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Designing of a Standalone Photovoltaic System for a Residential Building in Gurgaon, India

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Abstract Photovoltaic power system, through direct conversion of solar irradiance into electricity, can be used as electrical power source for home to meet its daily energy requirement. In this paper detailed design of a standalone photovoltaic power system for uninterrupted power supply of a residential building in a typical urban area is presented. The process of acquiring photovoltaic power involves designing, selecting and determining specifications of different components that are used in the system conforming the load estimation. Accomplishment of this process depends on a variety of factors, such as geographical location, weather condition, solar irradiance, and load consumption. This paper outlines in detail the procedure for specifying each component of the standalone photovoltaic power system and as a case study, a residence in Gurgaon, India with typical energy consumption is selected. Detailed cost analysis including installation and maintenance of a solar PV system during its life span have been carried out also. The analysis shows though the initial investment is high, still, within few years it not only returns this amount but also gain substantial dividend during the system life span.

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

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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]. Hence alternative or clean renewable energy sources have to be explored and developed to meet future energy requirement. Solar energy, wind energy, etc. are clean, inexhaustible and environment- friendly resources among the renewable energy options.

Utilizing solar energy we can fulfil our daily energy needs during sunshine hours. But neither solar nor wind energy system can provide a continuous supply of energy demand throughout a day, like in the night time or in other conditions when sunshine or wind power is not there or not enough to fulfil the demand. At that off-time extra energy storage devices are required to meet the demand. In this context, standalone solar power systems are now being contemplated.

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]. India 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 India 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, Gurgaon area inthe state of Haryana in India. For this purpose, a typical residential building in Haryana 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 Haryana in Section 4, we introduce different components of a standalone PV system and their functions in briefin 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. Standalone Photovoltaic System

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 [3]. 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. The components of such a system are: 1) Solar PV array, 2) Charge Controller, 3) Inverter, 4) Battery, 5) Cables and 6) Protection devices. Depending on load requirement and radiation intensity at the location, the components of the system will have to be specified. Figure 1 gives a schematic diagram of interconnection of components of a typical stand-alone photovoltaic power system.

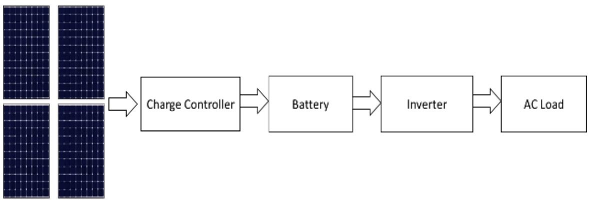

Figure 1. Standalone PV system components

In the following subsections we give a brief review of the functions of the components [5].

2.1. Solar Photovoltaic Panel

Photovoltaic cell or solar cell, which generates electricity from the sun light, is the main and primary component in a PV system. Current and voltage generated depend on the area of the cell. A 13.5”x13.5” size solar cell can generate voltage of about 0.55volt and a current density of 30–35mA/cm^2 [5]. A solar panel is made of a collection of these basic solar cells. To meet voltage and current requirements of a particular system, a number of panels are connected in series (to increase voltage) and in parallel (to increase current) combinations forming a solar PV array.

2.2. Storage Battery

Storage battery is the vital component a standalone PV system. Its function is to store energy during sunshine hours and supply current to load during non-sunshine hours. Lead Acid battery, VRLA battery, Lithium-ion battery, etc. are different types of batteries that can be incorporated in solar PV system.

2.3. Charge controller

To regulate and monitor current flow between PV array and battery, a device, called charge controller, is used. The main function of solar charge controller is to limit the flow at which electric current is added to or drawn from batteries. It prevents overcharging and protect battery from voltage fluctuation [6]. Two types of charge controllers are available: solar charge controller with PWM based technology and solar charge controller with MPPT based technology. In this paper MPPT design based charge controller is employed.

2.4. Inverter

Inverter (also known as power conditioning unit) is the heart of the system. Most of the applications in a residential building generally use AC current, whereas PV module and battery bank are power source of DC current. Inverter does the job of converting DC power to AC power in a PV system.

2.5. Balance of the System Components

Components such as protective devices, blocking & bypass diodes, lightning-protection system, fuses, bus bar and cable wiring constitute what is known as balance of system components [7]. These components are required to protect the system in an efficient way. Cable size should be chosen in such a way that voltage drop or cable loss is minimized.

2.6. Load

Power consumption units are load for a PV system to be planned. A proper load estimation is necessary for designing a standalone PV system. For the purpose of PV system design, electrical loads may be classified broadly as either resistive or inductive. Resistive loads do not necessitate any significant surge current when energized. Like light bulb, electric heater etc. are resistive loads. On the other hand, inductive load requires a large amount of surge current when first energized which is about three times the normal energy requirement. Fan, electric motor, air-conditioner etc. are inductive load. Depending on the load estimation of a building a proper design can be implemented.

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. 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: Determine capacity of Inverter.
Step 5: Determine capacity of Battery.

Step 6: Charge controller specification.
Step 7: DC Cable Sizing.
Step 8: Solar PV array specification and design layout.
Step 9: PV Module orientation and land requirement.
Step 10: Cost Analysis.

3.1. Site Inspection and Radiation Analysis

The first step and the most important part of the design is site inspection and radiation analysis [8]. It will determine whether a stand-alone system is viable or not. According to the radiation data of the location we can find out the number of sunny days in a year. Amount of electrical energy that can be generated depends on the radiation intensity throughout the year. Maximum, minimum and average temperature is required to measure the cell temperature which will affect the module voltage and current output. Shadow analysis will help to find out the time duration for which solar radiation falls on solar arrays. Azimuth angle and altitude angle is required to find out the sun path at that location [9].

3.2. Calculation of Building Load Requirement

The electrical load of a specific house will dictate how powerful a PV system has to be installed. The residence load profile is determined by listing all the residential applications with their power ratings and hours of operation at different seasons to obtain the total average energy demand in watt-hours. Inductive load and resistive load should be separately calculated to specify inverter rating. Table 1 gives an idea of how to estimate load. AP_n represents the name of electrical applications in a building, for example light, fan, TV etc. whereas N_n is its total quantity (n= 1, 2, 3, …). Here n is the representing serial number of applications. According to Table 1 total power rating (TP) is the summation of the rated power of individual load multiply by no of products, i.e.$\Sigma_n WT_n$.

Table 1. Load Estimation

Name of the Application (AP_n)	Rated Power of Application (W_n)	Quantity (N_n)	Wattage (W_{Tn})	Summer(A)		Autumn(B)		Winter(C)		Spring(D)	
				Hours used (AH_n)	Wh/day (AWH_n =)	Hours used (BH_n)	Wh/day (BWH_n=)	Hours used (CH_n)	Wh/day (CWH_n=)	Hours used (DH_n)	Wh/day (DWH_n=)
AP_1	W_1	N_1	W_1*N_1	AH_1	AH_1*W_{T1}	BH_1	BH_1*W_{T1}	CH_1	CH_1*W_{T1}	DH_1	DH_1*W_{T1}
AP_2	W_2	N_2	W_2*N_2	AH_2	AH_2*W_{T2}	BH_2	BH_2*W_{T2}	CH_2	CH_2*W_{T2}	DH_2	DH_2*W_{T2}
AP_3	W_3	N_3	W_3*N_3	AH_3	AH_3*W_{T3}	BH_3	BH_3*W_{T3}	CH_3	CH_3*W_{T3}	DH_3	DH_3*W_{T3}

Total energy required at the residence is $\Sigma_n AWH_n$in summer time and similarly for winter, spring and autumn seasons. In the design we have to take the load profile which is maximum of these four seasons. Let us denote this by E_{daily}.

3.3. Choice of System DC Voltage and Components

Once the building load is determined, DC Voltage of the PV system has to be fixed. Generally, it should be taken as high as possible so that less current will be required to meet the high energy requirement [3]. Lower current through cables will reduce electrical energy loss, because cable has resistivity and high current will cause joule heating of cable. Otherwise, much thicker wires are required which will increase cost of the system. In a typical standalone system, in addition to PV panels, other subsidiary components required are battery, inverter, charge controller, cables and mounting structure.

3.4. Determining Capacity of Inverter

Solar PV system delivers DC voltage and power. So an inverter, which convert DC power to AC power, is needed as most of the applications used in a house require AC power. There are still some applications of DC power in some areas. But in this paper, to keep it simple, we have not considered them.An inverter is rated by its output power (P_{KVA}) and DC input voltage (V_{dc}). Power rating of the inverter should not be less than the total power consumed in different loads. On the other hand, it should have the same nominal voltage of battery bank that is charged by solar PV module. In a household consumption of power in appliances can be classified into two categories: resistive power (P_{res}), such as in light, heater, iron, etc., and inductive power (P_{ind}), such as in fan, motor, etc.Typically, capacity of the inverter is taken to be the sum of all the loads running simultaneously and 3.5 times the total power of the inductive loads to take care of surge protection. Further, the obtained value is to be multiplied by 1.25 to get the requirement, if an option of 25% extra is kept for a reasonable future load expansion [3]. As this is not mandatory, so in our analysis we neglect this. We get the power(P_{inv1}) that should be deliveredby inverter as follows:

$$P_{inv1} = \left(TP + 3.5{*}P_{ind}\right) \tag{1}$$

Here, total power rating of all loads TP =P_{res}+ P_{ind}. However, this is an ideal situation. This power calculation has to be corrected for power factor of inverter.

Power rating of inverter (P_{output}) is related to the real power that is delivered by inverter as output and it is given by the following expression of power factor (PF) [12].

$$PF = \frac{\text{Deliverable Real power}}{\text{Power rating of Inverter}} \tag{2}$$

Here 'Real power' is the power that is consumed for work on the load (P_{inv1} in this case) and it is as calculated from Equation (1).Value of PF is generally taken as 0.8 for most of the inverters. So,

$$P_{KVA} = \frac{P_{inv1}}{PF} \tag{3}$$

Inverter converts DC power to AC power. But this conversion is not 100% efficient. So, efficiency (η_{inv}) of inverter is an important parameter which has to be taken care of. Continuous AC power load, which is the total power (TP as obtained above) needed when all the appliances are running at steady state condition, has to come from a DC power source, such as battery. Therefore, the continuous power load to the inverter(TP1) is given by [11]

$$TP1 = \frac{TP}{\eta_{inv}} \quad (4)$$

Now continuous (DC) input current (I_{dc}) to an inverter from PV modules can be determined, if the system DC voltage (V_{dc}) is specified, according to the following equation,

$$I_{dc} = \frac{TP1}{V_{dc}} \quad (5)$$

This parameter is needed for battery selection and design.

In terms of energy, daily input energy to the inverter (E_{inv}) is daily maximum energy requirement (which is E_{daily} as stated in Sec 3.2) divided by the inverter efficiency, that is,

$$E_{inv} = \frac{E_{daily}}{\eta_{inv}} \quad (6)$$

This much amount of energy must come from battery daily to fulfill the load requirement of inverter. System DC voltage also should be specified for the inverter that will allow further calculation to be done accordingly.

3.5. Determining of Capacity of Battery

The battery type generally suggested for use in solar PV power system application is deep cycle battery, specifically designed such that even when it is discharged to low energy level it can still be rapidly recharged over and over again for years. The battery should be large enough to store sufficient energy to operate all loads at night, cloudy or rainy days. Battery storage is conventionally measured in Ah (ampere hour) unit.

The charge storage capacity, which is essentially the energy storage capacity, of the battery bank (B_{Ah}) is determined by the daily energy requirement and number of days for backup power (N_{backup}) using the following equation [12],

$$B_{Ah} = \frac{E_{inv} * N_{backup}}{V_{dc} * DoD} \text{ in } AHr \quad (7)$$

The percentage of total charge, that is, energy of battery that can be allowed for running the load is referred as depth of discharge (DoD) of the battery. C-rating is also an important part of choosing a battery. It tells us what will be the optimum charging and discharging rate of a battery. Typically C-10 rated batteries are available in the market. So optimum battery bank (BO_{Ah}) should bechosen at that rate according to the following formula,

$$BO_{Ah} = \frac{TP}{V_{dc} * \eta_{inv}} * C\_rating \quad (8)$$

To meet requirements of the application load a number of batteries has to be connected in series for system voltage specification and in parallel for current specification. The number of batteries connected in series (B_S) is obtained by system DC voltage and voltage of individual battery using the following equation,

$$B_S = \frac{V_{dc}}{\text{Voltage of a single battery}} \quad (9)$$

The number of batteries which will be connected in parallel (B_P) can be obtained by the following equation,

$$B_P = \frac{B_{Ah}}{\text{Ah capacity of a single battery}} \quad (10)$$

The total number of batteries (N_B) can then be obtained by the following equation,

$$N_B = B_S * B_P \quad (11)$$

If we take battery efficiency (η_{Bat})to be about 85% typically for lead acid battery [12], then energy required(E_{Bat}) from solar PV array to charge the battery bank is given by the following equation

$$E_{Bat} = \frac{V_{dc} * B_{Ah}}{\eta_{Bat}} \quad (12)$$

3.6. Charge Controller Specification

The solar charge controller is generally sized in a way that will enable it perform its function of current control. A good charge controller must be able to withstand the array current as well as the total load current and must be designed to match the voltage of the PV array as well as that of the battery bank. MPPT charge controller is specified based on PV array voltage handling capacity. Now-a-days, MPPT charge controller usually comes with inverter. There is a recommend voltage range, within which we have to choose the PV array DC voltage. Let's take the PV array voltage to be CC_{volt} which should be greater than system DC voltage.

3.7. Solar PV Array Specification and Design Layout

The Solar PV array is the main component of a standalone PV system. When PV modules are connected in series in a small group it is called PV string and PV array is a collection of PV strings. According to the voltage and current rating PV array design should be done. From PV to battery there are long cable so we must consider the voltage and energy loss in it. Let us denote the cable efficiency by η_{Cable}. Typically in a standalone system 3% voltage loss is considered [11] giving $\eta_{Cable} =$ 97%. So, PV array voltage minimum should be V_{PV}, given by

$$V_{PV} = \frac{CC_{Volt}}{\eta_{Cable}} \quad (13)$$

Similarly, energy required from the PV array (E_{PV}) can be calculated by the following equation

$$E_{PV} = \frac{E_{Bat}}{\eta_{Cable}} \quad (14)$$

whereas current requirement from PV array per hour can be calculated from

$$I_{PV} = \frac{E_{PV}}{V_{PV} * \text{Daily Sunshine hour}} \quad (15)$$

Here Daily sunshine hour is the average sun hour available per day at the installation site. It depends on average radiation at the site and temperature of the module.

A number of PV modules has to be connected in series (S_{PV}) to form a string and a number of strings then has to be connected in parallel (P_{PV}) to obtain the rated voltage and current of the array. Let maximum voltage of an individual PV module is V_m and maximum currentI_m. In our calculations we have taken Standard Test Condition (STC) and followed theIEC standard 60891(2009) to get the correct values of V_m and $I_m$according to ambient condition of the PV power plant installation site.

Now, if V_{PV} and I_{PV} are voltage and current requirements of PV array, respectively, then S_{PV} can be obtained from

$$S_{PV} = \frac{V_{PV}}{V_m} \tag{16}$$

First, modules are connected in series. So, voltage of the PV string is equal to V_{PV}, but its current rating is only the current which is generated by individual PV module. Then, per PV string voltage and current rating is (V_{PV}, I_m).

Current requirement from PV array, I_{PV}may be high. But to protect the modules from current surge few strings are connected first in parallel and a fuse is put into the circuit. The number of such parallel strings (p) in a bunch depends on current fuse rating, let's say 20A, and depends on module manufacture.The value of 'p' is determined by dividing the fuse dc current of PV module by the rated current of one module as in equation (5).

$$p = \frac{20}{I_m} \tag{17}$$

And the number of such bunch of strings required to complete the array is given by the following formula

$$P_{PV} = \frac{I_{PV}}{p * I_m} \tag{18}$$

So total number of PV modules required are N_{PV}, given by

$$N_{PV} = P_{PV} * S_{PV} * p \tag{19}$$

3.8. DC Cable 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. There are two types of DC cable: Inverter to Battery DC cable, SPV to inverter DC cable.

3.8.1. Inverter to Battery Cable Sizing

The maximum continuous input current (I_{BI}) that should be used as the basis for inverter cable wiring.

$$I_{BI} = \frac{TP}{\eta * V_{LB}} \tag{20}$$

Lowest voltage of the battery (V_{LB}) is just above at the voltage at which it will get disconnected to prevent further discharging. This value is usually mentioned in the inverter specification sheet.

3.8.2. SPV to Inverter Cable Sizing

There are 3% voltage loss and energy loss in the cable is considered [11]. According to this assumption current rating of the cable (I_{DC}) is

$$I_{DC} = I_{PV} * 1.25 * 1.25 \tag{21}$$

Usually safety practice is to oversize the wire by 25% above the continuous current that the wire might handle due to high radiation intensity. Voltage drop in the cable is $V_{DROP\_DC} = V_{PV} * 3\%$

$$V_{DROP\_DC} = \frac{2 * L_{DCcable} * I_{DC} * \rho}{A_{DC\_Cable}} \tag{22}$$

Here ρ is the resistivity of the cable material, L_{DC_CABLE} is the length of the cable and A_{DC_Cable} is the area of the cable. With the help of the area of the cable, cable diameter can be calculated. In market cables are available according to the AWG or SWG rating.

3.9. Energy of Solar PV System and Corresponding Inverter Rating: Summary

The essential features of the analysis we presented above can be summarized as follows:

Total energy needed from PV system per day can be calculated using the following equation

$$E_{PV} = \frac{E_{daily} * N_{backup}}{\eta_{inv} * \eta_{cc} * \eta_{Bat} * DoD * \eta_{Cable}} \tag{23}$$

And the corresponding inverter rating comes as

$$\text{Inverter rating} = \frac{E_{PV}}{PF * \text{Daily Sunshine Hour}} \tag{24}$$

4. Case Study of a Residential Building at Gurgaon in India

Gurgaon, a town located in the northern hemisphere part of the earth at latitude and longitude of 28.6°N and 77.2°E respectively, in the north-west part of India. This geographical location of Gurgaon implies that the solar array should be inclined at an optimal angle of about 26° facing southward for all year round to maximize solar energy receive if it is oriented fixed. The average radiation of this location is about 5.5 kWh/m^2/day and average ambient temperature is about 30°C, whereas maximum and minimum ambient temperatures are 45.3°C and 7°C, respectively, if the location is devoid of overcasts from nearby trees and buildings. A residential building/house in this location is chosen for the analysis of a standalone PV system.

Table 2. Monthly average radiation data of the site

Month	Irradiance (kWh/m^2/day)
January	4.26
February	5.47
March	6.49
April	6.55
May	6.35
June	6.03
July	5.44
August	5.25
September	6.05
October	6.17
November	5.01
December	4.32

4.1. Layout of the building

The layout of a building is shown in Figure 2

Figure 2. Floor plan of a typical bungalow in Gurgaon

It is a typical bungalow type building in Gurgaon having 3 bedrooms and 2 toilets plus hall, kitchen, etc. The solar power plant will be installed besides the building, about 20m away.

4.2. Load Profile of the Building

The load profile can be determined by summing up the power rating of all the appliances in the building. The energy requirement of the building can be determined based on the hours of usage per day. An estimation of the requirement done for the building is shown in Table 3. According to this calculation power consumption at different season has dissimilar requirements. As per the table it is observed that in summer time the energy demand is maximum compare to other seasons throughout the year. In our calculations, we have to consider the maximum energy demand which is at summer time.

The energy requirement per day in summer is about 26 kWh or 26 units. Total inductive load power rating is 4225W and resistive load power rating is 8865W. Extra load and energy requirement for future provision is included in this estimation. So the total load power rating is 13.01kW.

Table 3. Total energy requirement and power rating of the building

	Power Rating (watt)			Energy rating (kWh/day)			
	Inductive	Resistive	Total	Summer	Autumn	Winter	Spring
Per room	60	1357	1417	3.42	2.86	3.67	3.67
Per Bathroom	60	470	530	0.75	0.75	0.75	1.2
Kitchen	780	815	1520	3.75	4.15	3.79	3.79
Hall	1201	2978	4257	8.86	7.94	4.68	4.65
Balcony & Staircase	855	1072	1927	1.69	1.64	1.66	1.66
Total for (3 Bedroom+2 Bathroom)	3139	9876	13015	26.056	23.831	22.642	23.51

4.3. Inverter specification

Inverter should be specified according to the resistive load and inductive load requirements of the building which have be shown above in Table 3. According to this load estimation the summery of the inverter sizing is given in Table 4. In this system, specifications of a typical inverter, for example, ReneSola 30KVA/360VDC inverter, is used. As per the inverter data sheet [13] it has overload handling capacity of 150% for 10 seconds which is sufficient to run high inductive load of the building. Efficiency of the inverter is 90% at peak condition. System Voltage is 360VDC.

Recommended MPPT voltage range is 450-550 VDC [13]. According to inverter datasheet maximum voltage handling capacity of MPPT is 750 VDC and maximum current handling capacity is 120A [13]. We have taken PV array MPPT voltage of about 500VDC.

Table 4. Inverter summary

Parameters	**Calculated Parameter Value**	
Inductive Load(P_{ind})	3139W	As per Table 3
Resistive Load(P_{res})	9876W	As per Table 3
Total Continuous output power (TP)	13kW	As per Table 3
Efficiency (η_{inv})	90%	As per inverter data sheet [13]
Input power to the inverter (TP1)	14.5kW	Using Equation4
Input DC voltage (V_{dc})	360VDC	As per inverter data sheet [13]
Input DC current to inverter (I_{dc})	40ADC	Using Equation5
Total Inverter Power (P_{inv1})	24kW	Using Equation 1
Power factor (PF)	0.8	As per inverter data sheet [13]
KVA rating (P_{KVA})	30KVA	Using equation 3
Energy coming from inverter (E_{daily})	26kWh (in Summer)	From Table 3
Energy input to inverter (E_{inv})	28.8kWh	Using equation 6
Output AC voltage	240VDC	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})	500VDC	As per inverter data sheet [13]

4.4. Battery Specification

In order to estimate the battery bank size, energy requirement should be known. For inverter total input energy needed is 28.8kWh or 28800Wh from battery. System Voltage is 360VDC. So Battery voltage should be near about 360VDC. Days of autonomy is also a vital part to determine the size of the battery bank. The summary of the battery sizing is given in the following table.

Table 5. Battery Summery

Usage/day	7 hours	Taken
Autonomy (N_{backup})	3	Taken
Battery type	Lead Acid type	As per Battery data sheet [14]
Depth of discharge (DoD)	80%	As per Battery data sheet [14]
Required capacity of battery bank (B_{Ah})	300Ah	Using equation 7
Battery bank operating voltage(V_{dc})	360VDC	As per Inverter data sheet [13]
Each battery voltage	2V	As per Battery data sheet [14]
Each battery capacity	400Ah	Using equation 8
Total number of strings (B_P)	1 (connected in parallel)	Using equation 10
No. of batteries in each strings (B_S)	180 (connected in series)	Using equation 9
Total no of battery required (N_B)	180	Using equation 11
C-rating	C-10	As per Battery data sheet [14]
Energy require to charge battery(E_{Bat})	127.33kWh	Using equation 12

4.5. PV Array Specification

PV array should be designed according to the energy requirement to charge the battery bank. There are different parameters required to design the PV array in proper way. In this designing we have chosen the SunPower 345W_P module. PV array layout will be designed according to maximum voltage (V_m), maximum current (I_m), temperature coefficient and fuse rating of the module. Cable loss is also require to calculate the proper voltage and energy requirement from the PV array. Let Wire loss is about 3% and MPPT voltage is 500V chosen. So, Array voltage minimum should be: 500/0.97 = 515Volt (V_{PV}) and energy from the SPV array (E_{PV}) should be: 127.33/0.97= 131.27 kWh, so current-hour required would be about 131270/515= 255Ah.

In Gurgaon, Haryana location daily average solar energy is above 5kWh/m^2/day. Daily sunshine hour is 5Hrs. So per hour current requirement is 255/5 ≈ 51A (I_{PV}) from solar array. Solar PV Array specification should be at least (515Volt, 51A). Let cell temperature average be 55°C. Taking into account the temperature coefficient of Module, we get V_m: 54.4V, I_m: 6.01A. Voltage will degrade when the cell temperate will increase.The detail calculation procedure is mentioned in the methodology section. The following table has given the summary of the PV array sizing.

Table 6. Solar module specification

Power rating per PV module	345W_p	As per PV module data sheet [15]
V_{OC}	68.2V	
V_m	57.3V	
I_{SC}	6.39A	
I_m	6.02A	
Module efficiency	21.5%	
Power tolerance	0-5%	
Technology	96 Mono-crystalline	
Maximum system voltage	1000V IEC	
Maximum series fuse	20A	
Power temperature coefficient	-0.3%/°C	
Generated power for first 5 years	95%	

Table 7. Solar PV array specification

Total PV array capacity	31kW_P	Total no of module * wattage rating per module
Array voltage output (V_{PV})	544V	Using equation 13
Array current output (I_{PV})	54A	Using equation 15
No. of strings (P_{PV})	3	Using equation 18
No. of modules in series (S_{PV})	10	Using equation 16
No. of modules in parallel connected in string (p)	3	Using equation 17
Total no of module	90	Using equation 19
DC wire length	20m x 2	Taken

4.6. System cable sizing

In a PV system choosing proper cable is a very important part in designing. If a DC cable draw more current than its current carrying capacity then it will damage the cable. That's why the cable current rating should be chosen more than the actual capacity. In this design aluminum cable is chosen.

4.6.1. Inverter to Battery Cable Sizing

As per equation (20) the maximum continuous input current that should be used as the basis for inverter cable wiring =14KVA/0.9/315V = 50A. So, current capacity of inverter wire is 50A * 1.25 = 63A

Wire should be chosen as per cable ampere rating.

4.6.2. SPV to Inverter Cable Sizing

Cable loss has taken 3% .Current rating as per equation (21) is 54A * 1.25 * 1.25 = 86A. So, in battery to get 360 VDC through MPPT voltage require is 500/0.97= 515Volt. DC voltage Drop is about (515-500)= 15Volt.

Then as per equation (22), the area of the cable is 1123x10^{-8} meter square. So diameter of the wire is 3.8mm.

4.7. PV Array Orientation and Land Requirement

As per the PV module specification sheet PV module dimension is 41.2” x 61.4”. The row spacing between two modules which are facing towards sun and located just behind on another is measured by [14] the following equation.

$$\text{Row Spacing}(Y) = (X).\frac{\cos\cos(\text{Azimuth Angle})}{\tan\tan(\text{Altitude Angle})} \quad (25)$$

Where X is the height of the module from ground as shown in the Figure 3.

In this design module tilt angle is taken as the latitude of that location which is 28°. Shadow length will be taken according to December 22 because at that day shadow length of any object in northern hemisphere will be maximum compare to other days in a year [4].

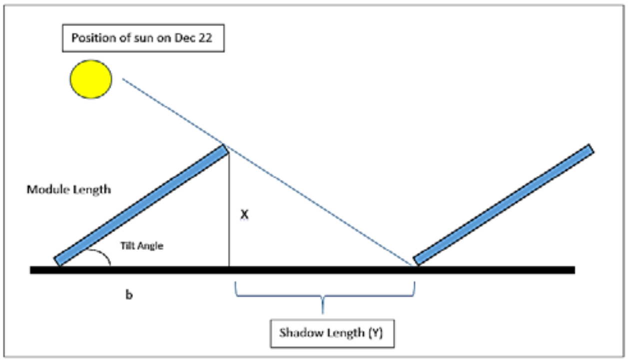

Figure 3. Calculating the minimum distance between rows

Azimuth and altitude anglesat Gurgaon are chosen according to 10AM of that day [19]. Module length is 41.2”, as in [15]. So according to the above formula shadow length will be 28.8”. Calculating the value of b as shown in Figure 3 one module installation length required is minimum(36.4”+28.8”) =65.2”.

So total length required for parallel connection is: 65.2*8 + 36.4= 588”≈ 14.2m and taking 2m extra spacing= 16.2m. Total length require for series connection is 61.4 * 10 = 614” ≈ 15.6m and 1.5m extra spacing = 17.2m. So total area requirement is 16.2m X 17.2m = 277 m^2 ≈ 2982 ft^2. Extra length is taken for maintenance work or for other purposes.

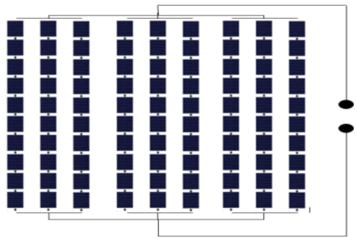

Figure 4. 17.2m x 16.2m Area of the PV array

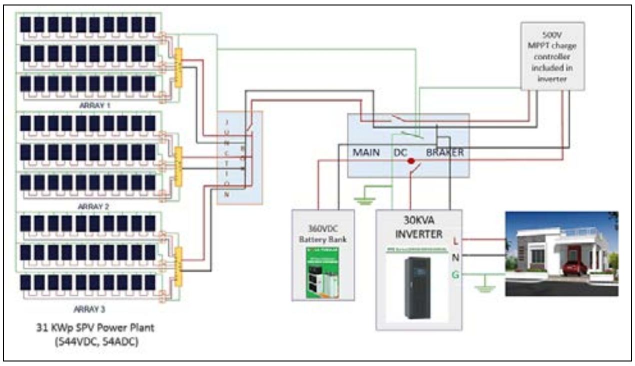

Figure 5. Wiring diagram of a standalone PV array

4.8. 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 components which are used in this system and the total cost are given in the following tabular form (as shown in Table 8). PV module cost per watt peak is taken Rs.50/-, and battery cost per watt peak is taken Rs.15/- per Ah. Now we want to see how much is the initial investment and what will be the payback period, if there is any. It will also establish financial feasibility of the PV system. The payback period is the time required to cover up or fulfill the initial investment including the installation cost. Life of the solar PV modules are typically 25 years and batteries have to be replaced after 5 years period because usually the life of the battery is not more than 5 years, usually. So taking this assumption 4 times the battery bank has to be replaced. We have assumethe price of the battery will remain same during this 25 years.So initial investment cost of the project throughout the 25 year is the summation of the first materials cost, installation cost, maintenance cost and the present value of the future investment for the battery cost

Table 8. Initial investment for the PV system

No.	Name of The Component	Quantity	Price per quantity(Rs.)	Total Price(Rs.)
1	Solar Panel (SunPower) Model No.X21-345W_p	90	17,250/-	15,52,500/-
2	Exide Battery LMXT (400AH, 2V)	180	6,000/-	10,80,000/-
3	ReneSolar Inverter (30KVA,360VDC)	1	7,88,400/-	7,88,400/-
	Total cost of above materials			**34,20,900/-**
5	Cost of cable, design, Labor, Metering, junction box and Control Device etc. are lamp together as 20% of equipment cost and add on			**6,84,180/-**
	Total Initial investment			**41,05,080/-**

Price of the land is not included in this calculation. In this calculation, inflation rate and discount rate is taken 5% and 7% respectively.

Following is the step by step procedure to find the payback period and financial feasibility of the system.

Step1 : Determine no. of units generated by PV system during day.

The average number of daily sun shine hour in the location is about 5.5 hours. This 31kW_p solar PV system has efficiency near about 75%. According to module specification sheet PV module efficiency is 95% and it will last for first 5 years and after that it will degrade at the rate of 0.4% per year. So per day unit generation for first year will be (5.5 * 31 * 75% * 95%) = 121 units. Similarly 25 years calculation can be done which is shown in Figure 6.

Step 2: Find out rate of electricity from conventional grid connection:

Rate of electricity in India varies in different locations and so also energy consumption rate per month. In Haryana where the system is supposed to be installed has conventional electricity rate of Rs.6.75/unit [16]. It has a tendency to increase at the rate 6% per annum. Also by diesel generator per unit generation cost is Rs.20/. Diesel rate also changing day by day. In this calculation we assume that the diesel rate is increasing 2% per annum.

Step 3: Determine present value of future investment for battery bank.

First we have to calculate the present value of the future investments using the following equation [17].

$$\text{Present value} = \text{Future value}*\left(\frac{1+\text{inflation rate}}{1+\text{discount rate}}\right)^{n} \quad (26)$$

where, present value is the present valuation of the future investment and future value is cost of product after n years. Inflation rate is the rate at which value of money decrease with time and discount rate is the rate at which the value of money increases with time due to interest it can earn. Here *n* is number of years.

According to such calculation the total present value of the 25 years battery investment cost is about Rs.34lakhs. If we invest half of that money as a fixed deposit in a bank at interest rate of 8.75%, then at each time of battery purchase we can get back that money. Also after 25 year we can get back Rs.2.4lakhs of this investment. So we can say that the total initial investment including the battery cost is Rs.58lakhs.

Step 4: Determine the savings per year.

After installing the PV system there will be no electricity cost. So that will be the savings per year deducting the maintenance cost per year. In this calculation 10% of the yearly savings is used for maintenance purpose of PV system. For example in first year electricity consumption will be (121*6.75*365) = Rs.2,99,504/- and out of that 10% will be used for maintenance purpose, so overall savings will be Rs.2,69,554. In that way after 25 year savings will be about 1.4 crore and the present value of that savings is 1.07 crore. So, the saving after 25 years is (commutative savings + extra bank savings for battery – maintenance cost), which is, according to the calculation, about Rs.85lakhs and net present value of that amount is Rs.50lakhs. This is a positive value (shown in Figure 6). So this project is feasible and acceptable because according to the financial strategy if the NPV of any system is positive then the project is feasible and acceptable. The payback period of the system is 14 years. The detailed calculation is shown in Figure 7.

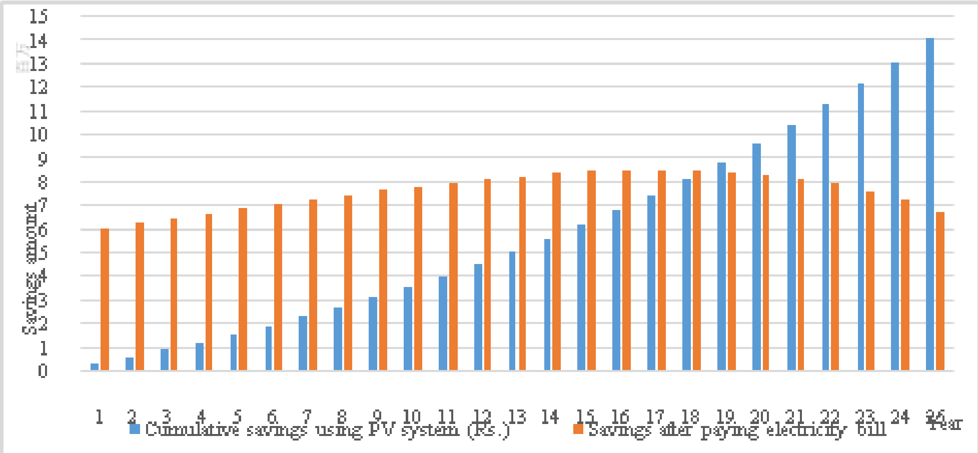

Figure 6. Savings after Investment in PV system vs fixed deposit in bank (Comparing with conventional grid connection)

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	5.00%	0.9813=(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)	Rate of electricy (Rs./ unit)	Yearly savings (Rs.)	Maintenance cost @10% of the yearly savings (Rs.)	Net yearly savings (Rs.)	Cumulative savings (Rs.)	Let, Inflation rate is 5.0% and discount rate is 7%	The present value the savings	Real saving in nth year		Bank interest rate 8.75% on fixed deposit	Savings after paying electricity bill
1	5.5	31	128	95	121	6.75	299,504	29,950	269,554	269,554	0.98	269,554	269553.99		6,329,883	6,030,379
2	5.5	31	128	95	121	7.16	317,475	31,747	285,727	555,281	0.96	280,384	549938.11		6,558,037	6,240,562
3	5.5	31	128	95	121	7.58	336,523	33,652	302,871	858,152	0.94	291,649	841587.51		6,786,611	6,450,088
4	5.5	31	128	95	121	8.04	356,715	35,671	321,043	1,179,195	0.93	303,367	1144954.80		7,014,471	6,657,756
5	5.5	31	128	95	121	8.52	378,117	37,812	340,306	1,519,501	0.91	315,556	1460510.78		7,240,310	6,862,193
6	5.5	31	128	94.6	121	9.03	399,117	39,912	359,205	1,878,706	0.89	326,852	1787363.13		7,462,634	7,063,518
7	5.5	31	128	94.2	120	9.58	421,275	42,128	379,148	2,257,854	0.88	338,547	2125910.19		7,681,575	7,260,300
8	5.5	31	128	93.8	120	10.15	444,655	44,466	400,190	2,658,043	0.86	350,654	2476564.06		7,895,577	7,450,921
9	5.5	31	128	93.4	119	10.76	469,325	46,932	422,392	3,080,436	0.84	363,187	2839751.10		8,102,877	7,633,552
10	5.5	31	128	93	119	11.40	495,354	49,535	445,818	3,526,254	0.83	376,161	3215912.37		8,301,488	7,806,134
11	5.5	31	128	92.6	118	12.09	522,816	52,282	470,535	3,996,789	0.81	389,592	3605504.15		8,489,171	7,966,354
12	5.5	31	128	92.2	118	12.81	551,792	55,179	496,612	4,493,401	0.80	403,494	4008998.43		8,663,410	8,111,619
13	5.5	31	128	91.8	117	13.58	582,362	58,236	524,125	5,017,527	0.78	417,885	4426883.45		8,821,385	8,239,024
14	5.5	31	128	91.4	117	14.40	614,613	61,461	553,152	5,570,679	0.77	432,781	4859664.24		8,959,939	8,345,325
15	5.5	31	128	91	116	15.26	648,639	64,864	583,775	**6,154,454**	0.75	448,199	5307863.20		9,075,541	8,426,902
16	5.5	31	128	90.6	116	16.18	684,535	68,454	616,082	6,770,536	0.74	464,157	5772020.64		9,164,256	8,479,720
17	5.5	31	128	90.2	115	17.15	722,404	72,240	650,163	7,420,699	0.73	480,675	6252695.40		9,221,696	8,499,292
18	5.5	31	128	89.8	115	18.18	762,352	76,235	686,117	8,106,816	0.71	497,770	6750465.47		9,242,980	8,480,628
19	5.5	31	128	89.4	114	19.27	804,494	80,449	724,044	8,830,861	0.70	515,463	7265928.62		9,222,683	8,418,189
20	5.5	31	128	89	114	20.42	848,948	84,895	764,053	9,594,914	0.69	533,774	7799703.07		9,154,781	8,305,833
21	5.5	31	128	88.6	113	21.65	895,840	89,584	806,256	10,401,170	0.67	552,725	8352428.13		9,032,593	8,136,753
22	5.5	31	128	88.2	113	22.95	945,304	94,530	850,773	11,251,944	0.66	572,337	8924764.95		8,848,718	7,903,415
23	5.5	31	128	87.8	112	24.32	997,478	99,748	897,730	12,149,674	0.65	592,632	9517397.20		8,594,963	7,597,486
24	5.5	31	128	87.4	112	25.78	1,052,509	105,251	947,258	13,096,932	0.64	613,635	10131031.83		8,262,266	7,209,756
25	5.5	31	128	87	111	27.33	1,110,554	111,055	999,499	**14,096,431**	0.62	635,368	10766399.84		7,840,610	**6,730,056**
											Total=	**10,766,400**				
		Initial Investment for system=			**4105080**	Plus Present cost of future invertment for Battery=			**5,820,582**			**After 25 years**	**NPV of B.savings**			
	Net saving after 25 years = total saving in 25 years - initial investment====>>						**8,520,253**				**Save in Bank=**	**6,730,056**	**4,198,205**			
NPV of savings using PV =			**5,098,277**													
	Present Battery cost=		1,080,000													
						Present Value	**Bank interest after**									
	Replacement cost of battery for first time after 5yr =					982,727	2,609,382									
	Replacement cost of battery for second time after 10yr=					894,215	2,326,281									
	Replacement cost of battery for third time after 15yr=					813,675	1,895,668									
	Replacement cost of battery for fourth time after 20yr PV=					740,389	1,240,681	SAVINGS	NPV							
			Total present cost for battery=			**3431004.44**		244,405	152,460							

Figure 7. Cost analysis of standalone PV array

Similar way, we compare cost of diesel generated electricity with that of PV system to get the payback period and feasibility study. If we follow the same procedure, according to diesel generator electricity cost, the payback period of the system will be 8 years and savings will be much more than grid connected system. It is also shown in Figure 8 that if we invest this amount of money in bank at an interest rate of 8.75%, then after paying the electricity bill the saving after 25 years will be less than the savings we can get installing the PV system.

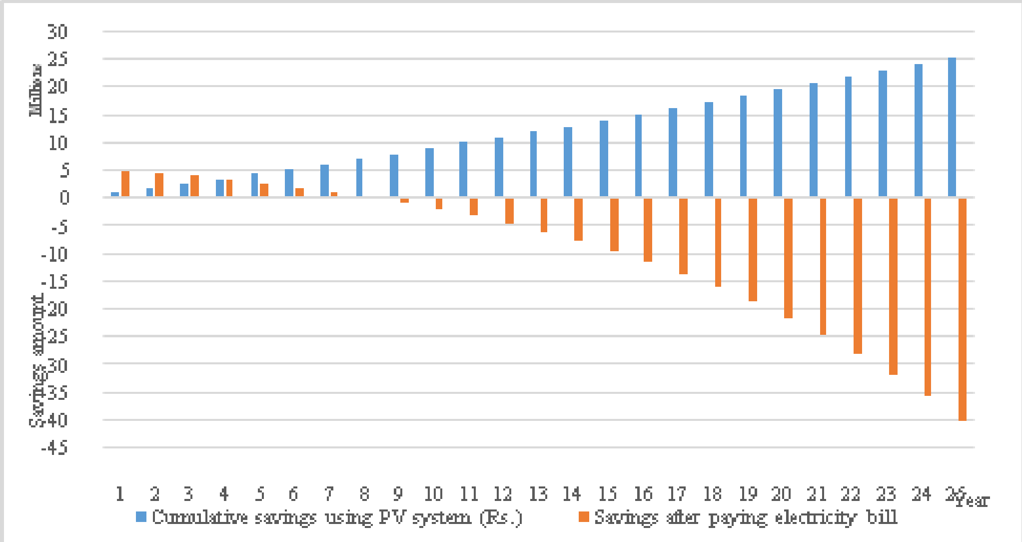

Figure 8. Savings after Investment in PV system vs fixed deposit in bank (Comparing with Diesel generator)

5. 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. Urban areas hardly utilize this for energy needs as conventional energy available from grid is much cheaper and initial investment of PV system is quite high. In the urban area of Haryana, for example in Gurgaon, the solar radiation varies from 400W/m^2 to 1100W/m^2, depending on different climatic conditions. This is enough to provide the energy requirement of a building in this area if efficiently tapped. In this paper we present a complete design of a solar PV system step by step and its life cycle cost analysis. The results of this study indicate that at the optimal configuration for electrifying a typical building about 13 kW of power is needed. The initial installation cost of the standalone PV system is high, about Rs.42 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 areasgrid connection system is readily available, but there also people can invest money initially for fulfilment 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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