Design and Development of a Cost Effective Standalone PV System for a Residential Building in Pabna, Bangladesh

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Abstract- The aim of this paper is to present a detailed design of standalone photovoltaic power system for uninterrupted power supply of a residential building in a typical urban area of Pabna, Bangladesh. Photovoltaic power system involves designing, selecting and determining the specifications of the different components employed in the system. In this study, direct current (DC) appliances and alternative current (AC) appliances were considered. The results show that the average daily load requirement of the selected residential unit is 31.5 kWh/day. For functioning this load in off-grid necessary components are chosen and also a system design has been proposed. Installation and maintenance cost analysis of this PV system also been estimated. Therefore, for sustainability, reliability and accessibility of power, the use of stand-alone solar photovoltaic technology is recommended.

Keywords: Battery, Charge controller, Inverter, Photovoltaic array, Solar PV panel, Standalone systems, System design.

1. INTRODUCTION

Over the last 2 decades the economies of Asia started growing at a faster rate. In today's world more than 80% of the energy used comes from fossil fuel generating 33 billion metric tons of carbon dioxide every year [1] – the main component of global warming. Time has come for us to think and rethink about our ways of life, our dependence on energy and at the same time to think of ways and means to reduce greenhouse gas emission [2]. It is becoming a vital question of survival for our future generation.

Bangladesh is heavily dependent on fossil fuel for its power generation. As per Bangladesh Power Development Board [3] data, out of total installed capacity of about 12000 MW, 64% of the energy comes from natural gas, 2.0% comes from coal, 27% comes from diesel/furnace oil, 2% comes from hydro and remaining approximately 5% is imported. With dwindling supply of gas, the power sector of Bangladesh is facing a serious threat and the diversification of primary source has become a necessity. Diversification of primary energy resources has its own fall out effects – coal is highly polluting, diesel and furnace oil is quite expensive and hydro resources are very limited. Considering the cost and inherent advantage of non-requirement of fuel, solar PV applications have great potential for both on grid and off grid applications, particularly the off grid rural areas. In case of solar energy fuel is the sun light which makes solar energy option a very attractive one in rural Bangladesh. Solar Photo Voltaic (PV) panels was introduced in Bangladesh in late eighties/early nineties as a possible solution for household lighting. In early years of 1990, the cost of a solar panel was around USD 15/Watt peak. Since then, the price of the panels had been falling on a regular basis and the present day price is USD 0.6/watt peak [4]. 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.

In this paper, the design of the various components of a photovoltaic power system for the purpose of residential use is presented. Thereafter, a residence model with average energy requirements in Pabna (Bangladesh) will be considered as a practical case study for which a detailed a step-by-step design procedure will be provided including cost estimates.

2. STANDALONE PHOTOVOLTAIC SYSTEM

Photovoltaic power generation is the process of generating electricity directly from sunlight. Standalone photovoltaic system is a collection of interconnected electrical components, using which we can generate electricity from sun light and satisfy our daily energy requirement without worrying about any interval when the sunlight may not be available [5]. This type of system is useful only when there is requirement of load to run in night time or in other time when sunlight is unavailable for some period.

3. METHODOLOGY FOR PV SYSTEM DESIGN

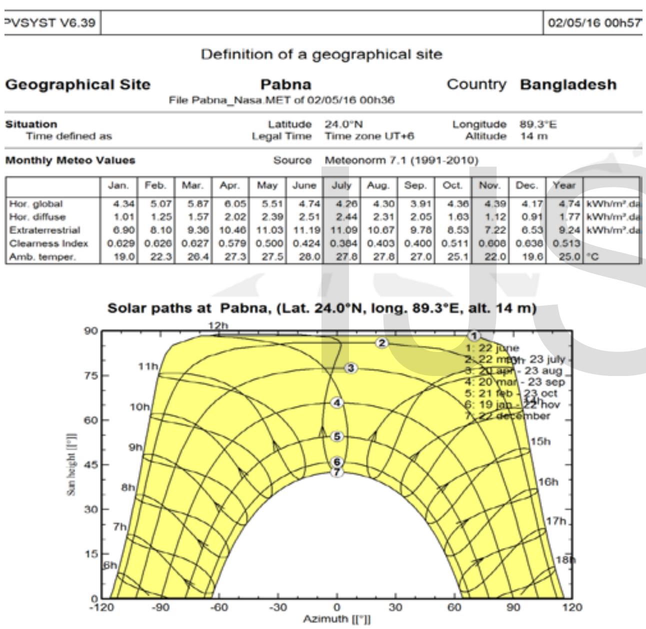
PV system design is a process of determining capacity (in terms of power, voltage and current) of each component of a stand-alone photovoltaic power system with the view to meeting the load requirement of the residence for which the design is made [6].

The designing is done following the steps given below:
Step 1: Site inspection and radiation analysis.
Step 2: Calculation of building load requirement.

Step 3: Choice of system voltage and components.
Step 4: Solar PV array specification and design layout.
Step 5: Determine capacity of Battery.
Step 6: Determine capacity of Charge Controller.
Step 7: Determine capacity of Inverter.
Step 8: Combiner Box specification.
Step 9: DC Cable Sizing.
Step 10: PV Module orientation and land requirement.
Step 11: Cost Analysis.

3.1 SITE INSPECTION AND RADIATION ANALYSIS:

Pabna is situated 24.0 degrees north and 89.3 degrees east, which is an ideal location for solar energy utilization. Another thing is that the sunlight falls directly in summer and transversely in winter. Here daily average solar radiation varies between 4 to 6.5 kWh per square meter. Maximum amount of radiation is available on the month of March-April and minimum on December-January.



	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. Monthly average radiation data of the site.

3.2.1 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 [7]. 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. As working with DC load is complicated, though that is economically beneficial, we will not be using DC loads in our system right at this moment. We will be working on DC loads later.

3.2.2 LOAD CALCULATIONS:

The total load power used in a home state is listed in the following chart (Table-1) (summer & winter time):

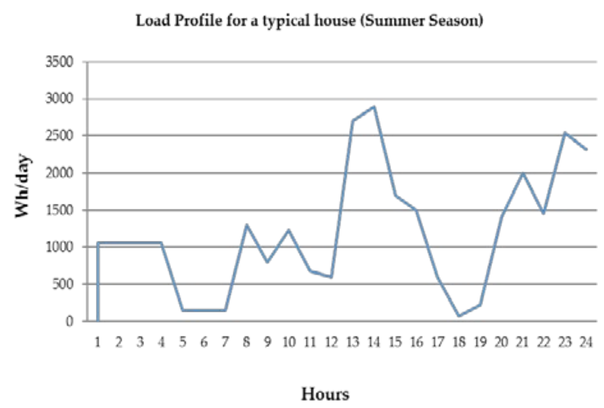


Fig. 2. Investigate load profile for a typical house.

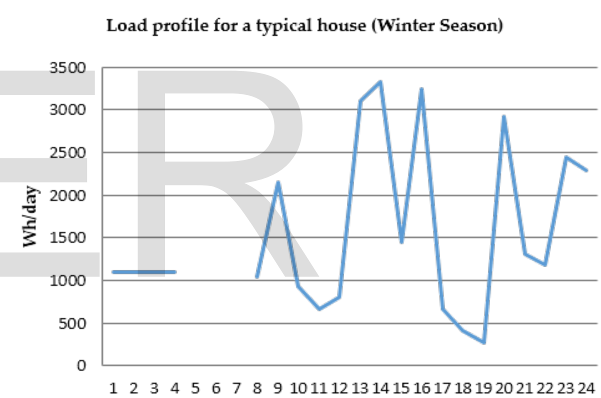


Fig. 3. Investigate load profile for a typical house.

3.2 DESIGN OF PV ARRAY

In order to satisfy load requirements, all the components of the system (PV array can be excluded) should be rated to the maximum demand [8]. The load profile for a typical house was investigated and it's shown in Figure2. There are Four peaks during Summer Season at 2700 W, 2890 W, 2533 W & 2314 W, this is due to the operation of the clothes dryer and air condition units respectively, which are bulky loads.

There are Four peaks during Winter Season at 3106 W, 3330 W, 3240 W & 2929 W, this is due to the operation of the clothes dryer and electric space heater units respectively, which are bulky loads. Since the refrigerator is connected and disconnected automatically, it was taken into account that the refrigerator is operating all the day when calculating the maximum demand.

To calculate the required number of modules, we can project the available solar radiation values from the Historical meteorological data to the irradiance-output characteristics of the selected module and calculate the output power for each module [8]. This step yields an average solar radiation of 530W/m2, and output power of 70% of the maximum output power- according the available data sheet from the manufacture the maximum output power of the module is 190 W. Thus,
Eout = Pout × Nh = 133 W × 5.5h = 732 Wh
Then the total number of modules is given by:
Nmod = (Erequired × S.f)/ Eout
Where S.f is a safety factor accounts for system losses (such as losses in the DC-DC converter and DC-AC Inverter) usually this factor is selected to be 1.1-1.2, it will be selected here as 1.15.
Nmod = (Erequired × S.f)/ Eout = (31914 × 1.15)/732 = 50
This step gives the number of required modules as 50 PV modules. PV array will consist of 50 modules, to determine how many modules will be selected in series we have to select the voltage of the DC bus. Many researchers have investigated the DC bus voltage selection; based on these studies the DC voltage will be selected as 48 V to reduce the system losses. 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.

TABLE 1
PARAMETERS OF THE CHOSEN PV MODULE [9]

Rohim Afrooz Polycrystalline Module	
Wattages available: 155, 160, 165, 170, 175, 180, 185, 190, 195	
Average cell efficiency: 15.7%	
Electrical characteristics chart:	
Maximum Power (P_{max})	190W
Open Circuit Voltage(V_{oc})	45.0V
Short Circuit Current (I_{sc})	5.48A
Maximum Power Voltage(V_{mp})	36.0V
Maximum Power Current (I_{mp})	5.28A
Module Efficiency (%)	14.90%
Cell Efficiency (%)	17.00%
Tolerance	+/-3%
Temperature Coefficients of (P/V/I)	-0.48%/K/-0.34%/K/+0.05/%K
Maximum System Voltage (IEC/UL)	1000V/600V
Electrical characteristics at Standard Test Conditions (STC), defined as Irradiance of 1000 W/m^2, Spectrum AM	

3.3 BATTERY BANK SIZING:

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 Vdc batteries in parallel will make a 10,000 Ah 12 Vdc battery bank, which is enough to support our system.

TABLE 2
SIZING THE BATTERY BANK AND COST ESTIMATION [11]

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_dxD_{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 Pabna ,(B_{bcost})	B_{bcost}= N_{tb}xB_{cost}	BDT 8,46,400

3.4 CHARGE CONTROLLER SIZING

Sizing a suitable charge controller starts by computing the required total current that the controller should withstand. From the results of the required current, the total number of charge controllers can then be computed and once the cost of a single charge controller is known, the total cost of the controllers can then be determined.

TABLE-3
CHARGE CONTROLLER SIZING AND COST ESTIMATION [12]

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}^MxN_{pm}xF_{safe}	301.4 A
Number of Charge Controllers (N_{cc})	N_{cc}= I_{rcc}/I_{cc}	1
Cost of Charge Controllers in Pabna (C_{tcost})	C_{tcost}= N_{cc}xC_{cost}	BDT 90,000.00

3.5 INVERTER SPECIFICATION

Inverter should be specified according to the load estimation of the building. The summery of the inverter sizing is given in Table 4. In this system, specifications of a typical inverter, for example, FR-UK33-SPO-A, Xiamen Kehua Hengsheng Co., Ltd (30KVA, 348 VDC) inverter is used. As per the inverter data sheet [13] it has overload handling capacity of 125% of rated load last for 10 minutes, 150% of rated load last for 1 second which is sufficient to run high inductive load of the building. Efficiency of the inverter is 95% at peak condition. System Voltage is 348 VDC.

Recommended MPPT voltage range is 450-550 VDC. According to inverter datasheet maximum voltage handling capacity of MPPT is 750 VDC and maximum current handling capacity is 120A [12]. We have taken PV array MPPT voltage of about 500VDC.

TABLE 4
INVERTER SUMMARY [11]

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]

3.6 COMBINER BOX SIZING:

For our sample off-grid system with a normal inverter, a two array strings the combiner box we purchase 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 5
COMBINER BOX SIZING AND COST ESTIMATION [12]

Selected Combiner Box : MNPV12 (HV)			
Max VDC		600	As per combiner box data sheet
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 Pabna	BDT 18,600		

3.7 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. The following cables links in the PV system must be appropriately selected:

i. The dc cable from the PV array to the battery bank through the charge controller.
ii. The ac cable from the inverter to the distribution board (DB) of the residence.

Table 6 presents the summary of the procedure for selecting the correct cable sizes for these two important links.

TABLE 6
SUMMARY OF PROCEDURE FOR SELECTING CABLE SIZES [13]

PV System Cable Link	Current Rating of Cable (I_{cab})	Selected Cable Size and Type
PV Array to Battery Bank through Charge Controller	$I_{cab}= I_{rcc}= I_{sc}^{M} \times N_{pm} \times F_{safe}$ = 301.4 A	3x35 mm² Insulated Flexible Copper Cable
Inverter to DB of Residence	Current Produced by Inverter Output $I_{oi}= P_i/(V_{oi} x pf)$ = 23000/(240x0.8) = 120 A	3x4 mm² Insulated Flexible Copper Cable

Icab = Cable Current between Array and Battery Bank;
Ioi = Current at Inverter Output;
Pi= Power rating of Inverter;
Voi= Inverter Output Voltage;
pf= Power Factor

3.8 PV ARRAY ORIENTATION AND LAND REQUIREMENT

3.8.1 ARRAY CONFIGURATIONS

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

3.8.2 ROOF SPACING ANALYSIS

Considering all the facts mentioned before we assumed the usable area for solar establishment.

TABLE 7
ROOF SPACING ANALYSIS DATA

Sl. No	Total Space			Usable for Solar Establishment		
	X	Y	Sq Ft	X	Y	Sq Ft.
1	56.17	28.25	1586.8025	40	21	840

3.8.3 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 Pabna City the Sun ray falls in 60o angle, and we are setting up our PV Modules at 30o angle with the ground, where the northern part of the module will be at height.

Here, in the Fig. 4 the 'E' arm is PV module and 'A' arm is considered to be the Sun ray. From here we get
E = 2.65 ft
D = 2.65Sin30 = 1.325
D = ASin60
A = 1.325/Sin60 = 1.53
B = ACos60 = 1.53 x Cos60 = .765 ft
C = ECos30 = 2.65 x Cos30 = 2.3ft
So 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 [3.8.2] we have seen that in the building we will easily have 840 sq. ft of space at the roof for PV establishment.

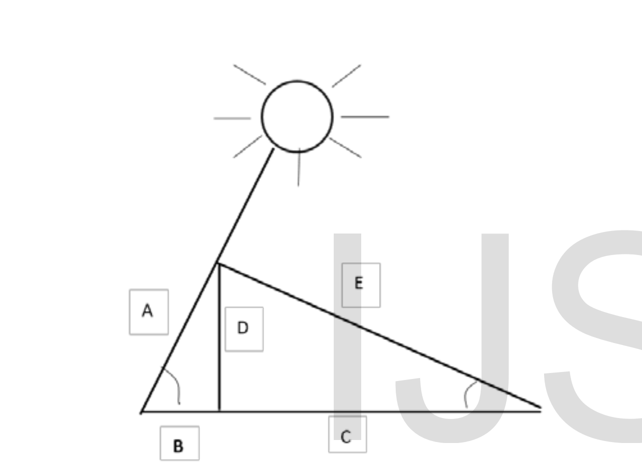


Fig. 4. Space determination.

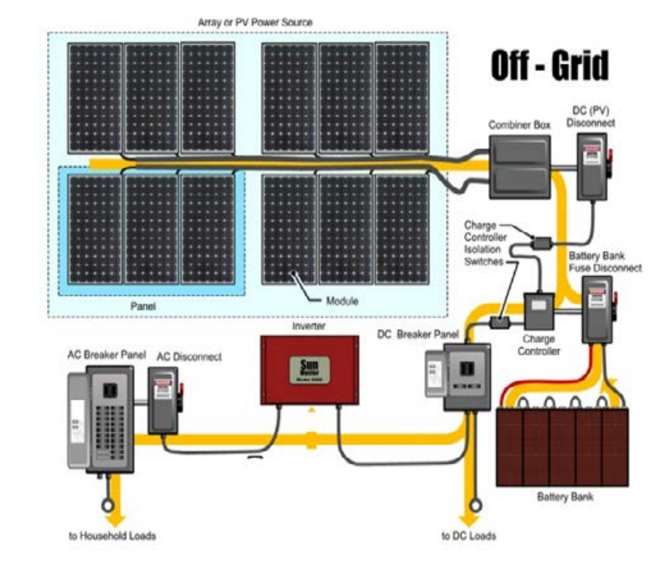


Fig. 5. Proposed system design.

3.9 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 [6]. We have done cost analysis to see whether it would be cost effective in the long run, even if initial investment is high.

TABLE 8
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/-

4. 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 22.5 lakh. Here using the PV system the initial cost may rise a little but for rest of the life it will generate electricity for free of cost. Most of the PV modules come with 40-50 years guarantee and battery with 5 years. 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.

ISSN 2229-5518

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