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Optimal Sizing of Stand-Alone Photovoltaic Systems for Rural Electrification

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Abstract:

Solar system became very important sector in these days and expected to play a very significant role in the future especially in developing countries. The paper is considering off-grid solar system to cover the required load for rural area during the day hours. This study is taken in one of the rural villages which located in Vhembe District Municipality, Limpopo, South Africa. Sizing of stand-alone photovoltaic system to electrify rural areas is a suitable alternative source to power the rural households. The study presents a sizing of PV system to cover the required load during the day for the selected village. The load and solar radiation data of the typical household in the target village has been used to size the stand-alone photovoltaic system. Due to the high cost of batteries, the batteries will not be considered in this study; the viability of a batterryless system is facilitated by the high solar radiation at the selected site and long daily average insulation duration. MATLAB software being used to size the PV system. This software can be implemented to any site with different weather conditions.

Key Words:

Rural Electrification, Stand-alone Photovoltaic system

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I. INTRODUCTION

Due to the dispersion in rural areas of the specific energy demand and its low intensity, it seems difficult to provide conventional sources (oil, coal, electricity from national grid), especially because of the high transportation costs. The increasing demand of electricity due to continuous population growth and high development rate, together with socio-economic conditions and the high level of renewable energy potential in South Africa make Renewable Energy Sources a feasible alternative for covering energy needs.

Renewable energy sources such as wind and solar can be used to generate electricity, but PV energy has become the most environmentally friendly, non-polluting, noise free and requires less maintenance than other renewable sources. Photovoltaic energy with its advantages becomes attractive to rural electrification. The average daily solar irradiance in South Africa ranges between 4.5 and 6.5 kWh/m^2, [2].

Mpheni Lituwangadzebu village is a rural area in Limpopo with a population of around 200 citizens. The paraffin and candles are mainly used for lighting and the wood is for cooking and heating in this village. In rural areas where is no access to the utility grid, residences spend more money on fuel than others to electrified places. Based on the department of energy there are around 78% of non-electrified homes used candles against 3% to electrified homes [3].

Mpheni village is located in lower altitudes where is very good solar radiation. The daily sunshine hours of the selected village have an annual average between 7-10 hours/day [2]. The PV system will only be used during the day when the solar radiation is available. This is due to the high cost of batteries, the batteries are not considered in study; the viability of a batterryless system is facilitated by the high solar radiation at the selected site and long daily average insulation duration. The electrical load in the selected site is mostly small and can be covered by solar photovoltaic system to produce the electricity during the day. This study presenting sizing of stand-alone PV system to electrify Mpheni village.

II. AN OVERVIEW OF RURAL ELECTRIFICATION USING PHOTOVOLTAIC TECHNOLOGY

Rural Electrification by photovoltaic technology have been implemented in different region across Africa, e.g. Lucingweni village and Hlulekha nature reserve in Eastern Cape. Solar PV was used for satellites in 1950s and 1960s. In 1970s and 1980s the PV technology started to be used in rural areas. Following this development, the price of PV also lowered. Electrification of rural areas in the case of long-term investments is beneficial and adequate compared to conventional energy [4].

According to [5,6] an assessment of solar and wind energy potential in eastern region of Rwanda was presented. The study of wind and solar energy was compared. The data used were obtained from the Rwanda Meteorological Agency from January 2016 to December 2017. Hargreaves equation was used to determine solar energy potential while wind energy potential was used to determine by Weibull distribution model. Most of the research has been conducted in regions where conditions for electrification using solar energy was favorable.

Rwanda is well benefited with solar energy, even during the rainiest seasons there is adequate daily sunlight, especially in the eastern region, which is known as its high radiation values [6,7]. A PV power flow layout diagram is provided in Figure 1 below. It shows the operation of PV module to supply a load.

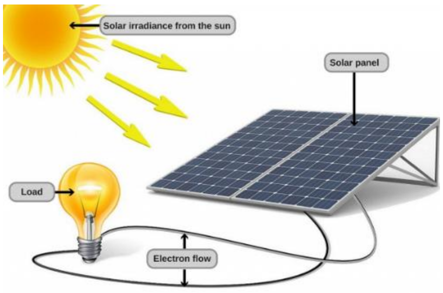

Fig 1: Operation of PV module to supply a load

III. SIZING METHODOLOGY OF PV SYSTEM

A. Description of Selected Site

Mpheni village located in Vhembe District Municipality, Limpopo, South Africa. It has a latitude and longitude of 23°7'60" S, 30°7'0" E respectively.

Temperature is similar in both seasons (summer and winter. The average temperature for summer is around 30°C whilst in winter it ranges from 20°C to 25°C. The village has a population of 50 families, with a total population of 200 citizens, distributed over an area of approximately 20 km^2. The villagers live in houses or huts. Figure 2 shows terrain of the village.

Fig 2: The terrain of the selected village

B. Solar Radiation and Ambient Temperature

In order to study the performance of PV panels to determine the maximum power, the effect of solar radiation and temperature on a solar PV panel is considered. The study location is known for abundance radiation. Figure 3 below shows the monthly solar radiation and temperature for 2018 in the selected site [8]. The average temperature is 21.2°C and annual radiation is 1834.4 kWh/m².

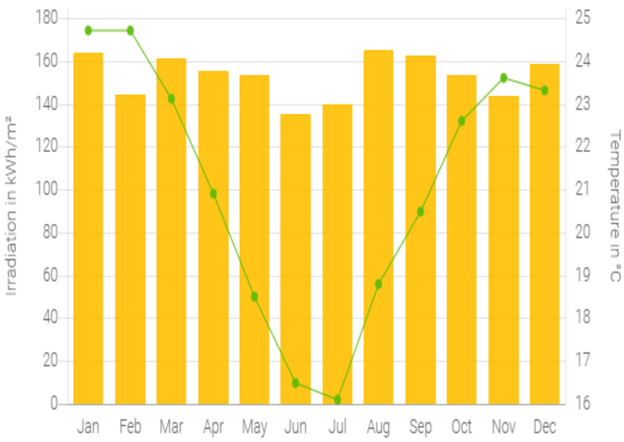

Fig 3: Monthly average irradiation and temperature

C. Characteristics of PV System

PV Modules: In this study Sinetech AEG AS-PS07 module has been used. The module specifications are shown in Table 1.

TABLE 1: SINETECH AEG AS-PS07 MODULE SPECIFICATIONS

Characteristics	AEG AS-PS07
Cells	Polycrystalline solar cell
No. of cells and connections	60(6X10)
Module dimension	1640 mm x 992 mm x 40 mm
Maximum power (Pmax)	285W
Rated voltage at P(max)	31.7V
Current at Pmax (Imp)	9A
Open-circuit voltage (Voc)	38.7A
Short circuit current (Isc)	9.42A
Temperature coefficient	-0.41 %/°C
Operating temperature	-40°C to 85°C

D. Optimum Tilt Angle

PV modules must always face the sun at particular angle. The value of the angle plays an important role in module's performance. The irradiance fallen on modules surface varies in time and place. The module's performance depends on two main angles, tilt angle and azimuth angle as show in Figure 4.

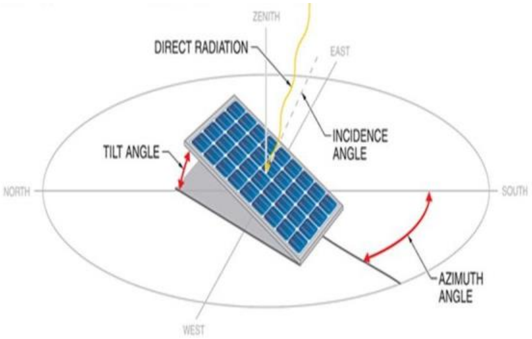

Fig 4: Module's angles

In the study, the application calculates and provides the optimal angle for each month to obtain better performance. The tilt angle can be calculated with the following equations [4], [10]:

$$S = \Phi - \delta \tag{1}$$

Where:

S : The tilt angle of PV modules.

Φ : The site latitude.

$$\delta = 23.45 \times sin\left(\frac{(284+n)}{365} \times 360\right) \tag{2}$$

Where:

δ : The declination angle.

n: The recommended day for each month.

Equations (1) and (2) can be used to calculate the best monthly tilt angle (S) by taking the recommended average day for each month (n). n is not valid for a site location with latitude, > 66.5◦ [4], [8-10].

Table 3 shows the calculation for the recommended average day for each month (n) for the calculation of declination angle (δ) to achieve the best tilt angle of PV modules.

TABLE 3: RECOMMENDED AVERAGE DAY FOR EACH MONTH

Month	n for i^{th} day of month	For the Average Day of the Month	
		Date	n
January	i	17	17
February	31+i	16	47
March	59 + i	16	75
April	90 + i	15	105
May	120 + i	15	135
June	151 + i	11	162
July	181 + i	17	198
August	212 + i	16	228
September	243 + i	15	258
October	273 + i	15	288
November	304 + i	14	318
December	334 + i	10	344

E. Electrical Load Analysis for the Target Village

The basic electrical loads of the households to enhance the living conditions in the village are specified in Table 4. There are 50 simple houses in the selected village. Table 4 summarize the electrical load per house in the target village where every single house assumed to have on average: 3 rooms, a kitchen and a bedroom.

As a result, the total power consumption per day of the target village can be obtained by;

Energy consumption (W/day/house) x Number of houses

$50 \times 7.846 = 392.3 \approx 392$kWh/day.

If supposed that the electrical loss is about 5% (39kW) consequently, this system requires generating about 372kW.

TABLE 4: ELECTRICAL LOAD PER HOUSE IN THE TARGET VILLAGE

Electrical Load	Power (W)	Time (h)	Number	Energy uses (w/day)
Incandescent Globes	60	4	5	1200
Stove	1000	3	1	3000
Refrigerator	180	24	1	4320
TV	120	6	1	720
Radio	55	10	1	550
Mobile charger	10	1	2	20
Other Devices	60	0.30	2	36
Total	1485W/ house	48.3	13	7.846kWh/house

F. Sizing of PV arrays to cover the energy needs.

Figure 5 shows the steps of the sizing procedure utilized for stand-alone PV system to supply power to the rural households in the target village. Steps carried out to size the PV array are listed below [8], [10].

1. Determining energy needed from the PV panels using (3).

$$P_{required} = \frac{P_{load}}{\eta_{inverter}} \tag{3}$$

Where:

$P_{required}$: Energy required to cover PV array.

P_{load} : Load (households load) in watt-hour.

$\eta_{inverter}$: Inverters efficiency.

2. Determining modules energy output per day using;

$$P_{module} = P_{max} \times t_{peak} \tag{4}$$

Where:

P_{module} : Modules energy output per day.

t_{peak} : Average daily peak sunshine hours.

3. Determining the number of modules needed to cover 100% of power needs using (5).

$$\eta_{pv} = \frac{P_{array}}{P_{module}} \quad (5)$$

Where:

η_{pv} : Total number of PV modules.

P_{array} : Output of PV array in watt-hour.

P_{module} : Output of one PV module in watt-hour.

4. Determining the number of modules connected in series (number of strings) by using (6)

$$n_{series} = \frac{V_{Bus}}{V_m} \quad (6)$$

Where:

n_{series} : PV modules connected in series

V_{Bus} : DC bus voltage of the system

V_m : Rated voltage of one module.

5. Determining the number of strings connected in parallel by using (7).

$$n_{parallel} = \frac{n_{pv}}{n_{series}} \quad (7)$$

Where:

$n_{parallel}$: PV strings connected in parallel.

6. Calculation of average daily output from PV array using (8).

$$E_{array} = n_{pv} \times P_{max} \times t_{peak} \quad (8)$$

Where: E_{array} : Average daily output from PV array.

7. Calculation of effective area using,

$$A = n_{pv} \times M_w \times M_L \quad (9)$$

Where:

A: Effective area of array.

M_w : Modules width.

M_L : Modules length.

IV. RESULTS AND DISCUSSION

Sizing of stand-alone photovoltaic system without battery for rural electrification in Limpopo village has been implemented by MATLAB software. The required data for MATLAB application is presented in following Table.

TABLE 5: REQUIRED DATA FOR MATLAB APPLICATION

Description	Value
The site latitude for the location (degrees)	23.1333333
Total village energy required per day (Kw)	372
Hours of PV operations	6
Max power of module (Kw)	0.285
DC bus voltage (V)	60V
Rated voltage (V)	31.7
Temperature coefficient of module (1/C)	0.35e-3
Total losses percentage (%)	0.05
The length of PV module (m)	16.49
Width of PV module (m)	0.992

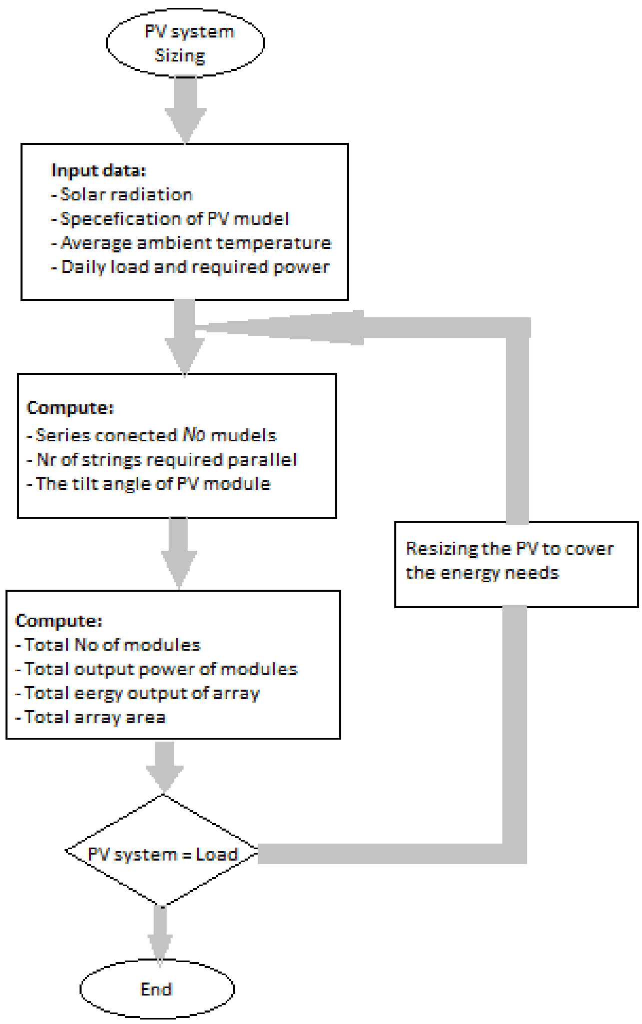

Fig 5: Flow chart of sizing PV array

Monthly tilt angles were calculated using MATLAB software to optimize tilt angles of PV panels. Results are depicted in Figure 6 shows the monthly optimum tilt angle which varies from the smallest angle value in December with 7° to the largest angle value in June with 53.18°. A fixed-tilt angle is set at 30° as an average in case of the tracking mechanism systems is not available.

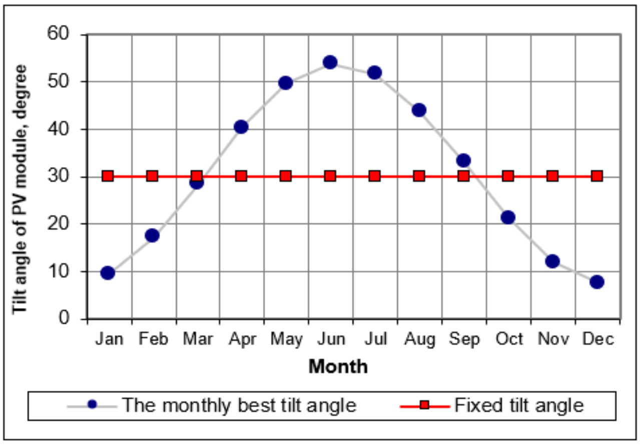

Fig 6: Monthly optimum tilt angle

Number of PV panels required is 218 modules has been calculated by MATLAB. Number of modules connected in series and parallel are 2 and 109, respectively. PV array surface area required for these PV panels depends on the panel tilt angle, the height of the structure and the latitude of the region. Surface area required was calculated to be 3566.061 m^2.

Figure 7 shows monthly average energy output from PV array (E_a) and energy load (E_L). The energy output from PV array is at minimum between June and July and from September sharply increases as observed from figure 7.

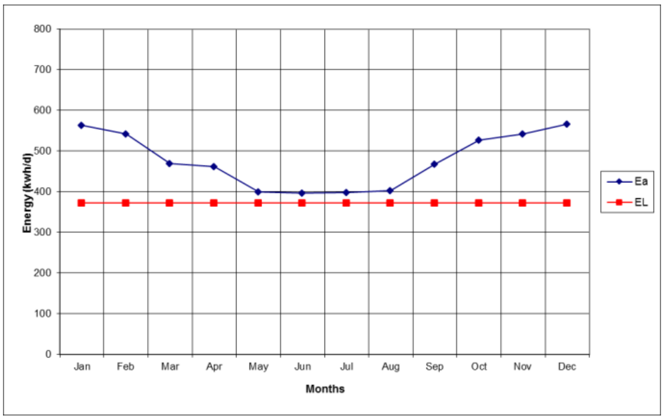

Fig 7: Monthly average energy load vs energy output from PV array.

V. CONCLUSION

The main target of this paper is to provide a general concept of how to size a PV system to power small loads. The methodology for optimal sizing of PV system suitable for a rural village, has been studied in this paper. It has been found that the application of a PV system plays an important role as an alternative source to supply rural areas. Due to the sparsely distributed population in South Africa, the establishment of renewable energy is highly recommended. The theoretical sizing calculation results of a small-scale PV array were approved by using MATLAB software. The high solar irradiance of the selected village showed how PV technology is the best source of supplying electricity to the rural areas. The MATLAB program can be functional to any site with different weather conditions. Concluded remarks can be made as follow:

1. The purpose of the study was to supply 100% of the power needs with minimum energy cost.
2. This project presented a simplified method for sizing a stand-alone PV system to power a small village by using specific software developed.
3. Ambient temperature and solar radiation are the most important factors which influence the energy production of the PV system.
4. The array tilt angle is an important factor to be taken into account to size a PV system.
5. The optimum tilt angle varies from month to month, increasing in winter and decreasing in summer.
6. Small scale PV system represents a possible alternative energy source for rural electrification.

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Author Biographical Statements

	Mudzunga Khonani Davhana was born in Limpopo (Venda) Province in 1997. She acquired BTech in Electrical Engineering from Cape Peninisula University of Technology. She shows interest in photovoltaic systems and hopes to improve villages in Limpopo through Renewable Energy.
	Ali M. Almaktoof was born in Libya in 1978. He received the B. Eng. from AlTahady University, Libya in 2001 and M.Sc. from University of Tripoli, Libya in 2008, and DTech from CPUT in 2015 all in electrical engineering. He is currently Lecturer/Researcher in Electrical Engineering, DEECE, CPDES, Cape Peninsula University of Technology. He is a member of Institution of Engineering and Technology (MIET) and World Society of Sustainable Energy Technology (WSSET). Dr. Almaktoof research interests include control of power converters, model predictive control, multilevel converters, reat-time simulators and renewable energy systems applications.
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