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Designing of an Off Grid Photovoltaic System for a Residential Building

Md. Raquibul Hasan[1], Md. Asaduzzaman Shobug[2]

[1]Assistant Professor, Department of Civil Engineering, Pabna University of Science & Technology, Bangladesh
[2]Assistant Professor, Department of Electrical & Electronic Engineering, Pabna University of Science & Technology, Bangladesh
E-mail: raquibulh@yahoo.com

Abstract

Photovoltaic power system, can be used as electrical power source for home to meet its daily energy requirement, through direct conversion of solar irradiance into electricity. A detailed design of a standalone photovoltaic power system for uninterrupted power supply of a residential building in a typical urban area is presented. Designing, selecting and determining specifications of different components are used in the system conforming the load estimation. A procedure to specify the components of standalone PV system and a detailed cost analysis has been carried out in this paper. The analysis outlines that though the initial investment is high, but within few years this amount returns back with a gain in substantial dividend during the system life span.

Keywords: photovoltaic array, charge controller, battery, module orientation, payback period.

1. Introduction

Energy plays a fundamental role in our daily activities. The degree of development and civilization of a country is determined by the amount of energy utilized by its human beings. Energy demand is increasing day by day due to increase in population, urbanization and industrialization. The world's fossil fuel supply viz. coal, petroleum and natural gas, main source of energy until now, will thus be exhausted in a few hundred years [1]. On one hand, the rate of energy consumption increasing, on the other hand, fuel supply depleting - it will lead to energy crisis one day. It will also results in inflation, poverty and global warming [2].

Different places on the globe experience different climatic conditions. Total solar irradiance that reaches the surface of earth varies with time of day, season, location and weather conditions. Therefore, design of a standalone solar system cannot have only one standard. Location is a major aspect that will affect photovoltaic power system design and it varies from place to place [3]. Bangladesh is blessed with enough sun shine which can meet our energy demand without any compromise and it is also pollution free. Standalone PV system is a popular concept in rural areas of Bangladesh where national electricity grid connection facility is not available. But in urban areas where grid connection system is easily available, it is not a common practice to use solar power. There is a general impression that grid energy from conventional sources is much less costly compared to solar and other alternate energy sources.

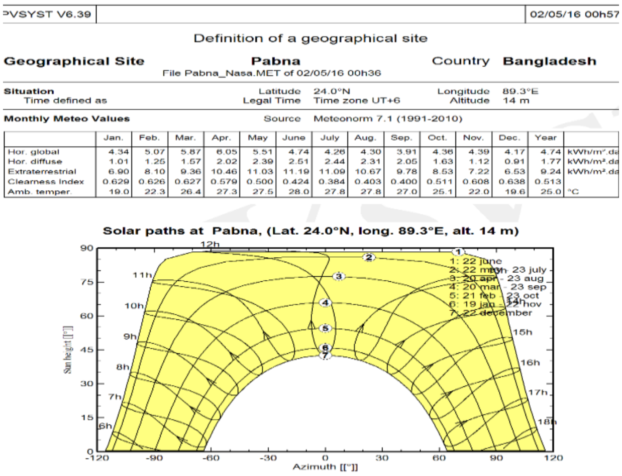
One of the objective of this paper is to estimate the potential of solar photovoltaic power system in urban areas taking for example, Sirajgonj District, Bangladesh. For this purpose, a typical residential building in Sirajgonj is taken up for designing and developing a system based on its daily load requirement. Equipment specifications are provided based on availability of the best components in market. In addition to the design considerations, we have done a detailed cost analysis of the system in this paper. As expected initial cost of solar power plant installation has been found to be very high and so, the cost of solar energy consumption unit is much more than conventional energy unit. And this is quite discouraging for general public to go for solar power plant. However, more interestingly, our estimation of the long term cost and area requirement of a standalone SPV power plant installation establishes our other objective that, contrary to general perception, it is a very much economical and cost effective system. Before presenting the results and analysis of the case under study, i.e. of a typical residential building in Sirajgonj, we introduce different components of a standalone PV system and their functions in briefing the following section. In Section 3 the steps that are followed for designing the PV system and the method for determining the design parameters are described. Finally, in Section 5 we present the concluding remarks.

2. Methodology for PV system design

PV system design is a process of determining capacity (in terms of power, voltage and current) of each component of a stand-alone photovoltaic power system with the view to meeting the load requirement of the residence for which the design is made [6]. The designing is done following the steps: Step 1: Site inspection and radiation analysis, Step 2: Calculation of building load requirement, Step 3: Solar PV array specification and design layout, Step 4: Determine capacity of Battery, Step 5: Determine capacity of Charge Controller, Step 6: Determine capacity of Inverter, Step 7: Combiner Box specification, Step 8: DC Cable Sizing, Step 9: PV Module orientation and land requirement, Step 10: Cost Analysis.

2.1 Site inspection and radiation analysis

We have selected Sirajgonj, a district of Bangladesh as our inspection site. The solar radiation of this region is shown in Fig. 1.


PVSYST V6.39 02/05/16 00h57

Definition of a geographical site

Geographical Site Pabna Country Bangladesh
File Pabna_Nasa.MET of 02/05/16 00h36

Situation Latitude 24.0°N Longitude 89.3°E
Time defined as Legal Time Time zone UT+6 Altitude 14 m

Monthly Meteo Values Source Meteonorm 7.1 (1991-2010)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Hor. global	4.34	5.07	5.87	6.05	5.51	4.74	4.26	4.30	3.91	4.36	4.39	4.17	4.74	kWh/m².da
Hor. diffuse	1.01	1.25	1.57	2.02	2.39	2.51	2.44	2.31	2.05	1.63	1.12	0.91	1.77	kWh/m².da
Extraterrestrial	6.90	8.10	9.36	10.46	11.03	11.19	11.09	10.67	9.78	8.53	7.22	6.53	9.24	kWh/m².da
Clearness Index	0.629	0.626	0.627	0.579	0.500	0.424	0.384	0.403	0.400	0.511	0.608	0.638	0.513	
Amb. temper.	19.0	22.3	26.4	27.3	27.5	28.0	27.8	27.8	27.0	25.1	22.0	19.6	25.0	°C

Fig. 1: Solar radiation data in Sirajgonj

2.2 Daily load usage in home state

In a home state there different types of home appliances are being used. For designing a PV system the first and foremost task is to determine the approximate load that will be connected to the system. Each and every part of the PV system will be designed according to that load requirement. Designing a PV system will need loads in terms of ampere hour (AH) and watt hour (WH). The total wattage and peak current is also necessary for further calculation.

2.2.1. Hourly load characteristics

This is an approximation of the daily usages of loads connected to the PV system. This approximation is made as a 24 hours basis. Fig.2 is Daily load usages that shows which load is used for what span of time in summer and Fig. 3 shows which load is used for the span of time in winter Usages.

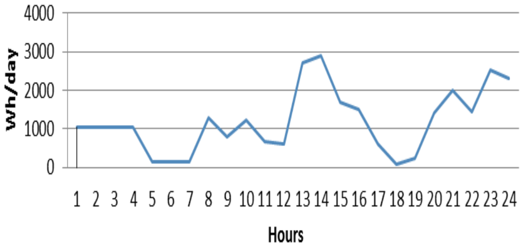


Fig. 2. Load profile for a typical house (Summer)

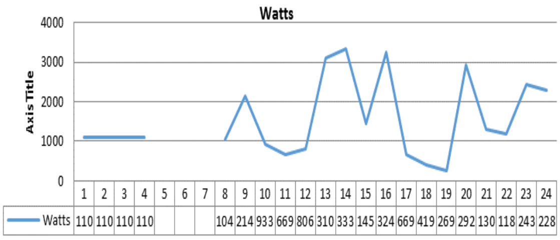


Fig. 3. Load profile for a typical house (Winter)

2.3. Design of PV array

The following calculation is done for the requirement of PV array,

$E_{out} = P_{out} \times N_h = 133\ W \times 5.5h = 732\ Wh$

The total number of modules is given by: $N_{mod} = (E_{required} \times S.f)/ E_{out} = (31914 \times 1.15)/732 = 50$

Since the maximum power point voltage of the PV module is 36.0 V, we can connect two in series to get a total voltage of 47.8V and use the DC-DC converter to adjust the output voltage to 48 V. Finally the array will be 2*22 modules.

2.4. Battery bank sizing

Battery bank required for the PV system is given in Table 1.

Table 1. Parameters of the chosen battery

Number of Days of Autonomy (D_{aut} **) =** 3 Days,		
Selected Battery: N200**, Replacement Warranty=** 3years		
Capacity of Selected Batteries Amp-hrs, C_b = 200 Ah,		
Rated Voltage of the selected Battery, V_b = 12 V,		
Maximum Allowable Depth of Discharge, D_{disch} = 80%,		
Daily Average Energy Demand, E_d = 31914 WH/day,		
System Nominal Voltage, V_{dc} = 12 V,		
Cost of Battery, B_{cost} = BDT 16,928		
Parameter Being Determined	**Working Formula**	**Computed Parameter Value**
Estimated Energy Storage ,(E_{est})	$E_{est}= E_d x D_{aut}$	95.742 kWh
Safe Energy Storage ,(E_{safe})	$E_{safe}= E_{est}/D_{disch}$	119.677 kWh
Total Capacity of Battery Bank ,(C_{tb})	$C_{tb}= E_{safe}/V_b$	9973.125 Ah
Total Number of Batteries in Bank ,(N_{tb})	$N_{tb}= C_{tb}/C_b$	50
Number of Batteries in Series ,(N_{sb})	$N_{sb}= V_{dc}/V_b$	1
Number of Batteries in Parallel ,(N_{pb})	$N_{pb}= N_{tb}/N_{sb}$	50
Cost of Battery Bank in Sirajgonj ,(B_{bcost})	$B_{bcost}= N_{tb} x B_{cost}$	BDT 8,46,400

As we know that the nominal voltage of our system is 12 V and the batteries we are using will be connected in parallel. 50 nos 200 Ah 12 V_{dc} batteries in parallel will make a 10,000 Ah 12 V_{dc} battery bank, which is enough to support our system.

2.5. Charge controller sizing

Sizing a suitable charge controller starts by computing the required total current that the controller should withstand. Table 2 presents the summary of the Charge Controller sizing procedure and its cost estimation.

Table 2. Summary of Charge Controller Sizing and Cost Estimate Required Information

Charge Controller: SPC048 MPPT 150, Xiamen Kehua Hengsheng Co., Ltd		
V_{cc}= 348 V, I_{cc}= 300 A (dc), C_{cost} = BDT 90,000.00		
Safety Factor (Fsafe) = 1.25		
Short Circuit Current of the selected module, I_{sc} = 5.48 A		
Number of modules in Parallel, N_{pm} = 50		
Parameter Being Determined	**Working Formula**	**Computed Parameter Value**
Required Charge Controller Current (I_{rcc})	$I_{rcc}= I_{sc}^M x N_{pm} x F_{safe}$	301.4 A
Number of Charge Controllers (N_{cc})	$N_{cc}= I_{rcc}/I_{cc}$	1
Cost of Charge Controllers in Sirajgonj (C_{tcost})	$C_{tcost}= N_{cc} x C_{cost}$	BDT 90,000.00

2.6. Inverter specification

Inverter should be specified according to the load estimation of the building. Recommended MPPT voltage range is 450-550 VDC [13]. We have taken PV array MPPT voltage of about 500VDC.

Table 3. Inverter summary

Parameters	**Calculated Parameter Value**	
Total Continuous output power (TP)	11.973 kW	As per Table 3
Efficiency (η_{inv})	90%	As per inverter data sheet [13]
Input power to the inverter (TP_1)	13.3 kW	TP_1= TP/ η_{inv}
Input DC voltage (V_{dc})	348 VDC	As per inverter data sheet [13]
Input DC current to inverter (I_{dc})	38 ADC	$I_{dc}=TP_1/V_{dc}$
Total Inverter Power (P_{inv1})	23 kW	P_{inv1}=TP+(3.5 * inductive power)
Power factor (PF)	0.8	As per inverter data sheet [13]
KVA rating (P_{KVA})	29 KVA	$P_{KVA}= P_{inv1}/PF$
Energy coming from inverter (E_{daily})	31.9 kWh (in Winter)	From Table 3
Energy input to inverter (E_{inv})	35.4 kWh	$E_{inv}=E_{daily}/ \eta_{inv}$
Output AC voltage	400 VDC	As per inverter data sheet [13]
Number of phase	Three phase	As per inverter data sheet [13]
Types	Solar PCU or Hybrid type	As per inverter data sheet [13]
MPPT voltage from PV (CC_{volt})	500 VDC	As per inverter data sheet [13]

2.7. Combiner box sizing

For our sample off-grid system with a normal inverter, a two array strings the combiner box must be rated for 600-DC volts (i.e. the standard size), accommodate the positive and negative conductor for at least two strings, and have a minimum 30-amp rating.

Table 4. Combiner Box Summery

Selected Combiner Box : MNPV12 (HV)			
Max VDC		600	As per combiner box data sheet [13]
Max input Circuit		10	
PV Source Circuits	Max OCPD Rating Amps	20	
	OCPD	Fuse	
	Wire Range AWG	14-6	
PV output Circuits	Max output Circuit	2	
	Max Cont. Current Amps	200	
	Wire range AWG	14-2/0	
Cost of Combiner Box in Sirajgonj	BDT 18,600		

2.8. System wiring sizing

The design of a PV power system is incomplete until the correct size and type of cable is selected for wiring the components together. Table 5 presents the summary of the procedure for selecting the correct cable sizes for these two important links.

Table 5. Summary of Procedure for Selecting Cable Sizes

PV System Cable Link	Current Rating of Cable (Icab)	Selected Cable Size and Type
PV Array to Battery Bank through Charge Controller	$I_{cab}= I_{rcc}= I_{sc}{}^{M}xN_{pm}xF_{safe} = 301.4$ A	3x35 mm^2 Insulated Flexible Copper Cable
Inverter to DB of Residence	Current Produced by Inverter Output $I_{oi}= P_i/(V_{oi}xpf) = 23000/(240x0.8) = 120$ A	3x4 mm^2 Insulated Flexible Copper Cable

I_{cab} = Cable Current between Array and Battery Bank;
I_{oi} = Current at Inverter Output;
P_i= Power rating of Inverter;
V_{oi}= Inverter Output Voltage;
pf= Power Factor

2.9. PV array orientation and land requirement

2.9.1. Array configuration

As Sirajgonj city is situated at 24°N / 89° 24' E so we will be setting up the panels at 30° angle so that our fixed arrays can give us maximum possible output.

2.9.2. Approximation of the required space

The PV module SF 190 polycrystalline has a dimension of 1580 x 808mm which is 5.18 x 2.65 ft [9]. On an average in Sirajgonj City the Sun ray falls in 60° angle, and we are setting up our PV Modules at 30° angle with the ground, where the northern part of the module will be at height. After calculation it is found that, the total space required for the Panel in Y-axis is (2.3 + .765) ft = 3.1 ft and as the Length (X-axis) of the Panel is 5.18 ft, it will need 5.18 ft x 3.1 ft Space for each panel to set up, which will be 16.058. So the total space required for 50 modules to setup is around 802.90 sq. ft. In Roof spacing survey, we have seen that in the building we will easily have 840 sq. ft of space at the roof for PV establishment.

2.10. Summary of the PV system components and cost estimation

Solar PV modules and the associated components are costly. So the generated electricity cost will be high. We have done a long term cost analysis [20] to see whether it would be cost effective in the long run, even if initial investment is high. The cost analysis is shown in table 6.

Table 6. Initial investment for the PV system

No.	Name of the Component	Qty	Price per quantity (Tk.)	Total Price (Tk.)
1	Solar Panel (Rohim Afrooz), Model No: 190 Wp	50	10,450/-	5,22,500/-
2	Navana Battery N200 (200AH, 12V)	50	16,928/-	8,46,400/-
3	Inverter, Brand: Kehua, Model: SPO 1140, (40KVA, 220 VDC)	1	4,50,400/-	4,50,400/-
4	Charge Controller, Brand: Kehua, Model: SPC048 MPPT 150	1	1,25,400/-	1,25,400/-
5	Combiner Box, Brand: Midnite Solar, Model: MNPV12 (HV)	1	18,600/-	18,600/-
			Total cost of above materials	**19,63,300/-**
6	Cost of DC Disconnect, DC Breaker, AC Disconnect, AC Breaker, cable, design, Labor, Metering etc. are lamp together as 20% of equipment cost and add on			**2,84,180/-**
			Total Initial investment	**22,47,480/-**

2.10.1. Payback period and financial feasibility

Following is the step by step procedure to find the payback period and financial feasibility of the system.
Step 1: Determination no. of units generated by PV system during day, Step 2: Find out rate of electricity from conventional grid connection, Step 3: Determine present value of future investment for battery bank, Step 4: Determine the savings per year**.** The detailed calculation is shown in Figure 3.

Here, we assume that the rate of electricity will grow at the rate of 6.0% per annum till the life of the system which is 25 years

Inflation rate 5% .9813=(1.05/1.07)
Discount rate 7%

Year	Daily Average sun hours (Hours)	Wattage of solar array (KW)	System is 75% efficient (KWh)	Module efficiency (%)	Units generated Number (KWh)	Yearly generated Number (KWh)	Rate of electricty (Tk./unit)	Yearly savings (Tk.)	Maintenance cost @ 10% of the yearly savings (Tk.)	Net yearly savings (Tk.)	Cumulative savings (Tk.)	Let, inflation rate is 5% and discount rate is 7%	The present value savings	Real saving in nth year	Bank interest rate 8.50% (compound) on fixed deposit, total interest on 5 years
1	5.5	13	54	95	51	18594	5.63	104,687	10,469	94,218	94,218	0.98	94218	94218.17	131250
2	5.5	13	54	95	51	18594	5.97	110,968	11,097	99,871	194,089	0.96	97874	192092.01	142734.38
3	5.5	13	54	95	51	18594	6.33	117,626	11,763	105,864	299,953	0.94	101629	293721.01	155223.63
4	5.5	13	54	95	51	18594	6.71	124,684	12,468	112,215	412,168	0.93	105482	399203.44	168805.70
5	5.5	13	54	95	51	18594	7.11	132,165	13,216	118,948	531,117	0.91	110622	509825.33	183576.20
6	5.5	13	54	94.6	51	18516	7.53	139,505	13,950	125,554	656,671	0.89	114254	624079.73	132249.5
7	5.5	13	54	94.2	51	18438	7.99	147,250	14,725	132,525	789,196	0.88	117947	742026.81	143821.34
8	5.5	13	54	93.8	50	18360	8.47	155,422	15,542	139,880	929,075	0.86	123094	865121.02	156405.71
9	5.5	13	54	93.4	50	18281	8.97	164,045	16,404	147,640	1,076,716	0.84	126971	992091.67	170091.21
10	5.5	13	54	93	50	18203	9.51	173,143	17,314	155,828	1,232,544	0.83	130896	1122987.58	184974.19
11	5.5	13	54	92.6	50	18125	10.08	182,742	18,274	164,468	1,397,012	0.81	136508	1259495.80	138842
12	5.5	13	54	92.2	49	18046	10.69	192,870	19,287	173,583	1,570,595	0.8	140602	1400097.81	150990.32
13	5.5	13	54	91.8	49	17968	11.33	203,555	20,355	183,199	1,753,794	0.78	146560	1546657.36	164201.97
14	5.5	13	54	91.4	49	17890	12.01	214,828	21,483	193,345	1,947,139	0.77	150809	1697466.66	178569.65
15	5.5	13	54	91	49	17812	12.73	226,721	22,672	204,049	2,151,188	0.75	157118	1854584.43	194194.49
16	5.5	13	54	90.6	49	17733	13.49	239,268	23,927	215,341	2,366,530	0.74	161506	2016090.38	147799
17	5.5	13	54	90.2	48	17655	14.30	252,504	25,250	227,254	2,593,784	0.73	168168	2184258.31	160731.85
18	5.5	13	54	89.8	48	17577	15.16	266,468	26,647	239,821	2,833,605	0.71	175069	2359327.60	174795.88
19	5.5	13	54	89.4	48	17498	16.07	281,198	28,120	253,078	3,086,682	0.7	179685	2539012.89	190090.52
20	5.5	13	54	89	48	17420	17.03	296,736	29,674	267,062	3,353,745	0.69	186944	2725956.47	206723.44
21	5.5	13	54	88.6	48	17342	18.06	313,126	31,313	281,814	3,635,558	0.67	194451	2920407.92	157492
22	5.5	13	54	88.2	47	17263	19.14	330,415	33,042	297,374	3,932,932	0.66	199241	3119648.43	171272.78
23	5.5	13	54	87.8	47	17185	20.29	348,652	34,865	313,787	4,246,719	0.65	207099	3326747.69	186259.15
24	5.5	13	54	87.4	47	17107	21.51	367,887	36,789	331,099	4,577,818	0.64	215214	3541961.81	202556.83
25	5.5	13	54	87	47	17029	22.80	388,176	38,818	349,358	4,927,176	0.62	223589	3765551.14	220280.55
													3765551		

Total Initial investment = 2,247,480

Plus Present Cost of Future Investment for Battery = 3,807,222

NPV of savings using PV = 2,278,133

Present Battery Cost = 846,400

Replacement Cost of Battery	Present Value	Bank Interest after every 5 Years (on fixed deposite)	Savings
Replacement cost of battery after 5 years	770,167	781590	11,423
Replacement cost of battery after 10 years	700,780	787542	86,762
Replacement cost of battery after 15 years	637,662	826798	189,136
Replacement cost of battery after 20 years	580,230	880141	299,911
	2,688,839		

After paying the replacement cost of Battery from interest of FD, total savings after 25 years 1,237,776

Fig 4. Cost analysis of standalone PV array

3. Conclusion

Solar Photovoltaic standalone system is a clean source of energy. Such systems are generally envisaged for use in rural remote areas where grid system is not available. The first and foremost part of designing a PV system is to know the electricity need. In this paper we present a complete design of a solar PV system step by step and its life cycle cost analysis. So in the first step of our study we have gone through the load calculations, where we have found that we have to produce around 31.5 kWh of energy. In this study, cost estimation of the whole system including cabling, design, labor, control devices and maintenance has also been provided. The same design procedure can be applied to other locations. The initial installation cost of the standalone PV system is high, about BDT 23 lakh. However, it is beneficial and suitable for long term investment as the payback period is less than 15 years while the system life expectancy period is about 25 years. If the initial prices of the PV systems are decreased, which is expected with the advent of technological uplift and the increase in production volume, then the payback period will further be reduced. So standalone PV energy source is a viable energy solution even for urban areas. It is a concept contrary to the general perception. With the help of this system we can fulfil our daily energy requirement at any scale. In urban areas grid connection system is readily available, but there also people can invest money initially for fulfillment of their daily energy need with standalone PV system and enjoy it free for long years without power interruption. It is also profitable compare to saving this investment amount in a bank and pay for the ever increasing cost of energy needs and inflation. In this study, cost estimation of the whole system including cabling, design, labor, control devices and maintenance has also been provided. The same design procedure can be applied to other locations. As a final remark, respective governments should get involved in providing financial support for procurement and installation of PV system, make it a popular choice and propagate this energy solution.

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