Design of Standalone PV System for a Typical Modern Average Home in Shewa Robit Town-Ethiopia

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Abstract In this paper a standalone PV system for the electrification of a typical modern average home in Shewa Robit (Longitude and Latitude of 10°00′N, 39°54′E respectively with an elevation of 1280 meters above sea level) that can meet the electricity power demand successfully has been designed. So as to know the daily energy consumption, load estimation has been done by considering the floor plan of the home and the daily power consumption and energy demand of the house at peak hour were found to be 5.048kW/day and 11.619kWh/day respectively. The design result shows that a typical modern average home in Shewa Robit can be electrified by using sixteen sm-130 PV modules, six 6E120-13, 12V, 808Ah batteries, one 3kW inverter, one Schneider (Xantrex) C35, 12/24V charge controller and 20m, 53.5mm^2 copper conductor with the total investment cost of $12,960.36 which gives a unit cost of energy (COE) of 0.058 $/kWh.

Keywords: PV system, inverter, charge controller, sizing strategy, load estimation, unit energy cost, day of autonomy, voltage drop index

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1. Introduction

Smart electrification will allow us to make better use of energy, reduce emissions and ultimately help to mitigate climate change. In Ethiopia there is a huge shortage of electric power which intern affects daily routines and overall performance of people [1,2]. When power is available, it is not free from power quality problems like fluctuations; harmonics, voltage sag and voltage swell [1,2,11,14]. Hence utilizing renewable energy resources in an off-grid manner with distributed generation for homes is an imperative solution to overcome this problem [10,11]. To design and implement such systems, the task is started from load estimation and resource potential assessment as described by Figure 1 below.

2. Load Estimation

Here the need is in order to properly size those components of the system indicated in Figure 1 by considering a load on the typical modern average home. A typical modern average home in Shewa Robit contains one salon, two bed rooms, corridor, terrace/veranda, one kitchen, one shower and one toilet. Usually the kitchen, toilet and shower are separated from the main house. So as to estimate the load, efficient household equipment has been selected and lamps used for this study are also compact florescent types (CFLs) with 11 W and 15W rating as presented in [2]. Table 1, Table 2 and Table 3 presented below shows the detailed load estimation for this study.
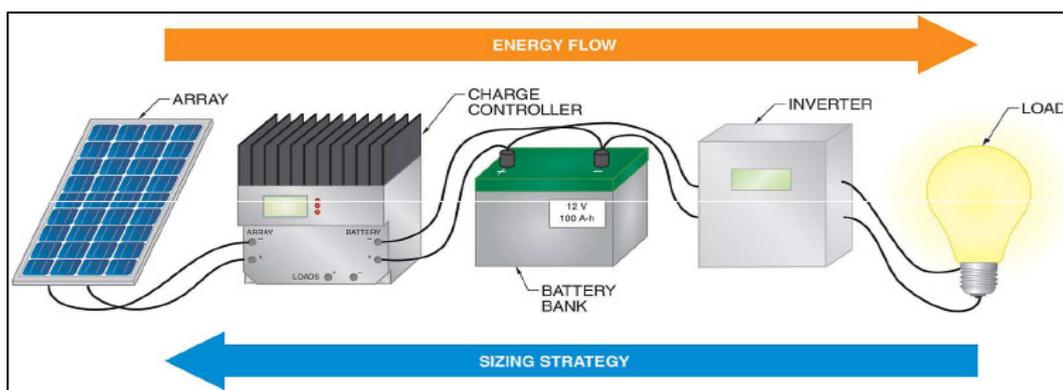

Figure 1. Generalized sizing (design) strategy and energy flow block diagram for PV system

Table 1. Summary of lighting loads in the typical modern average home

		Lighting Loads			
No.	Lamp Placement	Lamp Wattage (W)	Load (kW)	Operating hrs./Day	Energy Demand/ Day (kWh/Day)
1	Salon	15	0.015	4	0.06
2	Terrace/Veranda	15	0.015	1	0.015
3	Childes bed room	15	0.015	6	0.09
4	Kitchen	15	0.015	4	0.06
5	Parents bed room	11	0.011	2	0.022
6	Corridor	15	0.015	4	0.06
7	Toilet	11	0.011	1	0.011
8	Shower	11	0.011	1	0.011
9	Out door	15	0.015	3	0.045
	Total		0.123		0.359

Total Load/Day = 0.123kW and Total Energy Demand = 0.359kWh/Day = 131.035kWh/Year

Table 2. Summary of equipment loads in the typical modern average home

		Other Home Equipment's			
No.	Equipment's	Equipment Wattage (W)	Load (kW)	Operating hrs./Day	Energy Demand/ Day (kWh/Day)
1	Television (21")	75	0.075	8	0.6
2	Tape/Radio	15	0.015	8	0.12
3	VCD/DVD Player	25	0.025	4	0.1
4	Refrigerator	100	0.1	24	2.4
5	GSM Telephone	10	0.01	24	0.24
6	Electric "Mitad"	2500	2.5	2	5
7	Stove	1000	1	1	1
8	Computer	200	0.2	4	0.8
9	Electric Iron	1000	1	1	1
	Total		4.925		11.26

Total Load/Day = 4.925kW and Total Energy Demand = 11.26kWh/Day = 4109.9kWh/Year

Table 3. Summary of overall system load in the typical modern average home

		Overall System Load Table		
No.	Load Type	Total Wattage/Day (kW/Day)	Energy Demand/Day (kWh/Day)	Energy Demand/Year (kWh/Year)
1	Lighting Load	0.123	0.359	131.035
2	Equipment Load	4.925	11.26	4109.9
	Total	5.048	11.619	4240.935

Total Daily Load = 5.048kW/Day; Total Daily Energy Demand = 11.619kWh/Day and Total Yearly Energy Demand = 4240.935kWh/Year

From Table 3 above, we need to have 5.048 kW of power from the inverter output as we have this amount of connected load in to the PV system plant. Therefore; the efficiency of the inverter has to be taken in to account so as to know the adjusted wattage that has to be given by the battery and interred in to the inverter. So that we can have the rated output of 5.048 kW from the inverter output this is equal to the load wattage to be served.

Most literature showed that the inverter efficiency is equal to 85% [5,6,7,8] and we expect the output from the inverter to be 5.048kW. Hence, the input power to the inverter that has to be delivered by the battery is:

$$= \frac{\text{Connected Load(kW)}}{\text{Efficiency of Inverter}/100}$$

$$= 5.048 \text{ kW} / (85/100)$$

$$= 5.048 \text{ kW} / 0.85$$

$$= 5.938\text{kW}.$$

Therefore the total wattage expected to be supplied from the Battery is approximately equal to 5.938kW = 5938W.

3. Design (System Sizing)

3.1. Battery Sizing

Total amp-hour demand per day

$$= \frac{\text{Total energy demand per day}}{\text{Battery bus voltage}}$$

$$= 11.619 \text{ kWh/24 V}$$

$$= 484.125\text{Ah}$$

Required battery Capacity

$$= \frac{\text{Total amp} - \text{hour demand per day} \times \text{Days of autonomy}}{\text{Allowable depth of discharge}}$$

Day of Autonomy is days of storage desired and for a design purpose it is three to five days [4,5,7,16]. And for this application 4 days is selected.

$$= 484.125\text{Ah} \times (4/0.8)$$

$$= 2420.625\text{Ah}.$$

From the battery specification sheet *6E120-13, 12V, 808Ah* battery is selected for this study.

Note that when we are going to select a battery from the data sheets, we have to look for the battery which gives (Battery capacity (Designed))/Capacity of selected battery) near to a whole number.

$$\text{Battery strings in parallel}$$
$$= \frac{\text{Battery capacity (Designed)}}{\text{Capacity of selected battery}}$$
$$= 2420.625 / 808$$
$$= 3 \text{ Battery strings.}$$

$$\text{Number of batteries in series}$$
$$= \frac{\text{Battery bus voltage}}{\text{Selected battery voltage}}$$
$$= 24 / 12 = 2 \text{ Batteries.}$$

Therefore; we need to have a total of *2×3 = 6* batteries for the whole system. The two batteries have to be connected in series and then these strings have to be connected in parallel.

$$\text{Battery kilowatt} - \text{hour capacity}$$
$$= \left(\begin{array}{l} \text{battery amp} \\ -\text{hour capacity} \times (\text{Battery bus voltage} / 1000) \end{array} \right)$$
$$= 2424 \times 0.024 = 58.176 \text{kWh.}$$

3.2. Photovoltaic Array Sizing

3.2.1. Calculating the Area Needed by the PV Module/Array

The total annual energy consumption by the house hold is given by 4240.935kWh/year. The worst case (summer) solar radiation in Sehwa Robit (where the house in question is located) is equal to 5.28kWh/m²/day in July [9,12]. Hence, the annual solar power radiation is 5.28kWh/m²/day × 365 days/year = 1927.2 kWh/m²/year.

The area required to generate the required power is:

$$\mathbf{A} = \frac{(4240.935 \text{kWh} / \text{year}) / (1927.2 \text{kWh} / \text{m}^2 / \text{year})}{\text{PV module cell Efficiency}}$$
$$= 2.2 / 0.15 \text{ m}^2 = 15 \text{ m}^2.$$

The PV module of *Sm-130* is selected for this work. The efficiency of PV cell ranges from 6% - 30% [13,16]. And in this work 15% efficiency is assumed as it is the efficiency of the selected PV module.

3.2.2. PV Module Number Determination

Required array output / day
$$= \frac{\text{Total energy demand per day}}{\text{Battery efficiency}}$$
$$= 11619 \text{Wh} / 0.85$$
$$= 13669.412 \text{Wh}$$
Selected PV modules maximum power voltage is then = 17.6 × 0.85 = 14.96V

Selected PV modules guaranteed power output = 130 × 0.9 = 117 W and peak sun hour at optimal tilt is equal to 8 hours. Therefore;

Energy output / module / day $= 117 \times 8 = 936 \text{Wh}$

$$\text{Module energy output}$$
$$= DF \times \text{Energy Output} / \text{module} / \text{day}$$
$$= 0.90 \times 936 = 842.4 \text{Wh}$$

Modules required $(\mathbf{N})$
$$= \frac{(\text{Required array output} / \text{day})}{(\text{Module energy output at operating temperature})}$$
$$= 13669.412 / 842.4 = 16.22674$$
Approximating,
$$\mathbf{N} = 16 \text{ modules}$$

Modules required / string (Ns)
$$= \frac{\text{Battery bus voltage}}{\text{Selected PV modules maximum power voltage}}$$
$$= 24 / 14.96 = 1.60428.$$
Approximating,
$$\text{Ns} = 2 \text{ Modules}$$

Strings in parallel (Np)
$$= \frac{\text{Number of modules required}}{\text{number of modules required in string}} = 16 / 2 = 8$$

Hence, Np = 8 Modules.

3.3. Inverter Sizing

For stand-alone systems, the inverter must be large enough to handle the total amount of watts in the system. As a standard design procedure the inverter size should be 25-30 % bigger than total watts of peak wattage from the photovoltaic panels [6,15].

Since the total peak wattage required from the PV module is 2080 watts or 2.08 kW,

Invertwr capacity $= (2.08 + 2.08 \times 0.28) \text{kW} = 2.582 \text{kW}$

The inverter size should be about 3 kW or greater.

3.4. Solar Charge Controller Sizing

According to standard practice, in any PV system design, the sizing of solar charge controller is to take the short circuit current (Isc) of the PV array, and multiply it by 1.3 [2,3,18]. From the specification data sheet of the selected module, Isc = 8.13A. Hence,

$$\text{Charge controller rating}$$
$$= (8 \text{strings} \times 8.13 \text{A}) \times 1.3 = 84.448 \text{A.}$$

So the solar charge controller should be rated 85A at 24 V or greater.

3.5. Conductor Sizing

$$\text{VDI} = \frac{\text{Amps} \times \text{Cable length in feet}}{\% \text{Volt drop} \times \text{Voltage (DC)}}$$
$$= (60.516 \times 65.6) / (4 \times 24)$$
$$= 3969.8496 / 96 = 41.3526.$$

VDI is Voltage Drop Index where Amps indicate the nominal current of the PV module; cable length is assumed to be 20m = 65.6 feet as most modules are installed in the roofs of the house it is a reasonable assumption. % Volt drop is the acceptable voltage drop level (<10%) and Voltage (DC) is the system DC bus voltage. Then according to VDI result, an appropriate conductor size will be selected from the table.

From the universal cable size data sheet the nearest voltage drop index (VDI) to this value is found to be 49.Therefore; the size of the cable corresponding to this VDI is 53.5 mm^2.

4. Result Summery and Cost Estimation

The overall system architecture (system sizing result) of a standalone photovoltaic based power supply unit and its cost estimation is presented in table 4 below.

To evaluate the system unit energy cost, an assumption of 10% interest rate (represented by i) and a project life span of 25 years (represented by n) are taken in to consideration from [3,17]. Therefore; the annual total cost and the unit energy cost per year can be calculated as follows.

$$C_A = \frac{i(1+i)^n}{(1+i)^n - 1}C_I + C_{o+m}$$

Where:-

C_A = Total Annual Cost

C_I = Capital Cost = $12, 960.36

C_{O+M} = Operation and Maintenance Cost
$= 2\% \times \$12,960.36$
$= \$259.2072$

Hence,

$$C_A = \frac{0.1(1+0.1)^{25}}{(1+0.1)^{25} - 1}12960.36 + 259.2072 = 1687.025.$$

The unit energy cost is determined by dividing the total annual cost by the total energy consumed usefully per year.

$$Unit\ Energy\ Cost = \frac{C_{annual} + C_{O+M}}{\text{Energy Consumed Annually}}$$
$$= \frac{\$1687.025}{1927.2\text{kWh/m}^2/\text{year} \times 15\text{m}^2}$$
$$= 0.058\$/\text{kWh}.$$

Table 4. Overall system architecture and cost estimation

No.	Component	Specifications	Quantity	Unit Price	Total Price
1	PV module	Sm-130;Pm =130 W, Vm = 17.6 V, Im = 7.39 A, Isc = 8.13 A.	16	$ 1.5/W	$ 3120
2	Battery	6E120-13, 12V, 808Ah	6	$ 650	$ 3900
3	Charge Controller	Schneider (Xantrex) C35, 12/24V	1	$ 89.96	$ 89.96
4	Inverter	Selectronic Interactive Inverter 3kW, 24V	1	$ 5730	$ 5730
5	Cable	Copper 53.5mm^2	20m	$ 6.02	$ 120.4
Total investment cost					$ 12960.36

5. Conclusions

In short in this study deign of solar PV system for a modern average home in Shewa Robit is presented in a clear and step by step calculation approach. Hence the work can be used as a good reference material for PV system designers, researchers and for education purpose.

Based on the system sizing and cost estimation result, the author of this work believes that, implementation of such systems may be slightly worrisome when we see from the economy of residents' perspective. However, considering the shortage of power in the town and country at large (only 27.2 % coverage in the year 2017 [1]), the increment of day to day governmental and non-governmental organization subsidies towards renewable energies, this cost should not be seen as a significant impairment.

Moreover, regarding its role in the protection of vegetation and forestry and therefore the prevention of soil degradation, the improvement to the quality of life of the many people residing in the town, the future situation regarding fossil fuel sources, and its contribution to the reduction of pollutant emissions in to the environment such distributed energy systems are useful.

It should be also noted that free solar energy will also be utilized, load will be satisfied in an optimal way; help is given to the mobilization of investments towards clean energy; and, most of all, the poor will benefit from the electric light provide from the grid.

Acknowledgments

Conflict of Interests

The author of this work declares that there is no any conflict of interests regarding the publication of this paper.

Nomenclatures

$/kWh   Dollar per kilowatt-hour
A   ampere
A   Area
Ah   ampere hour
COE   Cost of Energy

C_A	Total annual cost
CFL	Compact Fluorescent Lamp
C_I	Capital cost
C_{o+m}	Operation and maintenance cost
DC	Direct Current
DF	Derating Factor
E	East
i	Interest rate
I_{sc}	Short circuit current
kW	kilowatt
kWh	kilowatt-hour
m	meter
m^2	meter square
mm^2	millimeter square
N	North
N	Number of modules
n	Project life span
N_p	Modules in parallel
N_s	Modules in series
P_m	Maximum power
PV	Photovoltaic
V	Voltage
V	volt
VDI	Voltage drop index
V_m	Maximum power voltage
W	watt

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