Design of Stand-Alone Photovoltaic System – A Case Study

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ABSTRACT

In this paper the design of a stand-alone photovoltaic system has been explained in two methods; method-I, considering the solar radiation data of the location and the load, and method-II, considering only the load. The various constraints considered in the preliminary phase and the later stages have been thoroughly discussed along with a case study pertaining to a college. The paper describes various parameters required for the design of a photovoltaic system taking the load conditions and economic constraints in the end. Cost analysis of conventional and stand alone photovoltaic system for both the methods is carried out.

Keywords – **photovoltaic system, PV system, solar energy, inverter**

I. INTRODUCTION

The ever increasing demand for electrical energy due to rapid industrialization and increasing population brings in a need to go for sustainable energy sources i.e. renewable energy sources like solar, wind, ocean energy, etc. Solar energy is ultimate source of energy which is abundant in nature and is available irrespective of location.

This paper attempts to design a standalone photo voltaic system in two methods. The Method-I is an analytical method which takes solar radiation data into consideration to design the PV system and the Method-II does not consider the data from solar radiation but still can give the design of the PV system. The Method-II can be considered to be more simple and practical. Cost analysis of conventional system and stand alone system for both analytical method and practical method are carried out and economical solution is recommended.

II. LIST OF NOTATIONS USED

H_{bm}	Direct solar radiation
H_{dm}	Diffuse solar radiation
H_{gm}	Ground reflected part of global solar radiation
H_{Tm}	Monthly average daily solar radiation
$(I_b)_{mi}$	Hourly direct solar radiation
$(I_d)_{mi}$	Hourly diffuse solar radiation
$(I_g)_{mi}$	Total solar radiation
$(I_{Tb})_{mi}$	Instantaneous solar radiation
L_{dm}	Average day time load
L_{nm}	Average night time load
PV	Photo voltaic
$(R_b)_{mi}$	Tilt factor for direct solar radiation
R_d	Tilt factor for daily diffuse solar radiation
R_r	Tilt factor for daily ground reflected solar radiation
X_C	Critical radiation
β	Tilt angle
δ_m	Declination angle
ϕ	Latitude of the location
ϕ_{mi}	Solar radiation utilizability
η_b	Average energy efficiency of the battery
η_c	Cabling efficiency
η_T	Maximum power point tracking efficiency
η_{vr}	Voltage regulator efficiency
η_w	PV array wiring efficiency
ω_{mi}	Hour angle
ω_{sm}	Sunset hour angle
ω_{stm}	Sunrise hour angle
PV	Photovoltaic

III. METHOD-I

The complete analytical methodology has been presented in Method-I. Solar radiation data, tilt factor and instantaneous solar radiation the location have been used to estimate the stand-alone PV system.

A. ESTIMATION OF ENERGY REQUIREMENT

The load demand must be met by the energy output of the PV array installed. So, for a certain load, the required daily output from the PV array $(E_{pl})_m$ should be equal to

$$(E_{pl})_m = (L_{dm} + L_{nm} / \eta_b)/(\eta_w\ \eta_T\ \eta_{vr}\ \eta_c) \quad (1)$$

where L_{dm} is the average daytime load, and L_{nm} is the average night time load, η_b is the average energy efficiency of the battery, η_w is the PV array wiring efficiency, η_T is the maximum power point tracking efficiency, η_{vr} is the voltage regulator efficiency,and η_c is the cabling efficiency.

Annual daily average energy E_{pl}, *required* by the load is given by

$$E_{pl} = \frac{1}{12}\sum_{m=1}^{12}\frac{(L_{dm} + L_{nm}/\eta_b)}{(\eta_w \eta_T \eta_{vr} \eta_c)} \qquad (2)$$

B. REQUIREMENT OF PV ARRAY AREA

PV array must be capable of covering load and power conditioning unit losses on a yearly basis for calculating minimum PV array area (*A*min) which can be estimated from the equation given by

$$A_{\min} = INT\left(\frac{\sum_{1}^{12}\frac{(L_{dm} + L_{nm}/\eta_b)}{(\eta_w \eta_T \eta_{vr} \eta_c)}}{\Delta A \sum_{1}^{12} H_{Tm}(\eta_e)_m(\eta_d)}\right)\Delta A \qquad (3)$$

where ΔA is the incremental step in array area, which depends on the array configuration (e.g., it can be the area of an additional module or sub-array). The maximum PV array area (A_{max}) can be estimated as a multiple (say two times) of A_{min}. For a given value of PV array area A, between A_{min} and A_{max}, it is possible to compute the energy flow in a PV system.

C. PV SIZING

The number of PV panels required for the system is estimated from PV array area 'A' required and area of the module chosen for the design.

$$\text{Number of panels required} = \frac{\text{A}}{\text{Area of Module}} \qquad (4)$$

D. BATTERY SYSTEM SIZING

The total capacity of battery required is obtained from supply watt hour and days of autonomy i.e. number of days the battery alone should supply power to load. This is taken based on number of cloudy days.

The supply watt hour is calculated by:

Supply Wh = Load Wh x Battery Autonomy (5)

The battery watt hour is calculated from:

$$\text{Battery Wh} = \frac{\text{Supply Wh}}{(\text{DOD} \times BEF \times ACEF)} \qquad (6)$$

And, battery ampere hour is obtained from:

$$\text{Battery Ah} = \frac{\text{BatteryWh}}{\text{V}_{\text{AT}}} \qquad (7)$$

E. INVERTER SIZING

Most of the electrical appliances work on alternative current and the electricity generated from PV system is direct current in nature. Hence inverters are used in PV system to convert DC electricity to AC and make it suitable for AC applications. Inverters are placed between PV arrays and the load. Various Inverters like Sine wave inverter, PWM inverter, etc are available in market which can be selected depending upon requirement.

Inverter o/p power rating = 1.5 x Total maximum load (8)

F. SOLAR RADIATION UTILIZABILITY

The PV battery systems are based on an important design tool, namely solar radiation utilizability which is very vital in designing of PV battery systems. This solar radiation utilizability (Φ) is defined as the fraction of total radiation incident on the array that exceeds a specified intensity called critical level. The critical level $(I_c)_{mi}$ is a radiation level at which the rate of electrical energy production is just equal to the hourly load $(L_d)_{mi}$ which is given by

$$(I_c)_{mi} = \frac{(L_d)_{mi}}{A((\eta_e)_m(\eta_d)(\eta_w)(\eta_T)(\eta_{vr})(\eta_c))} \qquad (9)$$

The solar radiation utilizability $(\Phi)mi$ is defined as

$$\phi_{mi} = \frac{(I_T)_{mi} - (I_c)_{mi}}{(I_T)_{mi}} \qquad (10)$$

The average daily utilizability is defined as a fraction of the monthly total solar radiation that is above a critical radiation level.

IV. METHOD-II

In Method-II, first a load chart is developed based on the load and consumption of energy. Different appliances, their wattage, number of appliances and duration of usage are required to develop the load chart. The load chart is prepared by multiplying the number of appliances with wattage of each appliance to get maximum watts. This maximum watt is multiplied with duty factor to get average watts. This is multiplied with number of hours of usage to get watt hours. For different appliances the maximum watts, average watts and total watt hours are aggregated individually for calculation purpose.

A. PV SIZING

PV sizing means determining the number of panels required to support the load. Initially the total power that is required to be generated from panels is calculated from the formula

$$\text{Peak PV watts (Total } W_p) = \frac{\text{Load Wh}}{(\text{PSH}) \times \text{SYSEF}} \qquad (11)$$

Here load Wh is obtained from the load chart. PSH is the average daily peak sun hour in design month for selected tilt and orientation of the PV array. This is the amount of time where useful solar energy is present. This value varies from location to location.

PSH – average daily peak sun hours in design month for selected tilt and orientation of PV array.

SYSEF is the overall system efficiency i.e. product of AC system efficiency, Battery efficiency and DC system efficiency.

SYSEF = DCEF x BEF x ACEF (12)

The number of modules required is estimated from the formula:

Number of PV modules = Total Wp / Module Wp (13)

The battery and inverter sizing are similar to Method-I.

V. CASE STUDY AND CALCULATIONS

Girls Hostel Block in Gayatri Vidya Parishad College of Engineering & Technology in Visakhapatnam, Andhra Pradesh, INDIA has been considered for making the model calculations. A panel or $280W_p$ manufactured by EMMVEE with area of $1.98m^2$ is considered for the purpose of calculation.

(i) METHOD-I

The collected data and the calculations are as below:
The total hostel load is as

Appliance	Qty	Wattage (W)
Tube lights	144	40
Fans	361	60
Geysers	10	2000
Television	2	150
Grinder (large)	2	1000

Table 1: Hostel Load

The daily load data of G.V.P.C.O.E. Girls Hostel has been tabulated as shown below:

Time (Hrs)	Appliance	QtyxWatts of appliance	Hrs	Energy (Wh)
6:00 to 9:00	Lights	32 x 40	3	3840
	Fans	61 x 60	3	10980
	Geysers	10 x 2000	2	40000
	Grinders	1 x 1000	1	1000
	Total	**25940W**		**55820**
9:00 to 16:00	Fans	25 x 60	6	9000
	Lights	4 x 40	6	960
	Television	2 x 150	6	1800
	Total	**1960W**		**11760**
16:00 to 18:00	Fans	361 x 60	2	43320
	Lights	144 x 40	2	11520
	Television	2 x 150	2	600
	Total	**27720W**		**55440**
18:00 to 23:00	Fans	361 x 60	5	108300
	Lights	144 x 40	5	28800
	Television	2 x 150	5	1500
	Total	**27720W**		**138600**
23:00 to 6:00	Fans	336 x 60	8	161280
	Lights	25 x 40	8	8000
	Total	**21160W**		**169280**

Table 2: Daily Load Data of G.V.P.C.O.E. Girls Hostel

A. ESTIMATION OF ENERGY REQUIREMENT

From Equation 2,

$$(E_{pl})_m = \frac{(123020 + \frac{307880}{0.80})}{(0.97 \times 0.95 \times 0.99 \times 0.98)} = 568062\text{Wh}$$

B. REQUIREMENT OF PV ARRAY AREA

From Equation 3,

$$A_{\min} = INT\left(\frac{568062}{1.98 \times 919}\right)1.98 = 618.13\text{m}^2$$

Where, $\frac{1}{12}\sum_{1}^{12} H_{Tm}(\eta_e)_m(\eta_d) = 919$ (Refer Appendix-A)

C. PV SIZING

From Equation 4,

$$\text{Number of panels required} = \frac{618.13}{1.98} = 312$$

Therefore, 312 panels of $280W_p$ are required.

D. BATTERY SYSTEM SIZING

From Equations 5, 6 and 7,

$$\text{Supply Wh} = 430890 \times 2 = 861780$$

$$\text{Battery Wh} = \frac{861780}{(0.60 \times 0.85 \times 0.90)} = 1877516\text{Wh}$$

$$\text{Battery Ah} = \frac{1877516}{96} = 19557\text{Ah}$$

E. INVERTER SIZING

From Equation 8,

Inverter o/p power rating = 1.5 x 27720 = 41580W

F. SOLAR RADIATION UTILIZABILITY

From Equation 9,

$$(I_c)_{mi} = \frac{123020}{721 \times 0.13 \times 0.90 \times 0.97 \times 0.95 \times 0.99 \times 0.98} = 1631.16$$

$$(I_T)_{mi} = (I_b)_{mi}(R_b)_{mi} + (I_d)_{mi} R_d + (I_g)_{mi} R_r \quad (14)$$

$$(I_g)_{mi} = (I_b)_{mi} + (I_d)_{mi} \quad (15)$$

$$\frac{(I_b)_{mi} + (I_d)_{mi}}{H_{gm}} = \frac{\pi}{24}(a + bCos\omega_{mi}) \times \frac{(Cos\omega_{mi} - Cos\omega_{sm})}{(Sin\omega_{sm} - \omega_{sm}Cos\omega_{sm})} \quad (16)$$

$$(I_d)_{mi} = \frac{\pi}{24} H_{dm} \times \frac{(Cos\omega_{mi} - Cos\omega_{sm})}{(Sin\omega_{sm} - \omega_{sm} Cos\omega_{sm})} \quad (17)$$

$$a = 0.409 + 0.5016\ Sin(\omega_{sm} - \frac{\pi}{3}) \quad (18)$$

$$b = 0.6609 - 0.4767\ Sin(\omega_{sm} - \frac{\pi}{3}) \quad (19)$$

here,
$\omega_{mi} = 30^0$
$\omega_{sm} = 89.686$
$\therefore$ a = 0.6574, b = 0.4124
$\therefore$ $(I_g)_{mi}$ = 92.8547, $(I_d)_{mi}$ = 18.7707 & $(I_b)_{mi}$ = 74.6839

and hence
$(I_T)_{mi} = 7179$

From Equation 10,

$$\phi_{mi} = \frac{7179 - 1631}{7179} = 0.772$$

The solar radiation utilizability ϕ =0.772 is 77%, i.e. 77% of the energy from the PV arrays is available for charging the batteries during day time.

(i) METHOD-II

A. PV SIZING

The load chart we considered for the calculations is shown below in Table 3.

Load	Watts	Qty	Total Max .Watt	Total avg. watts	Hours	Wh
Tube lights	40	144	5760	5760	7	40320
Fans	60	361	21660	21660	15	324900
Geyser	200	10	20000	20000	3	60000
Television	150	2	300	300	16	4800
Total			**47720**	**47720**		**430020**
Duty factor = 1.0 for all appliances						

Table 3: Load Chart

$$\text{Total } W_p = \frac{\text{Load Wh}}{5.6 \times 0.072} = \frac{430020}{5.6 \times 0.72}$$
$$= 106651W$$

$$\text{Number of PV panels} = \frac{106651}{280} = 381$$

381 panels of $280W_p$ are required.

VI. COST ANALYSIS

The cost analysis for the conventional system and stand alone photovoltaic system for both the methods has been done. Conventional cost analysis is same in Method-I and Method-II, whereas the stand-alone PV system cost analysis differs. 60% of the load is considered to be supplied from state electricity board (SEB), and 40% from diesel powered generators due to the power outages at the location selected.

A. CONVENTIONAL SYSTEM

Non peak hour unit cost = Rs.5.97/-
Peak hour unit cost = Rs.6.97/-
Diesel generation cost per unit = Rs.12/-
Non peak hour units = 292.3KWh

$$\text{Non peak hour KWAh} = \frac{292.3}{0.9} = 324.77\text{ KWAh}$$

Non peak hour units from S.E.B. = 194.86KWAh
Non peak hour units from S.E.B. cost per day = Rs.1163/-
Non peak hour units from diesel generator = 129.91KWAh
Diesel generation cost per day = Rs.1558/-
Non peak hour cost per year = 2722.2 x 365
= Rs.993615/-
Peak hour units = 154KWAh
Peak hour units from S.E.B. = 92.4KWAh
Peak hour units from diesel generator = 61.6KWAh
S.E.B. units cost per day = Rs.647/-
Diesel generation cost per day = Rs.739.2/-
Peak hour cost per year = 1358 x 365
= Rs.504868/-
KVA cost per year = Rs.75000/-
Total cost of the system = Rs.1573483/-

B. STAND-ALONE PV SYSTEM OF METHOD-I

Total watts of the system = No. of panels x peak power of each panel
= 364 x 280
= 101920W
Cost per one watt = Rs.165/-
Total cost of the system = 101920 x 165
= Rs.16816800/-
The payback period can be estimated by dividing the Total cost of the stand alone PV system by Total cost per year of conventional system.

$$\therefore \frac{16816800}{1573483} = 10.68$$

In this case the payback period is 10 years, 8 months.
Annual savings after payback period is Rs.1573483/-

C. STAND-ALONE PV SYSTEM OF METHOD-II

Cost per watt = Rs.165/-
Total maximum watts = No. of panels x peak power of each panel
= 381 x 280
= 106680W
Total cost of system = 106680 x 165
= Rs.17602200/-
The payback period can be estimated by dividing the Total cost of the stand alone PV system by Total cost

per year of conventional system.

$$= \frac{17602200}{1573483} = 11.18$$

Therefore payback period is 11 years, 3 months. Annual savings after payback period is Rs.1573483/-

D. COMPARISON BETWEEN METHOD I & II
A tabular column has been constructed using all the above data for comparison between the two methods employed so as to get a clear picture of the advantageous method based on resources. This tabular column is as shown in Table 4.

Sl. No.	Description	Method I	Method II
1	Total Energy	430890Wh	430020Wh
2	No. of PV panels required	364	381
3	Total Capacity of Battery (Ah)	19557Ah	19517Ah
4	Total Inverter capacity required	41580W	48000W
5	Total Cost of System	Rs.16816800/-	Rs.17602200/-
6	Payback Period	10 years, 8 months	11 years, 3 months
7	Annual Savings after payback period	Rs.1573483/-	Rs.1573483/-

Table 4: Comparison between Method I & Method II

VII. CONCLUSIONS

The objective of this paper was to design a standalone photovoltaic system on radiation data (available for the location) to optimize the space requirement and cost of installation. A standalone photovoltaic system for meeting the electrical energy and for the energy requirement for Girls Hostel is presented as a case study for explaining the methodology adapted.

From the work presented, it can be concluded that the design based on monthly average daily energy generated (Method I) gives a requirement of 364 panels whereas the calculation based on thumb rule (Method II) gives 380 panels.

The initial investment is very high; the rate of return is less, i.e. 10 years, 8 months for Method I and 11 years, 3 months for Method II. Assuming the life span of the panel to be 20 years as claimed by the industry, the remaining 50% of the life, electrical energy generated will be at a very small cost because of batteries and the maintenance.

Keeping in view, the present power shortages, and also frequent interruption of power supply particularly for institutions in rural areas (like ours), it is economical to utilize solar energy for meeting electrical energy requirement. This will improve reliability of power supply at a reasonably low cost which benefits the organization.

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APPENDIX-A

	Hbm (KWh/ m^2)	Hdm	Hgm	Rb	Htm= HbmRbm+HdmRd + HgmRr	A	H_{tm}*A*η_d
Jan	7000	1416	8416	1.206	9863.91	0.132	1171.83
Feb	7272	1490	8762	1.137	9764.04	0.131	1151.18
Mar	6589	1863	8452	1.064	8869.05	0.132	1053.64
Apr	5870	2167	8037	0.998	8011.35	0.132	951.75
May	5117	2640	7757	0.952	7484.79	0.132	889.19
Jun	2811	2965	5776	0.932	5541.07	0.136	678.23
Jul	2027	3100	5127	0.94	4955.28	0.138	615.45
Aug	2487	3046	5533	0.978	5431.41	0.137	669.69
Sep	3559	2552	6111	1.037	6210.4	0.136	760.15
Oct	5220	1829	7049	1.112	7623.16	0.131	898.77
Nov	6149	1555	7704	1.187	8853.06	0.132	1051.74
Dec	6650	1397	8047	1.228	9567.81	0.132	1136.66
				Sum		**Sum**	
				92175.33		**11028.28**	
				Average		**Average**	
				7681.28		**919.02**	