Stand-alone PV Solar System Design for Ezikhumbeni Village

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***Abstract*-Stand-alone PV solar system is the other way of supplying electricity energy to people who lives off-grid, not only to supply electricity to power the house but also can be used to power electric motor to supply clean water to the village. This is achieved by photovoltaic (PV) cells absorbing sun's irradiations and transforms it to direct current energy.**

Index Terms-Irradiation, Temperature, Photovoltaic.

I. INTRODUCTION

The system is designed to supply electricity to supply 25 houses, a population of 200 in the rural village called Ezikhumbeni village under Ulundi Municipality in the province of KwaZulu Natal South Africa. The site co-ordinate is 28.22° S, 31.32°E, annual global horizontal (GHI) irradiation per day is 5.5 kwh/m^2, average sunshine hours is 6.5 hours and average temperatures is 20.61°c. This provides high probability of enough energy to supply electricity that will power houses for the villagers and power motor to supply clean water. These are poor people who mostly rely on government pension fund to make a living for themselves.

II. STAND-ALONE SYSTEM

A stand-alone PV solar system consists of PV module, charge controller, batteries, stand-alone inverter and the load. There are two types of load i.e. direct current (DC) load and alternating current (AC) load. The AC load only is considered for Ezikhumbeni villagers.

Figure 1-1 shows the typical stand-alone system with AC load only.

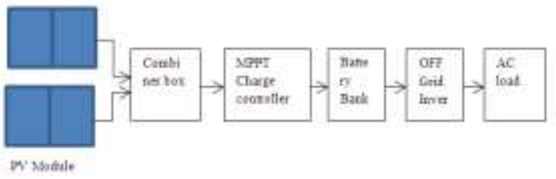


Figure1-1: Stand-alone system with AC load.

In the stand-alone PV solar system a PV module is used to absorb sun irradiation and turn it into DC energy. PV modules are connected in series to form PV string for the purpose of voltage increasing and string are connected in parallel to form a PV array which is connected to the charge controller. The voltage increase is sometimes not good for the batteries as well as stand-alone inverter, the charge controller than regulates or control the string voltage to be safely used by batteries and inverters. The batteries they store charge for future usage e.g. low irradiation or under supply of the from PV array. The inverter is operates to convert DC to AC energy, which is the energy mostly our households use.

III. DESIGN ANALYSIS

Motor Sizing

Let's start with sizing of the motor. The population is 200 and the rural water consumption is between 80-100 liters [1], but let's use 90L per person which gives 18kL. The aim is that the motor should never be powered by batteries in any case, so the motor should pump enough water that will sustain the villagers for 3 days, this gives a volume of $54m^3$. The motor to be used has an efficiency of 60%. Considering a head of 25 m the head loss should be 10% of the head [2]. The motor should run for 6 hours. Below are the relevant calculations when sizing the water pump motor.

$$H.\mathrm{E} = \frac{9.81\times \mathrm{V}\times \text{Pipe head}}{1000} \tag{1}$$

$$\mathrm{H.E} = \frac{9.81\times 54\times(25+2.5)}{1000} = \frac{14.57\mathrm{kJ}}{3.6\mathrm{kWh}} = 4.05\mathrm{kWh}$$

Now the hydraulic energy (H.E) is known the next step is calculated the flow rate (Q) per second.

$$(\mathrm{Q}) = \frac{\mathrm{V}}{\mathrm{h}\times 3600} = \frac{54000}{6\times 3600} = 2.5\mathrm{l/sec} \qquad (2)$$

$$(\mathrm{P}) = 9.81\times \mathrm{Q}\times \mathrm{pipeHead} \qquad (3)$$

$$(\mathrm{P}) = 9.81\times 2.5\times 25 = 613.12\ \mathrm{W}$$

The hydraulic power (P) is known the last step is to calculate the motor power.

$$\text{Motor Power} = \frac{\mathrm{P}}{\eta} \qquad (4)$$

$$\text{Motor Power} = \frac{613.12}{0.6} = 1022\ \mathrm{W}\ (1.4\ \mathrm{Hp})$$

The motor power and it consumption reflects in table 1-1.

PV Module sizing

The total load demand from the villagers is shown in table 1-1 below inclusive of the motor. The panel capacity should have a capacity to meet the consumption shown in the table. The system considers the system loss of 30% and a 250 Wp poly-crystalline PV Module.

$$\text{Panel Capacity} = \frac{\mathrm{kWh}}{\mathrm{day}}\times \text{system energy loss} \quad (5)$$
$$= 71\,319\times 1.3 = 92\,714.7\ \mathrm{kWh/day}$$

Total Wp of PV panel capacity needed,

$$\mathrm{W_p} = \frac{\mathrm{kWh/day}}{\mathrm{Irridiation}} \qquad (6)$$
$$\mathrm{W_p} = \frac{92\,714.7}{5.52} = 16\,796.14 = 17\ \mathrm{kW_p}$$

When excluding the substation auxiliary loads and the pump. Each house should be supplied by,

$$\mathrm{Wp} = 2547\times 1.3 = 3311.1\ \mathrm{kWh/day}$$
$$\mathrm{Wp} = \frac{3311.1}{5.52} = 600\ \mathrm{Wp}$$

$$\text{No. of module} = \frac{\mathrm{W_p}}{\mathrm{p_{Module}}} \qquad (7)$$
$$\mathrm{KW_p} = \frac{17\,000}{250} = 68\ \text{modules}$$

Charge Controller Sizing.

The charge controller is located between the solar field and the inverter and offers the means to isolate individual strings from the solar modules. DC generated from PV module is fed directly to MPPT Charge Controller. MPPT charge controller modulates the operating voltage so that module can produce maximum power, instead of operating at battery charging voltage [3]

$$\text{String Vmpp} = 2\ \text{module in series}\times \mathrm{V_{MPP}} \quad (8)$$
$$\text{String Vmpp} = 2\times 30.1 = 60.2\mathrm{V}$$

$$\text{Array Impp} = 6\ \text{strings}\times \mathrm{I_{MPP}}\times \mathrm{SF} \qquad (9)$$

$$\text{Array Impp} = 6\times 8.3 = 49.8\ \mathrm{A}$$

$$\text{Total Array Current} = 34\times 8.3 = 282.2\mathrm{A}$$

$$\mathrm{Pmpp} = \mathrm{Impp}\times \mathrm{Vmpp} \qquad (10)$$

$$\mathrm{Pmpp} = 60.2\times 282.2 = 17\ \mathrm{kW}$$

$$\text{No. of charge Controller} = \frac{\mathrm{T.Modules}}{\mathrm{Modules\ /Charge\ Controller}} \qquad (11)$$

$$\text{No. of charge Controller} = \frac{68}{12}$$
$$= 6\ \text{Charge Controllers}$$

The PV Module manufacture recommended a use of 15 A fuse per string. The DC Isolator was sized according to short circuit current that will be flowing out of the charge controller which is$I_{sc}\times Satefy\ factor = 8.87\times 6\times 1.3 = 70A$, the next size available is 80A.

Battery Sizing

Battery sizing is the capability of a battery system to meet the load demand with no contribution from the photovoltaic system. For a stand-alone photovoltaic system, the principal goal of battery storage is to ensure that the annual minimum photovoltaic system energy output equals the annual maximum load energy input. The photovoltaic system must also maintain a continuous energy supply at night and on cloudy days when there is little or no solar energy available. The amount of battery storage needed will depend on the load energy demand and on weather patterns at the site. Having too much energy and storage capacity will increase cost, therefore there must be a trade-off between keeping the cost low and meeting the energy demand during low-solar-energy periods. The recommended batteries that should be used in stand-alone photovoltaic power system are deep-cycle lead-acid batteries because of their high performance [4].

Below are the calculations involved in estimating batteries that will be used for this system excluding the motor pump as it will not be powered by batteries in case of low irradiations. The inverter size that is considered for this design it a stand-alone inverter that operates at 48V, this means that the system voltage is

48V, so as the charge controller and the battery voltage.

$$\mathrm{AH} = \frac{\frac{\mathrm{Wh}}{\mathrm{day}} \times \text{Days of Aut.} \times \text{Temp.F}}{\text{DOD} \times \text{System Voltage}} \qquad (12)$$

$$\mathrm{AH} = \frac{65187 \times 2 \times 1.1}{0.6 \times 48} = 4980\ \mathrm{AH}$$

$$\text{No. of Total Batteries} = \frac{\text{Battery sytem AH}}{\text{AH/battery}} \qquad (13)$$

$$\text{No. of Total Batteries} = \frac{4980}{152} = 32.7, \text{which is 33 battries}$$

$$\text{Number of Total Batteries} = 33 \times 4(12\mathrm{V}) = 132 \text{ batties}$$

$$\text{Charge Rate} = 10\% \text{ of C20 AH rating} \qquad (14)$$

$$\text{Charge Rate} = 0.1 \times 4980 = 0.498\ \mathrm{kA}$$

At night 8158 watts that will be supplied by batteries and that is 22% of the load. If the batteries are charged because of supplying 22% energy the previous night, so the charging rate will be$0.498\ \mathrm{kA} \times 22\% = 110\mathrm{A}$.

$$\text{Charging time} = \frac{\mathrm{AH}}{\mathrm{A}} = \frac{4980}{498} = 10\ \text{Hrs}, \qquad (15)$$

The charging after the battries have been discharged the previous night it will be $10\ \text{Hrs} \times 22\% = 2.2\text{Hrs}$

$$\text{Discharge Rate} = \frac{\mathrm{AH}}{20\mathrm{H}} \qquad (16)$$

$= \frac{4980}{20} = 249\mathrm{A}$, at night the discharge rate is $249\mathrm{A} \times 22\% = 55\mathrm{A}$

Discharge time is given by

$$\mathrm{I} = \frac{\mathrm{P}}{\text{Voltage}_{\text{system}}} = \frac{35783}{48} = 746\mathrm{A} \qquad (17)$$

$$\mathrm{t} = \frac{\mathrm{AH}}{\mathrm{A}} = \frac{4980}{746} = 6.7\text{hours} \qquad (18)$$

Discharge time during the night

$$\mathrm{I} = \frac{\mathrm{P}}{\text{Voltage}_{\text{system}}} = \frac{8158}{48} = 170\mathrm{A} \qquad (17)$$

$$\mathrm{t} = \frac{\mathrm{AH}}{\mathrm{A}} = \frac{1096}{170} = 6.4\text{hours} \qquad (18)$$

Inverter Sizing.

The inverter is required to convert the DC electricity to alternating current (AC). The stand-alone central inverter type for this design is recommended. 3 x 16 kW is used so that one faulty inverter can be taken for repair or maintenance while the other inverter continues supplying the load. This will result in continuously supply of power even if one inverter is out for maintenance. For safety, the inverter should be considered 25-30% bigger size [5].

$$\text{Inverter}_{\text{size}} = \frac{\mathrm{P_{AC}}}{\text{number of Inverter}} \qquad (19)$$

$$\text{Inverter}_{\text{sizel}} = \frac{36805}{3} \times 1.3 = 16\ KW$$

Determining the AC output from the inverter, considering 92 % inverter efficiency, P_{AC} is,

$$P_{AC} = \eta \times kW_p = 0.92 \times 6000 = 5520W$$

Table 1-1: Estimated load

items	Power (W)	unit	daily hours (h/day)	T power (W)	Daily energy(Wh/day)
CFL Light	18	100	5	1 800	9 000
2 plate cooking stove	1100	25	1	27 500	27 500
TV	150	25	2	3 750	7 500
Radio	5	25	7	125	925
Refrigerator	100	25	7.5	2 500	18 750
lights	18	6	14	108	1 512
pump motor	1022	1	6	1 022	6 132
				36805	71319

IV. PVSYST SIMULATION.

The simulation for the design is through the use of the PVSyst software. PVSyst stands among one of the most widely used simulation tools in the PV industry for grid connected and stand-alone PV systems. It is developed by the Centre of Energy at the University of Geneva, Switzerland. Its simulates energy yield estimation by considering the site characteristics, meteorological conditions, technical characteristics of standard PV components and the configuration (basic design) presented in this paper.

The figure 1-2 shows tilt angle and the plane orientation for this design. The southern hemisphere is orientated at 0 Azimuth and when tilt at 30° it yield 1.09 transposition factor which indicates high irradiation absorption from the sun with loss factor of 0.3% which is within the acceptable range for the design. Figure 1-3 shows the system configuration suggested by the software. The software considers the site behaviour throughout the year and suggests the Wp. The suggested 15.4 kWp is shown in figure 1-3 which is below the calculated value, to avoid overloading the system, 17kWp is considered. The whole arrangement proves the calculations made above in sizing the system. The software also suggests how the arrays and strings should be configured. To increase the Wp, the user should either change the series and or the parallel connections but should also consider the ratings of the charge controller and the inverter to be used.

The software also automatically calculates the amp hour for the load and the consumption. This paper does not consider the amp hour suggested but considers the amp hour manually calculated, simply because the software does not use the formula trusted by South African engineers which is shown in equation (12). The software further shows different battery and PV module manufacturers.

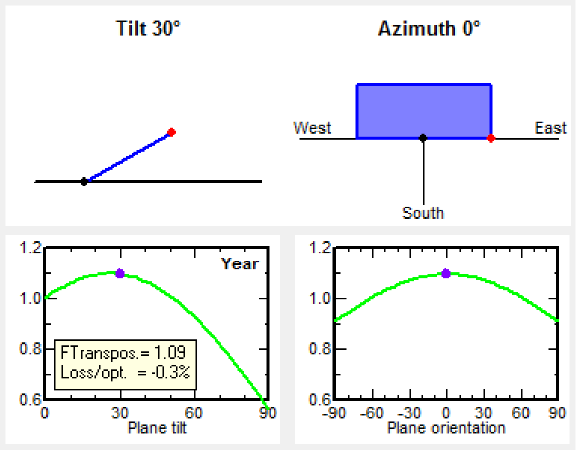
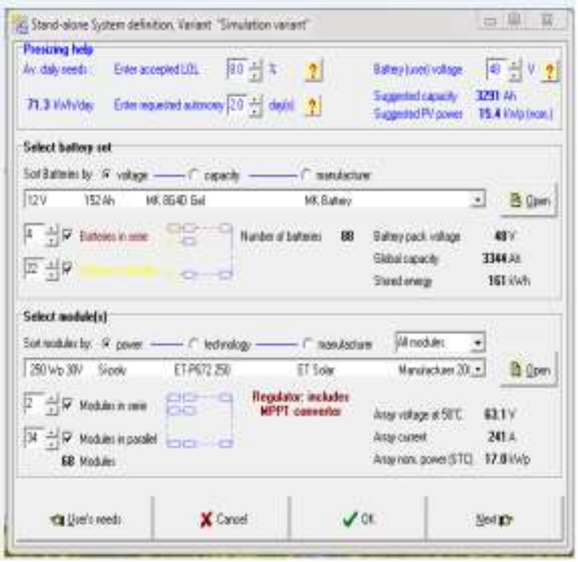


Figure1-2 PV module orientation


Stand-alone System definition, Variant "Simulation variant"

Presizing help

Av. daily needs : 71.3 kWh/day

Enter accepted LOL 8.0 %

Enter requested autonomy 2.0 day(s)

Battery (user) voltage 48 V

Suggested capacity 3291 Ah

Suggested PV power 15.4 kWp (nom.)

Select battery set

Sort Batteries by: ● voltage ○ capacity ○ manufacturer

12 V 152 Ah MK 8G4D Gel MK Battery

4 ☑ Batteries in serie

22 ☑

Number of batteries 88

Battery pack voltage 48 V

Global capacity 3344 Ah

Stored energy 161 kWh

Select module(s)

Sort modules by: ● power ○ technology ○ manufacturer All modules

250 Wp 30V Si-poly ET-P672 250 ET Solar Manufacturer 20…

2 ☑ Modules in serie

34 ☑ Modules in parallel

68 Modules

Regulator: includes MPPT converter

Array voltage at 50°C 63.1 V

Array current 241 A

Array nom. power (STC) 17.0 kWp

Figure 1-3 System simulation variant

The figure 1-4 below shows the V-I curve for the system produced by the software. The maximum tracking power point is indicated by the black dot on the resultant characteristics. If the system is oversaturated, the PV array output will drastically drops and lead to open circuit. For best system performance, oversaturation should be avoided or should not exceed the set point.

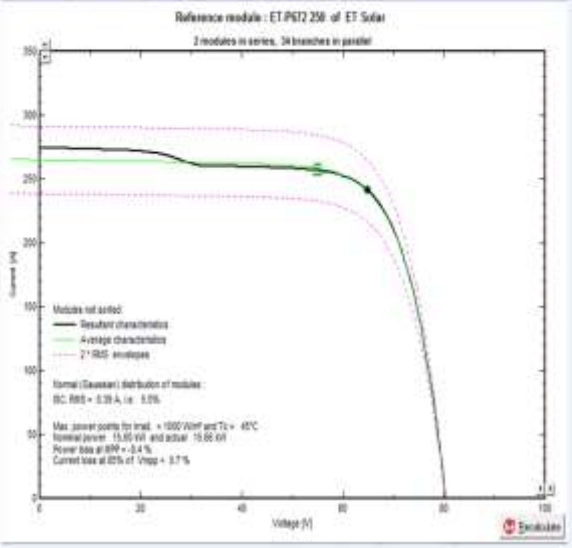


Figure 1-4 Current and Voltage Curve graph on the DC production.

Let first start off by explaining the key words of the graph in figure1-5. E-user is the energy that is supplied to the user or load, E-load is the energy that the load requires and lastly E-avail is the energy that is available on the PV array without considering any losses in the system. According to the results in the figure1-5 below, the system will produce close to unity for 9 months (Feb-Oct) each year. Again here the system under supplies the load during the summer season because of low irradiation in the site but the batteries are there to boost the system in case the system does not meet the load's demands. E-Available seems to be higher than any other energy this is because E-available corresponds with the site GHI, the higher your irradiation the more solar energy you have. Let's move to E-load which is fixed throughout the year, we can note that the system shows constant energy demand over the months, the drops and high depends on the number of days per month.

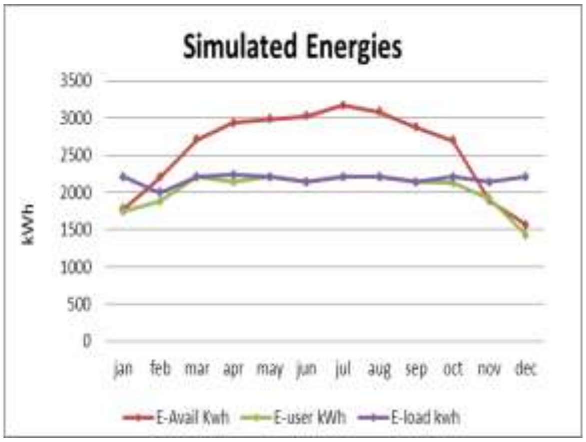


Figure 1-5 Simulated energies for Ezikhumbeni Village

V. ACKNOWLEDGMENT

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VI. CONCLUSION

The problem statement is solved through the use of a stand-alone design. The system design will supply the electricity and power the water pump motor. The system is designed to supply the fixed load for the villagers. Should the villagers wish to add additional load on the system, the system should be designed to meet the additional load otherwise the system will experience load shedding or power cuts due to overload.

The use of PVSyst software was a success and it gave trusted simulations which were close to calculated values. The energies produced by the system meet the load's demand and where the PV array produces less, the battery bank will discharge to boost PV array output. The batteries should be recycled every after 5 years because the life span for the batteries is 5 years. The batteries are gel type and will requires less maintenance but special care should be placed to batteries as they are the back-up of the system.

The overall system sizing is done in accordance to relevant standards. The villagers will soon experience the use of clean water as well as electricity supply form the PV system provided that the Municipality has enough fund to sponsor the project.

VII. REFERENCES

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