Assessing the Technical and Economic Feasibility of a Stand-Alone PV System for Rural Electrification: A Case Study

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ABSTRACT

Harnessing the solar energy to power electric appliances starts by converting the energy coming from the sun to electricity. Photovoltaic is the direct conversion of the solar energy into electricity. Exploiting of solar energy for domestic use is one avenue where the energy emitted from the sun is converted into electricity to power most if not all the appliances available at our homes and residences. Building a photovoltaic system is the process of designing, selecting and calculating the ratings of the equipments employed in the system. This paper presents a study on a stand-alone photovoltaic (PV) system to provide the required electricity for a single residential household in India. The complete design of the suggested system is carried out, such that the site radiation data and the electrical load data of a typical household in the considered site are taken into account during the design steps. Also, the life cycle cost (LCC) analysis is conducted to assess the economic viability of the system. The results of the study encouraged the use of the PV systems to electrify the rural sites in India.

Keywords- Renewable Energy Systems, Photovoltaic Stand-Alone Power System, PV array, storage battery.

I. INTRODUCTION

Renewable-energy sources are becoming more and more attractive especially with the constant fluctuation in oil prices. Solar has good potential and the direct conversion technology based on solar photovoltaic has several positive attributes especially in remote areas [1-4]. The Photovoltaic (PV) system is considered one of the important alternative sources in this regard. Because PV energy production is clean, freely infinitely available and of high reliability, it is a very attractive power source for many applications, especially in rural and remote areas in South Asian countries where they have a large quantity of solar radiation around the year.

India lies in the sunny belt of the world. The scope for generating power and thermal applications using solar energy is huge. Most parts of India get 300 days of sunshine a year, which makes the country a very promising place for solar energy utilization [5]. The daily average solar energy incident over India varies from 4 to 7 kWh/m^2 with the sunshine hours ranging between 2300 and 3200 per year, depending upon location [6]. The technical potential of solar energy in India is huge. The country receives enough solar energy to generate more than 500,000 TW h per year of electricity, assuming 10% conversion efficiency for PV modules.

India has successfully completed the plan for electrification for most of the villages through the utility grid. Due to remoteness and cost, for some parts of India it is unlikely that the main grid connection will ever be established. A stand-alone PV system with storage battery will be excellent choice for such areas [7].

Fig. 1 shows the suggested block diagram of the household stand-alone PV system. A photovoltaic (PV) cell converts sunlight into electricity. A PV or solar cell is the basic building block of a PV system. An individual PV cell is usually quite small. PV cells are connected together to form larger units called modules which can be connected to form even larger units called arrays. These arrays are connected in parallels and series to meet the required electricity demand. PV arrays produce power only when illuminated, and it is therefore standard to employ a large energy storage mechanism, most commonly a series of rechargeable batteries. To prevent harmful battery over-charge and over-discharge conditions and to drive AC loads, a charge controller and a converter must be implemented.

Kolhe et al employed a life-cycle cost (LCC) analysis of various mixes of PV and diesel generators for a school in India [8]. They concluded that a stand-alone PV system is the most viable option when the power needs for the school are minimal and that PV systems will become more competitive as their costs decline. Ajan et al explored the possibility of installing an off-grid system that mixes PV technology with a diesel generator for a school in the state of Sarawak in East Malaysia [9]. Their results provide a critical cost for PV technology below which it would be beneficial for the school to invest in a PV system. Nafeh designed a stand-alone PV system to supply electricity to a remote-area-household in Egypt [10]. The work studies a stand-alone photovoltaic (PV) system to provide the required electricity for a single residential household in Sinai Peninsula of Egypt. The complete design of the proposed system takes into consideration the site radiation data and the electrical load data of a typical household in the considered site.

Markvart noted that on a reasonable sunny site of insolation 20 $MJm^{-2}day^{-1}$, power produced from solar energy conversion technologies, PV and solar thermal, is significantly cheaper over extended use than that from diesel generators [11]. Ojosu argued that PV energy systems have special role to play in Nigeria power production, because of its substantial solar energy resources with daily solar radiation average of between 4 and 6 kW/m2/day [12]. Augustine and Nnabuchi showed that Port Harcourt city, which is located at the latitude of 04°40'N and longitude of 07°10'E, has adequate sunshine for PV and solar thermal technologies [13].

This paper presents a study on the design and economical analysis of a stand-alone PV system to provide the required electrical energy for a single residential household in India. The site selected for study is a rural area in Pune district which is situated at a latitude of 18°32'N and longitude of 73°51'E. The Pune district has an area of 14642 sq. km. It is located at latitude 18° to 19.2° (average 18.6°or 18° 36' north) and longitude 73.2° to 75.1° (average 74.15° or 74° 9'east). It is one of the largest districts in Maharashtra, India having good sunshine throughout the year.

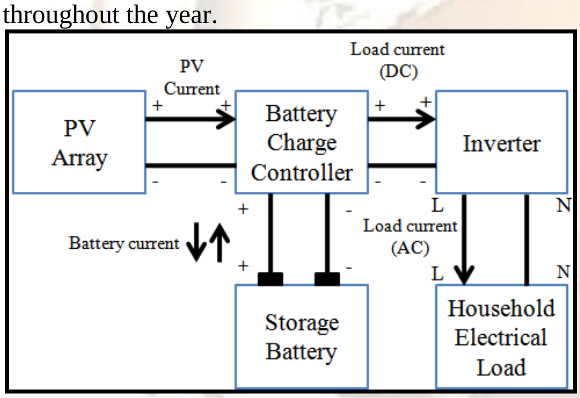

Fig. 1: The stand-alone PV system.

II. SITE METEOROLOGICAL DATA

To predict the performance of a PV system in a site, it is necessary to collect the meteorological or environmental data for the site location under consideration. National Renewable Energy Laboratory (NREL) [14] is a good source for these data. J. Polo et al. have also calculated the solar radiation over India using Meteosat satellite images [15]. The monthly average daily solar radiation data incident on horizontal plane of the site is shown in Fig. 2. It is clear from the figure that solar energy incident in the considered site is very high especially during the summer months, where it reaches 7 kWh/m^2/day on horizontal plane.

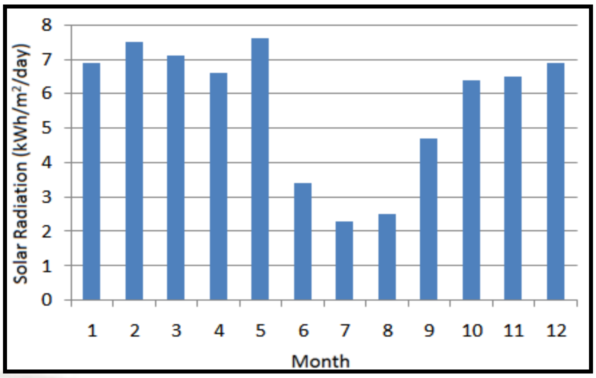

Fig. 2: Monthly average daily global radiation in Pune

III. ELECTRICAL DEMAND

Table 1: The Household Load Data

Electrical Load	Wattages (Watt)	Operating Hours Per Day	Daily Load (Wh/Day)
5 Lamps	5x40	4 lamps:17-22 1 lamp: 22-7	1000+360= 1360
2 Fans	2x100	12-17 & 20-6	3000
TV	80	12-15 & 19-22	480
Refrigerator	100	0-24	2400
Water Pump	120	12-14	240

The household in the remote area in Pune is assumed to be simple, not requiring large quantities of electrical energy. The electrical loads include lighting, ceiling fans, a water pump and other ordinary household electrical appliances. The daily electrical demand in a typical day for each device is shown in Table 1. It is assumed that this load is constant around the year. The corresponding load profile for a typical day is indicated in Figure 3. The average daily load demand EL can be calculated from Table 1 to be 7480 Wh/day. The corresponding load profile for a typical day is indicated in Fig. 3.

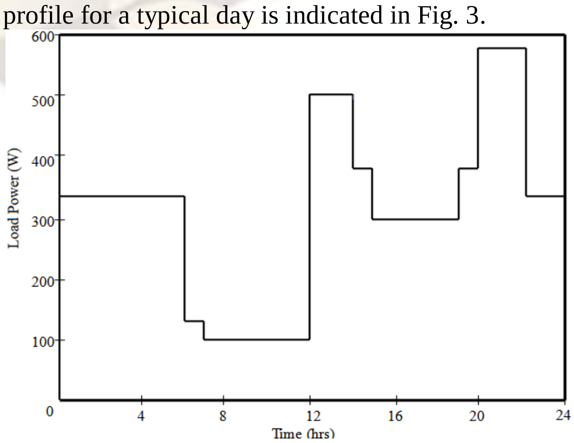

Fig. 3: The load profile of the household.

IV. PV SYSTEM DESIGN

To design a stand-alone PV system for the considered household, the following steps are required.

4.1. The Average Daily Solar Energy Input

Fig. 2 can be used to calculate the average daily solar energy input over the year (G_{av}) on a south facing surface tilted at an angle equal to the site latitude to be about 5.7 kWh/m^2/day.

4.2. The Average Daily Load Demand

The average daily load demand E_L can be calculated from Fig. 3, to be 7480 Wh/day.

4.3. Sizing of the PV Array

The size of the PV array, used in this study, can be calculated by the following equation [6]:

$$PV\ area = \frac{E_L}{G_{av} \times \eta_{PV} \times TCF \times \eta_{out}} \qquad (1)$$

Where,
Gav = average solar energy input per day
TCF = temperature correction factor
η_{PV} = PV efficiency
η_{out} = battery efficiency (η_B) x inverter efficiency (η_{Inv})

If the cell temperature is assumed to reach 60^{o}C in the field, then the temperature correction factor (TCF) will be 0.8 as indicated in [16]. Assuming η_{PV} = 12% and η_{out} = 0.85 x 0.9 = 0.765. Thus, using Eq. (1) the PV area is 11.3 m^2. The PV peak power, at peak solar insolation (PSI) of 1000 W/m2, is thus given by [16, 17]:

$$PV\ Peak\ power = PV\ area \times PSI \times \eta_{PV} = 1356\ W_P \qquad (2)$$

The selected modules are mono-crystalline silicon, with the following specifications at standard test conditions (i.e., 1000 W/m^2 and 25^{o}C):

- Peak power: 23.2 W_P
- Peak-power voltage: 9.6 V
- Peak-power current: 2.4167 A

Thus, 60 modules are used to supply the required energy for the residential house. The series and parallel configuration of the resulted PV array can be adjusted according to the required DC bus voltage and current, respectively. If the DC bus voltage is chosen to be 24 V, then 3 modules will be connected in series and 20 strings (each of 3 modules in series) will be connected in parallel.

4.4. Sizing of the Battery

The storage capacity of the battery can be calculated according to the following relation [17, 18]:

$$Storage\ Capacity = \frac{N_C \times E_L}{DOD \times \eta_{out}} \qquad (3)$$

Where,
N_C = largest number of continuous cloudy days of the site
DOD = maximum permissible depth of discharge of the battery

The largest number of continuous cloudy days NC in the selected site is about 4 days. Thus, for a maximum depth of discharge for the battery DOD of 0.8, the storage capacity becomes 35948 Wh (3). Since, the selected DC bus voltage is 24 V, then the required ampere-hours of the battery = 35948/24 ≈ 1500 Ah. If a single battery (Vision 6FM250D) of 12 V and 250 Ah is used, then 2 batteries are connected in series and 3 strings of batteries are connected in parallel; to give an overall number of 6 batteries.

Table 2: The Used Cost Data of All Items

Item	Cost
PV	$5/WP
Battery	$1.705/Ah
Charger	$5.878/A
Inverter	$0.831/W
Installation	10% of PV cost
M&O/Year	2% of PV cost

4.5. 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 50 A (i.e., 2.5A x 20) and to maintain the DC bus voltage to about 24 V.

4.6. 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 that presented in Table 1. Thus the rated power of the inverter becomes 1020 W. The specifications of the required inverter will be 1020 W, 24 V_{DC}, 220 V_{AC} and 50 Hz.

V. LIFE CYCLE COST ANALYSIS

In this section the life cycle cost (LCC) estimation of the designed stand-alone PV system is discussed. The LCC of an item consists of the total costs of owning and operating an item over its lifetime, expressed in today's money [11, 17-20]. The costs of a stand-alone PV system include acquisition costs, operating costs, maintenance costs, and replacement costs. All these costs have the following specifications [11]:

- 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, 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 [9, 16, 20, 21].

The lifetime N of all the items is considered to be 20 years, except that of the battery which is considered to be 5 years. Thus, an extra 3 groups of batteries (each of 6 batteries) have to be purchased, after 5 years, 10 years, and 15 years, assuming an 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 [11, 19]:

- PV array cost CPV = 5 x 60 x 23.2 = $6960
- Initial cost of batteries CB = 1.705 x 1500 = $2557.5

The PW of the 1st extra group of batteries (purchased after N = 5 years) CB1PW can be calculated, to be $1840.93, from:

$$C_{B1PW} = CB\left(\frac{1+i}{1+d}\right)^N \qquad (4)$$

The PW of the 2nd extra group of batteries (purchased after N = 10 years) C_{B2PW} and that of the 3rd extra group (purchased after N = 15 years) CB3PW are calculated, using Eq. 4, to be $1325.14 & $953.86, respectively.

- Charger cost C_C = 5.878 x 50 = $293.9
- Inverter cost C_{Inv} = 0.831 x 1020 = $847.62
- Installation cost C_{Inst} = 0.1 x 6960 = $696
- The PW of the maintenance cost C_{MPW} can be calculated to be $1498.35, using the maintenance cost per year (M/yr) and the lifetime of the system (N = 20 years), from [19]:

$$C_{MPW} = (M/yr)\ x \left(\frac{1+i}{1+d}\right) x \left[\frac{1-\left(\frac{1+i}{1+d}\right)^N}{1-\left(\frac{1+i}{1+d}\right)}\right] \qquad (5)$$

Therefore, the LCC of the system can be calculated, to be $16973.3, from:

$$L_{CC} = C_{PV} + C_B + C_{B1PW} + C_{B2PW} + C_{B3PW} + C_C + C_{Inv} + C_{Inst} + C_{MPW} \qquad (6)$$

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 dollars can be calculated, to be $1476.51/yr, from [11, 18]:

$$ALCC = LCC\ x \frac{\left[1-\left(\frac{1+i}{1+d}\right)\right]}{\left[1-\left(\frac{1+i}{1+d}\right)^N\right]} \qquad (7)$$

Once the ALCC is known, the unit electrical cost (cost of 1 kWh) can be calculated, to be $0.74/kWh, from:

$$\text{Unit electrical cost} = \frac{ALCC}{365 \text{ x } E_L} \qquad (8)$$

Therefore, in remote sites that are too far from the Indian power grid, the PV installers are encouraged to sell the electricity of their PV systems at a price not lower than $0.74/kWh to earn a profit. It is to be noted, here, that although this price is very high compared to the current unit cost of electricity in India ($0.1/kWh), this price will drop to $0.49/kWh if the future initial cost of the PV modules drops to $0.1/WP. At the same time, if the future unit cost of electricity in India becomes five times its current value, due to the rapid increase in the conventional fuel prices, therefore PV energy generation will be promising in the future household electrification (in India) due to its expected future lower unit electricity cost, efficiency increase, and clean energy generation compared to the conventional utility grid.

VI. Conclusion

Electrification of remote and rural sites worldwide is very important especially in the developing countries like India. The photovoltaic systems are considered as the most promising energy sources for these sites, due to their high reliability and safety. They represent, at the same time, a vital and economic alternative to the conventional energy generators. An electrification study for a single residential household in a remote rural site of Pune district is carried out using a stand-alone PV system. This study presents the complete design and the life cycle cost analysis of the PV system. The results of the study indicate that electrifying a remote rural household using PV systems is beneficial and suitable for long-term investments, especially if the initial prices of the PV systems are decreased and their efficiencies are increased.

References

[1] A. Guglielmo, S. Stefano Redi, A. Tatnall and T. Markvart, "Harnessing High-Altitude Solar Power," *IEEE Transactions Energy Conversion*, 24(2), 2009, 442-451.

[2] G. C. Bakos and M. Soursos, "Techno-Economic Assessment of a Stand-Alone PV/Hybrid Installation for Low-Cost Electrification of a Tourist Resort in

Greece," *Applied Energy*, 73(2), 2002, 183-193.

[3] W. M. Rohouma, I. M. Molokhia and A. H. Esuri, "Comparative Study of Different PV Modules Configuration Reliability," *Desalination*, 209(1-3), 2007, 122-128.

[4] D. Lowe and C. R. Lloyd, "Renewable Energy Systems for Remote Areas in Australia," *Renew Energy*, 22(1-3), 2001, 369-378.

[5] *Survey of renewable energy in India* (Tata Energy Research Institute, New Delhi, 2001).

[6] *Renewable energy in India* (MNES report, Government of India, 2001).

[7] Mani, A., *Handbook of solar radiation data for India* (Allied Publishers, New Delhi, India, 1980).

[8] Kolhe M, Kolhe S and Joshi JC, "Economic Viability of Stand-alone Solar Photovoltaic System in Comparison with Diesel-powered System for India", *J. Energy Economics*, 24 (2), 2002, 155-165.

[9] Ajan CW, Ahmed SS, Ahmad HBTF and Mohd Zin AAB, "The Policy of Photovoltaic and Diesel Generation Mix for an Off-grid Site: East Malaysian Perspectives", *J. Solar Energy*, 74, 2003 453-467.

[10] Nafeh, A.A., "Design and Economic Analysis of a Stand-alone PV System to Electrify a Remote Area Household in Egypt", *Open Renewable Energy J.*, 2009, 2, 33-37.

[11] Markvart T. *Solar electricity* (Wiley, London, 2000).

[12] Ojosu JO, "The Iso-radiation Map for Nigeria", *J. Solar and Wind Tech.*, 7 (5), 1990, 563-575.

[13] Augustine C and Nnabuchi MN, "Relationship etween Global Solar Radiation and Sunshine Hours for Calabar, Port Harcourt and Enugu, Nigeria", *Int. Journal of Physical Sci.*, 4 (4), 2009, 182-188.

[14] http://mnre.gov.in/sec/solar-assmnt.htm

[15] J. Polo, L. F. Zarzalejo, M. Cony et al., "Solar Radiation Estimations over India using Meteosat Satellite Images," *Solar Energy*, 85(9), 2011, 2397–2402.

[16] Alamsyah T.M.I., Sopian K., Shahrir A., "Technoeconomics Analysis of a Photovoltaic System to Provide Electricity for a Household in Malaysia", *Proceedings of the International Symposium on Renewable Energy: Environment Protection & Energy Solution for Sustainable Development*, Kuala Lumpur, Malaysia, 2003, 387-396.

[17] Mahmoud M.M., Ibrik I.H., "Techno-economic Feasibility of Energy Supply of Remote Villages in Palestine by PV-systems, Diesel Generators and Electric Grid", *Renewable Sustainable Energy Rev.*, 2006, 128-138.

[18] Wenham S.R., Green M.A., Watt M.E., *Applied photovoltaics* (Center for Photovoltaic Devices and Systems: Australia, 1994).

[19] Messenger R., Ventre J., *Photovoltaic systems engineering* (CRC Press LLC: Boca Raton, Florida, USA, 2000).

[20] Celik A.N. "Present status of photovoltaic energy in turkey and life cycle techno-economic analysis of a grid-connected photovoltaic-house", *Renewable Sustainable Energy Rev.*, 10, 2006 370-387.

[21] Celik A.N., "Effect of Different Load Profiles on the Loss-of-load Probability of Stand-alone Photovoltaic Systems", *Renewable Energy*, 32, 2007, 2096-2115.