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A User Friendly Approach for Design and Economic Analysis of Standalone SPV System

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Abstract

This paper presents the use of solar energy for generation of electrical energy through solar photovoltaic (SPV) system to meet the load requirement of a domestic building. Complete design and economic analysis of SPV system for different costs of SPV module is done and compared with grid electricity for with and without storage conditions. The results of the study encourage the use of SPV system for a residential building and show that SPV system is an economically viable option to meet the exponentially growing electricity requirement for household applications in India.

Keywords

Household Electrification, Solar Photovoltaics, SPV System Design, Cost Analysis

1. Introduction

India faces a significant gap between electricity demand and supply. Demand is increasing at a very rapid rate compared to supply. According to the World Bank, roughly 40% of residences in India are without electricity. In addition, blackouts are a common occurrence throughout the country. The World Bank also reports that one-third of Indian businesses believe that unreliable electricity is one of their primary impediments of doing business. In addition, coal shortages are further straining power generation capabilities. In order to meet the situation, a number of options are considered. Power generation from freely available solar energy is one such option. Most parts of India receive bright sunshine around 3000 hours in a year except Kerala, northeastern states and Jammu & Kashmir where sunshine hours are appreciable low.

During monsoon, a significant decrease in sunshine occurs over the whole country except Jammu and Kashmir where the maximum duration of sunshine occurs in June and July, and minimum during January due to its location. The northeastern states and southeast peninsula also receive relatively less sunshine during October and November due to the northeast monsoons. As far as the availability of global solar radiation is concerned,

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more than 2000 kWh/m^2/year are received over Rajasthan and Gujarat, while east Bihar, northwest Bengal and the northeastern states receive less than 1700 kWh/m^2/year. The availability of diffuse solar radiation varies widely in the country. The annual pattern shows a minimum of 740 kWh/m^2/year solar radiations over Rajasthan increasing eastwards to 840 kWh/m^2/year in the north eastern state, and southwards to 920 kWh/m^2/year.

India is thus endowed with rich solar energy resource. The average intensity of solar radiation received in India is 200 MW/km^2. With a geographical area of 3.287 million km square, this amounts to 657.4 million MW. However, 87.5% of the land is used for agriculture, forests, etc., 6.7% for housing, industry, etc. and 5.8 % are barren, snowbound or generally inhabitable. Thus only 12.5% of the land area amounting to 0.413 million km square, in theory, can be used for solar energy installations. Even if 10% of this land can be used, the available solar energy would be 8 million MW, which is equivalent to 5909 million tons of oil equivalent.

Launching India's national action plan on climate change on June 30, 2008, the prime minister of India Dr. Manmohan Singh stated "Our vision is to make India's economic development energy efficient. Over a period of time, we must pioneer a graduated shift from economic activity based on fossil fuels and from reliance on non-renewable and depleting sources of energy to renewable sources of energy. In this strategy, the sun occupies centre-stage, as it should being literally the original source of all energy. We will pool our scientific, technical and managerial talents, with sufficient financial resources, to develop solar energy as a source of abundant energy to power our economy and to transform the lives of our people. Our success in this endeavor will change the face of India. It should also enable India to help change the destinies of people around the world."

The economic viability of a standalone PV system in comparison to the most likely conventional alternative system, *i.e*. a diesel-powered system, has been analyzed for energy demand through sensitivity analysis [1]. The analysis shows that PV-powered systems are the lowest cost option at a daily energy demand of up to 15 kWh, even under unfavorable economic conditions. When the economic parameters are more favorable, PV-powered systems are competitive up to 68 kWh/day. These comparisons are intended to give a first-order indication when a standalone PV system should be considered for application. As the cost of PV systems decreases and diesel costs increase, the break-even points occur at higher energy demand.

A methodology is presented [2] for determining the optimum size and location of installing the solar photovoltaic based DG system for supplying the active power at the node in a radial distribution system for loss reduction.

Techno-economic feasibility of three different energy-supplying alternatives, namely the solar photovoltaic (SPV) system, diesel generator system and extending the grid connection for energy supply to a remote village located around 15 km away from the place where grid supply is available, is suggested [3]. The study suggests that the SPV systems are cheaper in remote villages where grid extension is costlier.

Literature presents several studies on energy payback time and life cycle analysis of PV technologies. The analyses of the PV system with reference to a fuel oil-fired steam turbine and their GHG emissions and costs revealed that greenhouse gases (GHG) emission from electricity generation from the PV system is less than one-fourth that from an oil-fired steam turbine plant and one half that from a gas-fired combined cycle plant. From the life cycle energy use and GHG emission perspectives, the PV system is a good choice of power generation. However, it also indicates that large scale exploitation of PV could lead to other types of undesirable environmental impacts in terms of material availability and waste disposal [3].

Life cycle assessment of electricity generation by PV panels considering mass and energy flows over the whole production process starting from silica extraction to the final panel assembling, using the most advanced and consolidate technologies for polycrystalline silicon panel production is presented [4]. Briefly, the most important results of the analysis are the calculation of a gross energy requirement (GER) of 1494 MJ/panel (0.65 m^2 surface) and of a global warming potential (GWP) of 80 kg of equivalent CO_2 panel. The energy payback time (EPBT) has been estimated to be shorter than the panel operation life even in the worst geographic conditions. The results of the LCA support the idea that the photo-voltaic electric production is advantageous for the environment. The authors in [5] analyzed foreseeable technological advancements in current and emerging PV technologies over the next few decades are likely to lead to significantly lower per-kWh impact than the one that characterizes the current state of the art of the PV sector.

A techno-economic analysis of standalone solar photovoltaic system has been presented [6]. In this work, complete analytical methodology for optimum relationship between PV array and storage battery capacity to supply the required energy at a specified energy load fraction is carried out. To estimate the performance of solar photovoltaic system the solar radiation utilizability concept and the monthly average daily PV array efficiency have been used. The techno-economic optimization of a PV system has been done by using levelized energy cost computation based on the total number of battery replacements (brp's) through battery life-cycle model. It has been found that energy load fractions as well as the number of brp's have a significant impact on the selection of optimum sizing of a standalone PV system. From the techno-economic and environmental points of view, the feasible sites in Egypt to build a 10 MW PV-grid connected power plant and recommended few sites for large scale PV power generation [7].

A techno-economic comparison of rural electrification based on solar home systems and PV micro-grids to supply electricity to rural community for domestic purpose has been performed [8]. Based on study it is concluded that a micro grid might be a more attractive option financially for the user, energy service company and the society if the village has a large number of households, which is densely populated and lies in a geo-graphically flat terrain and more than 500 densely located households using 3 - 4 low power appliances (e.g. 9 W CFLs) for an average of 4 h daily. However, in rough terrains solar home systems might be a better option if the community is small and sparsely populated. The economic analysis has been performed on the grid connected SPV system connected to the Spanish grid [9]. Using net present value (NPV) and payback period (PP) parameters, the profitability of the system was studied. The system was evaluated for its economic as well as environmental benefits and the results clearly showed that the system was profitable enough to be invested in, but very long payback periods were dissuading the investors.

A strong case of standalone SPV systems has been built by conducting feasibility study in an island of West Bengal India by the name Sagar Deep based on socio-economic and environmental aspects. The generation costs of SPV systems and conventional power has been compared to show how conventional power systems suffer from diseconomy when power needs to be transmitted to extremely remote locations. The social viability of SPV was apparent from a conspicuous improvement in commerce, trade, education and increased participation of women in activities other than household chores in the island [10].

The paper uses the solar radiation data of a particular site for complete design and cost analysis of proposed Solar Photovoltaic (SPV) systems, to be installed in a building to supply electricity.

2. Domestic Electrical Load

The main electrical loads necessary for improving living conditions in the village are: household appliances (lighting, TV, refrigerator, washing machine, water pump, electric iron and fan, AC). The ratings of these appliances are given in **Table 1**.

3. Solar Radiation Analysis

Solar radiation data provide information on how much of the sun's energy strikes a surface at a location on earth during a particular time period. These data are needed for effective research into solar energy utilization.

The daily average solar energy incident over India varies from 4 to 7 kWh/m^2 with about 1500 - 2000 sunshine hours per year, depending upon location. Theoretically, a small fraction of the total incident solar energy

Table 1. Household electrical load.

Electrical Load	No. of Units	Operating Hours Per Day	Wattage Per Unit Used	Total Units Consumed Per Day
Lighting Lamp	5	4 lamps from 18 to 24 & 1 lamp from 0 to 6	60	1.8
Washing Machine	1	from 11 to 13	250	0.5
Refrigerator	1	from 0 to 24	180	2.4
Water Pump	1	For three hours daily	120	0.36
TV	1	from 17 to 24	80	0.56
Fan	3	from 0 to 24	60	1.44
Electric Iron	1	For one hour in two days	1500	0.75
AC 1.5 ton	2	6 hours each daily	2000	24
	Total		6530 Watts	31.81

(if captured effectively) can meet the entire country's power requirements. In view of this, measuring efficiently solar energy radiations in a big country like India and preparing data for various applications are major challenges. The network of solar energy measuring stations is rather scarce throughout the world. In India, only IMD (Indian Meteorological Department) Pune provides data for quite few stations, which is considered as the base data for research purposes. However, hourly measured data of solar irradiance is not available, even for those stations where measurement has already been done. Due to lack of hourly measured data, the estimation of solar energy at the earth's surface is an important study in the present scenario to meet the energy requirement from green energy sources. Monthly averaged data of global and diffuse solar irradiance at New Delhi is shown in **Figure 1**.

4. Design of Stand Alone SPV System

The schematic diagram of a PV power system with battery storage is presented in **Figure 2**.

In **Figure 2**, the function of the PV generator is to convert the sunlight directly into DC electrical power and that of the battery is to store the excess power through using the battery charger. The load and storage control is used to convert the DC electrical power into AC power to match the requirements of the common household AC appliances.

1) Sizing of the PV generator

The most appropriate SPV power system to cover such a load is illustrated in **Figure 2**.

The peak power of the PV generator (P_{PV}) is obtained as follows:

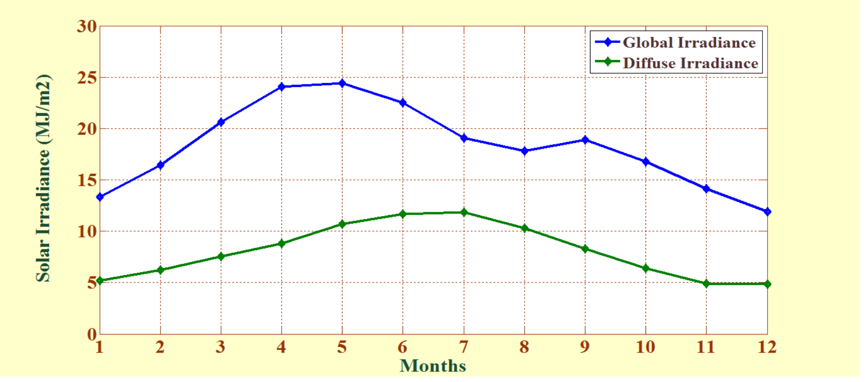

Figure 1. Monthly average daily global and diffuse solar irradiance on a horizontal surface at New Delhi.

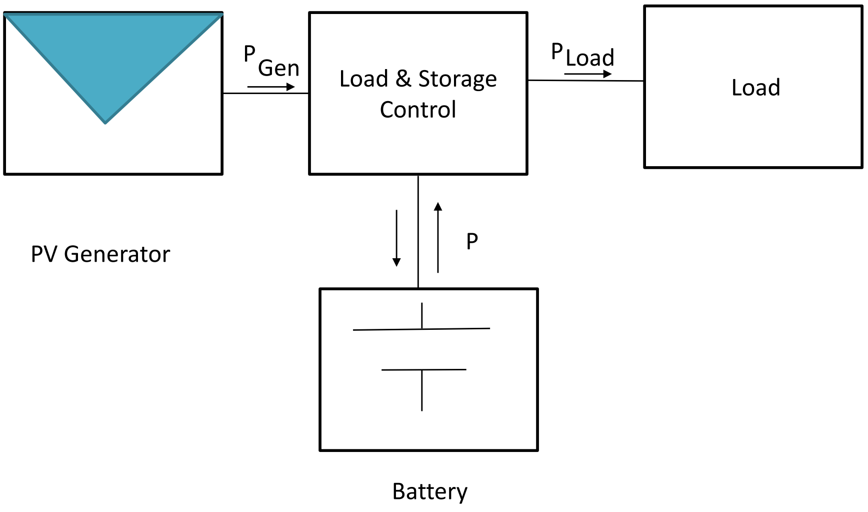

Figure 2. Schematic diagram of a PV power system with battery storage.

$$P_{\mathrm{PV}} = \frac{E_L}{\eta_V \eta_R \mathrm{PSH}} S_F$$

where $E_L\,(\text{daily energy consumption}) = 31.81\ \text{kWh/day}$, (PSH) peak sun hours $= 5$. The efficiencies of the system components $(\eta_R = 0.92, \eta_v = 0.9)$ and the safety factor for compensation of resistive losses and PV-cell temperature losses $S_f = 1.15$.

Substituting these values in the above equation, we obtain the peak power of the PV generator:

$$P_{\mathrm{PV}} = 8.836\ \mathrm{kW_p}$$

To install this power, a mono-crystalline PV module type MBPV-CAAP (this module is of Moser Baer company) of a gross area of $A_{\mathrm{PV}} = 1.65\ \mathrm{m}^2$, peak power of $P_{\mathrm{mpp}} = 200\ \mathrm{Wp}$ is selected. The number of the necessary PV modules (N_{pv}) is obtained as

$$N_{\mathrm{PV}} = \frac{P_{\mathrm{PV}}}{P_{\mathrm{mpp}}} = 44 \text{ modules are required}$$

V_{mp} for MBPV200 Watt Peak is 28.81 Volts.

No. of modules in series $= 220 \times 1.414 / 28.81 = 11$

Hence the number of modules in parallel = 4

For MBPV CAAP 200 $\mathrm{W_p}$ module

$V_{\mathrm{oc}}\,(\text{open circuit voltage}) = 35.99$ Volts and

$I_{\mathrm{sc}}\,(\text{short circuit current}) = 7.65$ Amperes

Now, we obtain an open circuit voltage and short circuit current for this SPV array as

$V_{\mathrm{oc}} = 35.99 \times 11 = 395.89\ \mathrm{V}$

$I_{\mathrm{sc}} = 7.65 \times 4 = 30.6\ \mathrm{A}$.

2) Sizing of the Battery Block

The storage capacity of battery block for such systems is considerably large. Therefore, special lead-acid battery cells (block type) of long life time, high cycling stability-rate and capability of standing very deep discharge should be selected. Such battery types are available but at much higher price than regulars batteries. The ampere hour capacity (C_{Ah}) and watt hour capacity (C_{wh}) of the battery block, which are necessary to cover the load demands for a period of 2.0 days without sun, is obtained as follows

$$C_{\mathrm{Ah}} = \frac{1.5 \times E_L}{V_B \times \mathrm{DOD} \times \eta_B \times \eta_V}$$

$$C_{\mathrm{wh}} = C_{\mathrm{Ah}} V_B$$

where V_B and η_B are voltage and efficiency of battery block, while DOD is the permissible depth of discharge rate of a cell. Assuming realistic values of $\eta_B = 0.85$, $\mathrm{DOD} = 0.75$ and $V_B = 220\ \mathrm{V}$, we obtain:

$$C_{\mathrm{Ah}} = 500\ \mathrm{Ah}$$

$$C_{\mathrm{wh}} = 110\ \mathrm{kWh}$$

3) Design of the Battery Charge Controller

The battery charge controller is required to safely charge the batteries and to maintain longer lifetime for them. It has to be capable of carrying the short circuit current of the PV array. Thus, in this case, it can be chosen to handle 31 A.

4) Design of the Inverter

The used inverter must be able to handle the maximum expected power of AC loads. Therefore, it can be selected as 20% higher than the rated power of the total AC loads. Thus the rated power of the inverter becomes 7836 W. The specifications of the required inverter will be 7836 W, 220 VAC, and 50 Hz.

The cost of the equipments required in the proposed SPV system is presented in **Table 2**.

5. Life Cycle Cost Analysis

In this section the life cycle cost (LCC) estimation of the designed standalone PV system is discussed. The LCC

Table 2. Cost of equipments used in the proposed SPV system.

Item	PV	Battery Cell for 510 Ah	Charger	Inverter	Installation	M&O/Year
Cost	Rs. 60/W_p	Rs. 5500/cell	Rs. 258/A	Rs. 36/W	10% of PV cost	2% of PV cost

of an item consists of the total costs of owning and operating an item over its lifetime, expressed in today's money.

The costs of a standalone SPV system include acquisition costs, operating costs, maintenance costs, and replacement costs. All these costs have the following specifications:

- The initial cost of the system (the capital cost) is high.
- There are no fuel costs.
- Maintenance costs are low.
- Replacement costs are low (mainly for batteries).

The LCC of the PV system includes the sum of all the present worths (PWs) of the costs of the PV modules, storage batteries, battery charger, and inverter, the cost of the installation, and the maintenance and operation cost (M&O) of the system. The details of the used cost data for all items are shown in **Table 2**.

The lifetime N of all the items is considered to be 25 years, except that of the battery which is considered to be 5 years. Thus, an extra 4 groups of batteries (each of 6 batteries) have to be purchased, after 5 years, 10 years, 15 years and 20 years assuming inflation rate i of 3% and a discount or interest rate d of 10%. Therefore, the PWs of all the items can be calculated as follows [6].

PV array cost $C_{\text{wh}} = C_{\text{Ah}} V_B C_{\text{PV}} = 60 \times 44 \times 200 = \text{Rs. } 528000$

Initial cost of batteries cells $C_B = 110 \times 5500 = \text{Rs. } 605000$

The PW of the 1st extra group of batteries (purchased after $N = 5$ years) C_{B1PW} can be calculated, to be Rs. 435479, from

$$C_{\text{B1PW}} = C_B \left(\frac{1+i}{1+d}\right)^N$$

The PW of the 2nd extra group of batteries (purchased after $N = 10$ years) C_{B2PW}, that of the 3rd extra group (purchased after $N = 15$ years) C_{B3PW}, 4th extra group of batteries purchased after $N = 20$ years C_{B4PW} are calculated to be Rs. 313450.5, Rs. 225665, Rs. 162563.5, respectively.

Charger cost $C_C = 258 \times 31 = \text{Rs. } 8000$

Inverter cost $C_{\text{Inv}} = 36 \times 7836 = \text{Rs. } 282096$

Installation cost $C_{\text{Inst}} = 0.1 \times 968000 = \text{Rs. } 52800$

Operation and maintenance cost per year = Rs. 10560

The PW of the maintenance cost C_{MPW} can be calculated to be Rs. 125355.5, using the maintenance cost per year (M/yr) and the lifetime of the system ($N = 25$ years), from

$$C_{\text{MPW}} = (\text{M/yr}) \times \left(\frac{1+i}{1+d}\right) \times \left[\frac{1-\left(\frac{1+i}{1+d}\right)^N}{1-\left(\frac{1+i}{1+d}\right)}\right]$$

Therefore, the LCC of the system can be calculated, to be Rs. 2613054, from:

$$\text{LCC} = C_{\text{PV}} + C_B + C_{\text{B1PW}} + C_{\text{B2PW}} + C_{\text{B3PW}} + C_C + C_{\text{Inv}} + C_{\text{Inst}} + C_{\text{MPW}}$$

It is sometimes useful to calculate the LCC of a system on an annual basis. The annualized LCC (ALCC) of the PV system in terms of the present day Rupees can be calculated, to be Rs. 206116.8/yr, from,

$$\text{ALCC} = \text{LCC}\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^N}\right]$$

Once the ALCC is known, the unit electrical cost (cost of 1 kWh) can be calculated, to be Rs. 17.5/kWh, from:

$$\text{Unit electrical cost} = \frac{\text{ALCC}}{365E_L}$$

6. Result and Discussion

Now, using the same procedure as given above, the cost of the PV system without batteries can be calculated by excluding the terms $C_B + C_{\text{B1PW}} + C_{\text{B2PW}} + C_{\text{B3PW}} + C_{\text{B4PW}}$ from the above calculations.

The unit cost of electricity for with and without batteries for different rates of PV modules is calculated using the same procedure as above and tabulated in **Table 3**.

The cost of electricity generated from solar photovoltaic system with batteries is calculated to be Rs. 22/kWh, whereas the cost of utility electricity supplied to consumers is approximately Rs. 6.8/kWh for domestic purpose. However, the cost of electricity generated from solar photovoltaic is decreasing rapidly as the initial cost of PV modules is coming down with time as shown in **Table 3**. As observed from **Table 3** and **Figure 3** that the cost of power generation from SPV systems is decreasing at a very fast rate. The cost of one unit of electricity generated from SPV system was Rs. 28 and Rs. 17 for with and without batteries respectively in 2007, when the cost of the PV modules was Rs. 150/W_p. The cost of PV modules has decreased to Rs. 100/W_p in 2012, consequently the cost of one unit electricity generated from SPV has also come down to Rs. 22 and Rs. 11 for with and without batteries respectively as presented in this chapter.

As shown in **Table 3**, if the cost of PV modules decreases to Rs. 60/W_p by 2017 and to Rs. 40/W_p by 2022, the cost of unit electricity generated from SPV systems would decrease drastically to Rs. 18 and Rs. 7 by 2017 and to Rs. 15 and Rs. 4 by 2022 for with and without batteries respectively. However, the price of electricity generated from SPV systems discussed above are without the 30% subsidy as provided by MNRE, government of India, if this 30% subsidy is also considered then the unit of electricity generated from SPV will further decrease as shown in **Table 3** above. At the same time, the cost of electricity generated from grid supply is in-

Table 3. Cost trends for spv systems.

Year	PV Panel Cost/W_p	Unit Cost of Electricity (INR)		Unit Cost of Electricity (INR)	
		With Battery		Without Battery	
		Without Subsidy	With 30% Subsidy	Without Subsidy	With 30% Subsidy
2007	150	28	19.6	17	11.9
2012	100	22	15.4	11	7.7
2017	60	18	12.6	7	4.9
2022	40	15	10.5	4	2.8

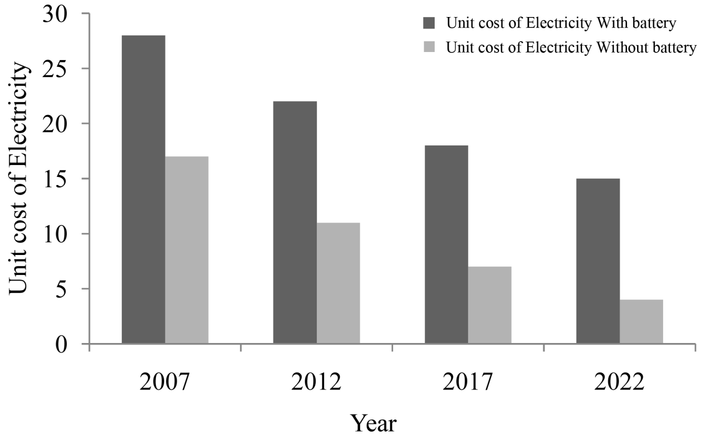

Figure 3. Cost trends for SPV systems.

creasing day by day, presently it is around Rs. 6.8/unit for domestic use. But in the near future, the cost of electricity generated from conventional fuels in India is expected to increase to around four times than its present value due to the rapid increase in the conventional fuel prices but the cost of unit electricity generated from SPV is decreasing as shown above. Hence SPV systems are expected to be a cheaper and good option for its use in residential purpose in the near future. Therefore the present results reflect the first order indication to energy planners in the near future. Hence the SPV power generation will be economically comparable to the grid connected power supply in the near future in India.

7. Conclusions

Proper utilization of renewable energy sources is very important worldwide especially in the developing countries like India. This study presents the complete design and the life cycle cost analysis of the PV system for single household application. The results of the study indicate that electrifying a single area household using PV systems is beneficial and suitable for long-term investments, because the initial prices of the PV systems are decreasing as the cost of PV panels is decreasing.

In this paper an electrification study for a single residential household is carried out using a standalone SPV system. The results of study reveal that although at present, the cost of electricity generated from SPV system is relatively high as compared to grid electricity but in the near future the cost of electricity from SPV systems will decrease rapidly and cost of electricity from grid is likely to increase. Also, the efficiency of the solar cells is increasing day by day which will make it further economical. As we know that solar power is one of the most promising and more predictable sources than other renewable sources and less vulnerable to change in seasonal weather. Whereas, generation of power from other renewable sources is limited to sites where these resources exist in sufficient quantities and can be harnessed, solar energy can produce power at the point of demand in both rural and urban areas. Hence, photovoltaic systems are considered as the most promising energy sources for these sites due to their high reliability and safety. Therefore, SPV system would be the better option for household electrification in India in the near future.

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