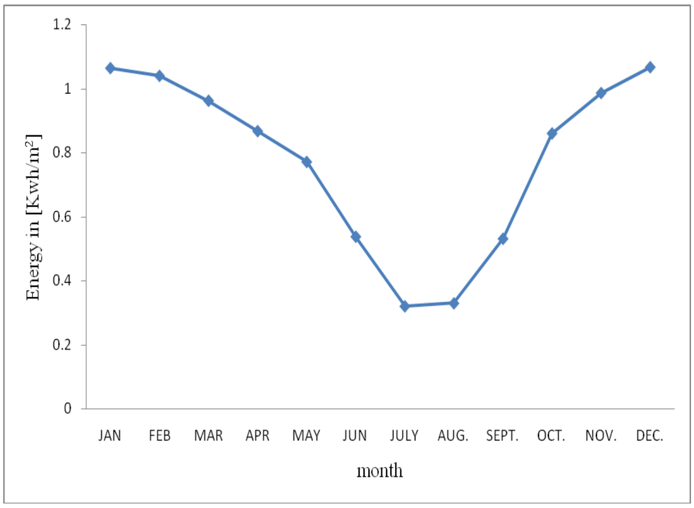

Figure 0-14 Monthly mean daily average energy available to the load without considering dust and cover effects

The array energy available to the load (E_A) can be obtained by the following relations:

$$E_A = E_p(1-\lambda_p)(1-\lambda_c) \qquad (12)$$

Where:-

E_p : Energy available to the charge controller

λ_p : Miscellaneous loss like dust cover on the PV array commonly taken as 4%

λ_c :Power conditioning losses commonly taken as 10%

The output of the array energy which is delivered to the inverter is calculated using equation 5.16 and given in the figure below.

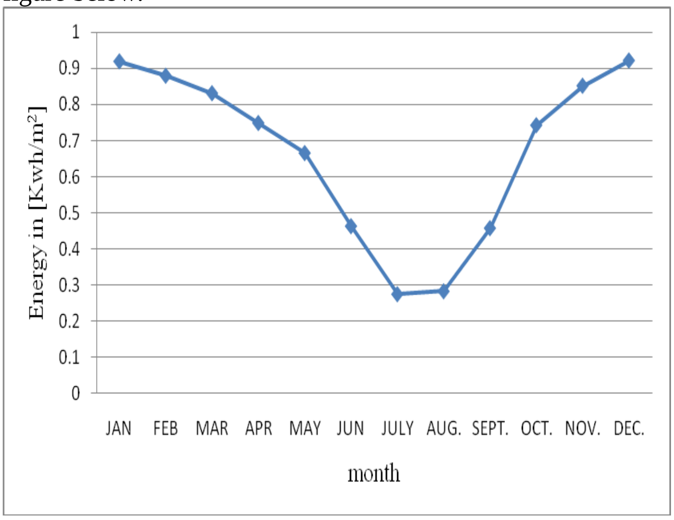

Fig-15 Monthly mean daily average energy available to the charge controller

Overall array efficiency:

The efficiency which incorporates all the losses in the components of photovoltaic pumping system.

$$\eta_A = \frac{E_A}{A_p \overline{H}_t} \qquad (13)$$

- Model of the PV Array

The off-grid model represents stand-alone systems, with or without an additional power generation. Energy from the PV array is either used directly by the load, or goes through the battery before being delivered to the load.

For an off-grid PV system, consumers should consider

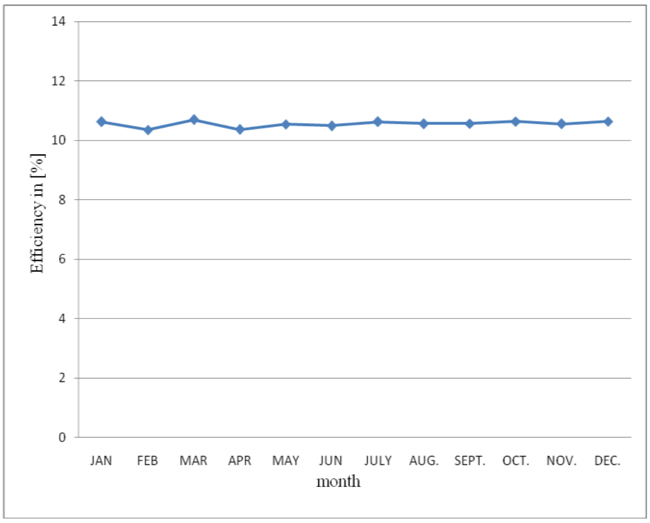

Fig-16 Variation of overall array efficiency with time

whether they want to use the direct current (DC) from the PV's or convert the power into alternating current (AC). Water pumps for AC are much more common and are generally cheaper, but the conversion of DC power into AC can consume up to 20 percent of all the power produced by the PV system.

The flow chart is as follows:

Monthly mean daily average energy available to the inverter. (E_A)

↓

Charge controller

↓

Monthly mean daily average energy available to the load (E_{delv})

Fig-18 Flow chart for off grid model of PV power generation

Taking the charge controller, which manages the energy that the photovoltaic panel receives from sun's rays(day light) and transformed into electrical energy, and Inverter have an efficiency of 85% the monthly mean daily average energy available to the load (E_{delv}) becomes,

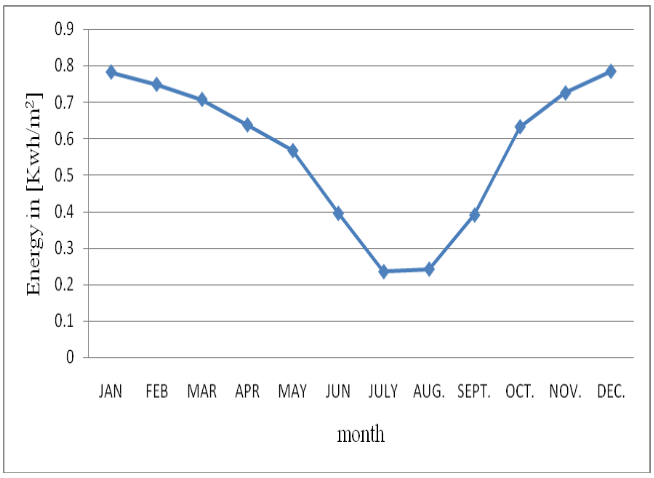

Fig-19 Monthly mean daily average energy available to the load.

- Charge controller

Charge controller manages the energy that the photovoltaic panel receives from sun's rays (day light) and transformed into electrical energy. The power output required if both wells are functional at the same time is 11200W and the voltage required for the system is 230V. So, the charge controller must work at a maximum current of

$$I_T = \frac{Poweroutput}{V_{cc}} = 49A \qquad (14)$$

II. Pump Energy Demand

Because of the reason that the daily energy requirement should be studied in designing and selecting the energy source, especially to know the PV panel area in the photovoltaic power generation. The power required to the pumps of 7.5 horse power each in both wells to start operation in the selected site of the village for an average of eight hour a day is calculated and tabulated as,

Table-1 Average Daily Energy Demand

No	Pump	Watt (Kw)	Daily use/hour	Daily Energy
1	Well no1	5.59	8	44.72
2	Well no2	5.59	8	44.72
	Total	11.2 Kw		89.44Kwh/day

A. Area of the solar panel

The PV panel of the solar pump system must be sized with the annual minimum of daily available PV electric energy to the load . (E_{net}) It occurs in month of July (with a value of 0.2348kwh/m^2)

The maximum daily energy consumption if both pumps operate at the same time is 89.484Kwh/day. Hence the required PV panel area will be

$$A_P = \frac{dailyEnergydemand}{E_{net}} = \frac{89.484kwh/day}{0.2348kwh/m^2} = 381m^2$$

From this, the energy available to the inverter from the PV panel, for the month of July (E_h =0.2762Kwh/m^2) , can be determined by:

$$E_p = E_h \times A_p = 0..2762 \times 381 = 105.2Kwh/day$$

In order to select PV panel in the market, the panel has to be specified in peak watts, which is the shown in power obtained with Irradiation of 1000W/m^2 at the cell temperature of 25ºC.

The monthly global irradiance ranges from 5.16KWh/day in July to 6.69 KWh/day in April as shown in fig 5.9. Hence, the effective hours with peak radiation (1000W/m^2) for the minimum case is 5.16hours that gives the same energy per day. As the temperature of the PV panel is not constant, a given correction factor (f_t) is taken as 0.89. From this, the peak power for a given PV panel from the daily available electrical energy of the panel can be obtained as follows:

$$P_p = \frac{E_p}{EEH \times f_t} = \frac{105.2Kwh/day}{5.16h \times 0.89} = 22.9Kw_p$$

B. Electrical Accessories

Installation of PV panel requires the following accessory parts:

• Wire from solar panel – Charge controller;
• Wire from Charge controller – inverter;
• Wire from inverter – pump motor in well no1;
• Wire from inverter – pump motor in well no2;

Inverter size

In this study the most reliable inverter from Solar Buzz is selected the size of inverter required is 11.2 Kw.

Conclusion

The calculation of the solar information , the tilt angle the extra terrestrial radiation, beam radiation, solar time calculation results result in the peak power for a given PV panel from the daily available electrical energy of the panel. which provides sufficient power for the two submersible pumps to be installed in the village.

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