Optimized Load Profile & Cost Analysis of Stand-alone Photovoltaic System for Rural Power Applications in Indian Scenario

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ABSTRACT
The energy demand across the world has increased in many decades due to the advancement of technology. A solar PV system can supply electrical power both in grid-connected and standalone mode. This paper presents an economic analysis of solar PV stand-alone systems for rural areas in India. Based on load profiles, a stand-alone system has been designed and simulated for rural areas of Jodhpur location. These systems are designed to provide solar electricity for small rural household using different load profiles. In this work, four types of load profiles are under consideration for the actual performance assessment of the system. Battery bank and PV modules size estimated for all load profiles under same environmental conditions. An optimized load profile is proposed and a standalone PV system designed to investigate its performance. The cost analysis shows that the optimized load profile type system is the most economical design for a standalone PV system.

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1. Introduction
India generates a major portion of its electrical power from conventional energy sources like coal, diesel, etc. [1–4]. However, conventional energy sources are limited in quantity, and due to the ever-increasing demand for energy, power sector cannot remain solely dependent on fossil fuel to accomplish its energy needs. Renewable energy resources such as PV, wind, etc. generates enormous energy, which is even devoid of any pollution. In fact, the renewable energy sources are the fastest growing energy sources around the world, and it is expected that it will increase 2.6% per year by 2040. India ranks fifth among renewable energy producing countries. Due to increasing emphasis towards solar, India is implementing strategies and policies to promote solar energy all over the country [5–8]. Many villages in India do not have electricity for more than six to eight hours a day, EU report says. High demand by metro cities and industries in India makes power availability for rural areas scarce. Under this condition, development of an alternate power supply in the form of solar PV system can be a solution. Since there are many remote areas in India with no access to electricity, stand-alone PV can be one of the best solutions and a logical alternative to supply power in rural areas.
Now, India is focusing on boundless financial assistance to carry out research and development programs in the field of renewable energy, including feasibility study analysis, modeling, control and experimental works. Optimizing the size and feasibility analysis of stand-alone PV systems, either for a field mounted, or rooftop must have a concern in the research area of solar energy [9–12]. Researchers studied different techniques for optimization of hybrid and standalone photovoltaic systems and concluded that every sizing method has its quality, potential and user's requirements [13–19]. At present, the existing power of a typical standalone photovoltaic system in India is 0.5–2.0 kW. These types of PV systems are providing power to the rural household, telecom installations, irrigation pump systems and lighting loads.

The basic need for standalone PV system is; it must be optimally designed to supply load demand in a defined availability of solar radiation [20,21]. The consumer load profile plays an imperative role in optimally designing a PV system. In this research work, an optimized load profile and cost analysis for standalone PV system are investigated for the rural location of Jodhpur (Latitude 26.30°N, Longitude 73.02°E) India. PVSyst simulation software is used to predict solar radiation and estimate the generated solar power for a specified location and subsequently design the system [22–27]. It is also used to determine a requisite PV module and battery bank size for a specific load profile.

In this work, four different types of load profiles are created to analyze the economic aspects of standalone PV systems according to consumer needs. For load profile -I, it is assumed that consumer demands a 24 h power supply. Second and third type of load profile shows that user needs power only 8 h during daytime & nighttime respectively. A fourth variety of load profile is an optimized load profile (OLP) which is proposed for the consumers of rural India addressing all their major needs. As per the availability of the solar insolation and according to the load profile, the optimum PV system rating with battery capacity estimated using PVSyst simulation tool. Further, the cost analysis of all the designed stand-alone PV systems is carried out. The optimized load profile is helpful to reduce the cost of stand-alone PV systems in the Indian scenario.

The organization of this paper is as follows. Section 1 contains the introduction of this paper. A standalone PV system and its operational challenges are described in Section 2. In Section 3, the introduction of load profile is given with three different types of load profiles. Section 4 proposes an optimized load profile with its features. Designing of standalone PV systems according to all four type load profiles and size estimation of the PV system is discussed in Sections 5 and 6. Performance and cost of the standalone PV system are analyzed in the Sections 7 and 8.

2. Standalone PV System

A standalone photovoltaic system comprises a PV array, storage battery bank, charge controller, inverter, and AC load. PV modules are connected in parallel and series; called a PV array as illustrated in Figure 1. A standalone solar PV system receives the solar radiation and converts it to DC power using solar modules. This solar DC power charges the battery bank associated with the system and convert solar DC power into AC power with the help of inverter to supply AC loads.

2.1. Challenges of Stand-alone Solar PV Systems

- Installations of solar PV stand-alone systems are quite expensive in comparison of grid-connected systems. These types of PV systems strictly need an energy storage device (battery) to store PV energy. The power providing capacity of these systems is bounded because of associated battery bank size. The energy storing components are costly which increases the system cost.
- As per capital availability, the land is a secret reserve in India. The requirement of the large land area is another challenge for solar PV systems. The space requirements of solar PV stand-alone systems are different, and sometimes not feasible. Standalone PV systems require space for PV modules as well as battery bank also. Space requirements for standalone PV systems are greater as compared to grid-connected PV systems.
- The maintenance of solar stand-alone PV systems is also high. Storage components in the systems like battery bank require high maintenance. It also needs to be replaced in about every three years. Conduction and ohmic losses are also present in both DC as well as AC side of the system. DC side involves much thick cables to flow current, specifically the batteries need thick connecting cables to link up to the system. On increasing the DC components, the system maintenance, and conduction losses are correspondingly high.

3. Consumer Load Profiles

A load profile graph or data shows the variation of consumer load concerning with time. Three (Commercial, Residential, and Industrial) load profiles exist in the literature [28–33]. The pattern of load profile is highly
dependent on atmospheric temperature and holidays. Usually, power-producing units use this load profile data to generate optimum power conferring to the need of the consumers.

Standalone photovoltaic systems are strictly dependent on solar radiation to generate the electrical power. The consumer load profile determines energy demands of the consumer and this energy demand decides the size of PV system. The cost of standalone system strictly depends on the load, which is to be run by photovoltaic electrical power. In this work, a standalone PV system is designed according to consumer load profile, and four type of load profiles are considered. LP-I, LP-II & LP-III type load profiles are a general type of load profiles according to the general perception of the consumer. The proposed LP-IV type load profile is for rural households consumers in the Indian scenario.

According to all four type load profiles, four PV systems are designed and simulated in PVSyst simulation environment. PVSyst simulation calculates the PV system

Table 1. List of Domestic Equipments used by Rural Indian Consumers.

| Load            | Quantity | Power consumption (W) |
|-----------------|----------|-----------------------|
| Lamp (LED)      | 10       | 20                    |
| Fan             | 5        | 60                    |
| TV/PC           | 2        | 80                    |
| Domestic appliances | 5   | 60                    |
| Other uses      | 5        | 60                    |
| Total           |          | 1600                  |

Table 2. Load profile-I (LP-I).

| Load            | Quantity | Power consumption (W) | Total power (W) | Uses (h/day) | Energy required (Wh/day) |
|-----------------|----------|-----------------------|-----------------|-------------|-------------------------|
| Lamp (LED)      | 10       | 20                    | 200             | 24          | 4800                    |
| Fan             | 5        | 60                    | 300             | 24          | 7200                    |
| TV/PC           | 2        | 80                    | 160             | 24          | 3840                    |
| Domestic appliances | 5   | 60                    | 300             | 24          | 7200                    |
| Other uses      | 5        | 60                    | 300             | 24          | 7200                    |
| Total           |          |                       | 1600            |             | 30,240                  |

Table 3. Load profile-II (LP-II).

| Load            | Quantity | Power consumption (W) | Total power (W) | Uses (h/day) | Energy required (Wh/day) |
|-----------------|----------|-----------------------|-----------------|-------------|-------------------------|
| Lamp (LED)      | 10       | 20                    | 200             | 8           | 1600                    |
| Fan             | 5        | 60                    | 300             | 8           | 2400                    |
| TV/PC           | 2        | 80                    | 160             | 8           | 1280                    |
| Domestic Appliances | 5   | 60                    | 300             | 8           | 2400                    |
| Other Uses      | 5        | 60                    | 300             | 8           | 2400                    |
| Total           |          |                       | 1600            |             | 10,080                  |

Figure 1. Standalone solar PV system.
rating and required battery bank according to consumer load profiles. The total annual PV power generation, battery SoC, and performance ratio are determined. The performance of the stand-alone photovoltaic system is carried out for four different load profiles described as follows. The list of basic home appliances often used by rural Indian consumers with their net power consumption is shown in the Table 1.

### 3.1. Load Profile-I

In this type of load profile (LP-I), it is assumed that the consumer needs electrical power for 24 h. The average availability of solar energy is 6 to 8 h/day during the whole year. A stand-alone photovoltaic system rigorously depends on the battery bank size to supply electrical power continuously. The large size battery bank greatly increases the cost of the system. Table 2 shows the total energy needed and operating hours of electrical equipment per day.

### 3.2. Load Profile-II

Under the load profile (LP-II) it is expected that consumer requires power for 8 h in the only daytime; specifically, 9 am to 5 pm. In this, the size of battery bank may be small as compared to other load profiles, due to reason that the sun is available for most of the time when power is required. Specifications illustrated in Table 3.

### 3.3. Load Profile-III

The third type of load profile (LP-III) shows that user needs the electrical power only at night time, i.e. 9 pm to 5 am. A large size battery bank is required to supply power during night time as the solar energy is available only in the daytime. This kind of load profile may increase the cost of the standalone system; related information is as shown in Table 4.

| Load       | Quantity | Power consumption (W) | Total power (W) | Uses (h/day) | Energy required (Wh/day) |
|------------|----------|------------------------|-----------------|--------------|--------------------------|
| Lamp (LED) | 10       | 20                     | 200             | 8            | 1600                     |
| Fan        | 5        | 60                     | 300             | 8            | 2400                     |
| TV/PC      | 2        | 80                     | 160             | 8            | 1280                     |
| Domestic appliances | 5 | 60                     | 300             | 8            | 2400                     |
| Other uses | 5        | 60                     | 300             | 8            | 2400                     |
| Total      |          |                        | 1600            |              | 10,080                   |

### Table 5. Proposed optimized load profile.

| S. No. | Load                  | Quantity | Power consumption (W) | Total power (W) | Operating time | Uses (h/day) | Energy required (Wh/day) |
|--------|-----------------------|----------|------------------------|-----------------|---------------|--------------|--------------------------|
| 1      | Lamp (LED)            | 10       | 20                     | 200             | 8hDayTime     | 20           | 4000                     |
|        |                       |          |                        |                 | 12hNightTime  |              |                          |
| 2      | Fan                   | 4        | 60                     | 240             | 10hDayTime    | 20           | 4800                     |
|        |                       |          |                        |                 | 10hNightTime  |              |                          |
| 3      | TV/PC                 | 2        | 80                     | 160             | 6hDayTime     | 8            | 1280                     |
|        |                       |          |                        |                 | 2hNightTime   |              |                          |
| 4      | Domestic Appliances   | 5        | 100                    | 500             | 4hDayTime     | 5            | 2500                     |
|        |                       |          |                        |                 | 1hNightTime   |              |                          |
| 5      | Other Uses            | 5        | 100                    | 500             | 2 h Day Time  | 2            | 1000                     |
| Total  |                       |          |                        | 1600            |               |              | 13,580                   |

**Figure 2.** Optimize load profile curve.
4. Optimised Load Profile (Load Profile-IV)

The load profile is optimized by scheduling the operating time of electrical equipment depending on user's requirement and solar PV availability. That is; by the scheduling of operating time, the cost of the standalone system optimized. Consumer load profile helps the PV system designer to decide the size of the battery bank. Optimized load profile (LP-IV) reduces the battery storage requirement, thus optimizing the cost of the standalone photovoltaic system. Table 5 illustrates the optimized load profile and Figure 2 shows the optimized load curve.

4.1. Features of Optimized Stand-alone Solar PV Systems

(a) This optimized load profile has beauty to provide electrical power at daytime as well as night time efficiently. The consumer can use electrical power generated by optimized solar PV system by paying an optimized cost.

(b) The cost of Solar PV stand-alone system reduces by optimizing the PV system size. Optimized load profile scales down the size of the battery bank and the system size, which reduces the cost. Thus, the designing of PV system according to optimized load profile jumps the barrier of high cost.

(c) As the size of standalone PV system reduced by optimized load profile, the problem of crises of land may be partly resolved. The optimized standalone PV system requires lesser space to install.

(d) The maintenance of solar stand-alone PV systems also goes down due to the lesser energy storing components. The interference of conduction and ohmic losses are also reduced.

5. Standalone PV System Design According to Load Profiles

Designing of standalone PV system is quite difficult due to the calculations associated with storage banks [34]. Standalone PV systems are designed considering that there must be some spare solar modules installed in addition to the load side demand. This extra power demand is required for charging the battery bank properly. According to an industrial opinion, size of standalone PV system should be taken 25% higher than required load value to charge the battery bank connected with PV system.
Table 11. Simulation results of LP-III.

| Month      | Incident solar radiation (kWh/m²) | PV power generated (kWh) | SOC (%) | Performance ratio (%) |
|------------|----------------------------------|--------------------------|---------|-----------------------|
| January    | 6.0                              | 326.9                    | 29.0    | 6.7                   |
| February   | 6.6                              | 329.7                    | 38.0    | 1.9                   |
| March      | 6.9                              | 380.7                    | 49.0    | 0.0                   |
| April      | 6.8                              | 364.0                    | 66.0    | 0.0                   |
| May        | 6.5                              | 359.3                    | 65.0    | 0.0                   |
| June       | 5.7                              | 274.3                    | 39.0    | 4.0                   |
| July       | 5.0                              | 275.1                    | 28.0    | 12.7                  |
| August     | 5.0                              | 323.4                    | 28.0    | 12.3                  |
| September  | 6.1                              | 356.0                    | 31.0    | 5.6                   |
| October    | 5.8                              | 306.6                    | 43.0    | 1.1                   |
| November   | 5.8                              | 307.9                    | 29.0    | 8.5                   |
| December   | 5.9                              | 323.9                    | 29.0    | 6.9                   |
| Year       | 6.1                              | 3922.7                   | 39.0    | 5.0                   |

Table 12. Simulation results of LP-IV.

| Month      | Incident solar radiation (kWh/m²) | PV power generated (kWh) | SOC (%) | Performance ratio (%) |
|------------|----------------------------------|--------------------------|---------|-----------------------|
| January    | 6.0                              | 349.2                    | 36.0    | 2.2                   |
| February   | 6.6                              | 352.2                    | 36.0    | 0.3                   |
| March      | 6.9                              | 406.7                    | 82.0    | 0.0                   |
| April      | 6.8                              | 388.8                    | 93.0    | 0.0                   |
| May        | 6.5                              | 383.9                    | 91.0    | 0.0                   |
| June       | 5.7                              | 323.4                    | 66.0    | 0.0                   |
| July       | 5.0                              | 293.0                    | 28.0    | 15.2                  |
| August     | 5.0                              | 323.4                    | 25.0    | 23.3                  |
| September  | 6.1                              | 293.8                    | 39.0    | 3.2                   |
| October    | 5.8                              | 345.5                    | 44.0    | 5.0                   |
| November   | 5.8                              | 327.3                    | 44.0    | 2.2                   |
| December   | 5.9                              | 346.0                    | 27.0    | 7.2                   |
| Year       | 6.1                              | 4190.5                   | 51.0    | 5.0                   |

6. Generation Estimation of PV Power Using PVSyst Simulation

PVSyst simulation tool estimates the yearly generation of the designed stand-alone PV systems. All four load profile based stand-alone PV systems are simulated, and monthly PV power generation is estimated according to the availability of incident solar radiation. Month-wise battery state of charge (SOC) and performance ratio are also calculated for the performance, discussed in the next section. Simulation results of all four types of stand-alone PV systems are given in the Tables 9–12.

7. Performance Evaluation of SPV Systems Based on Load Profiles

7.1. Performance Evaluation Indices

Performance of all four types of load profiles based designs of stand-alone PV systems is analyzed with the help of performance evaluation indices discussed below.

(a) Incident solar radiation

Incident solar radiation is the amount of sun’s energy incident on the surface of the earth per unit area, defined in a unit of kW/m². Solar radiation is scattered, reflected and absorbed by the atmosphere before reaching the earth surface. Thus, the amount of radiation reaching to the earth surface is less than what falls on the atmosphere. The amount of solar radiation reaching the earth surface is called direct radiation and rest part of the radiation is called diffused radiation.

(b) PV power generation

After scattering, reflection and absorption the solar radiation falls on the photovoltaic panels which directly converts solar energy into electrical energy. The PV power generation also depends on the efficiency of the PV modules. The efficiency of PV system is the ratio of the output
electrical power (Watt) and the incident radiation (W/m²), described in equation 1.

\[ \eta = \frac{\text{Output Electrical Power}}{\text{Incident Radiation}} \times 100 \]  

(1)

where \( \eta \) is efficiency

(c) Performance ratio (PR)

Performance ratio significantly defines the efficiency of solar PV plant. The performance ratio informs that how energy efficient and reliable the designed solar PV system is. Mathematically it is the ratio of actual and theoretical possible output energies as illustrated in equation 2.

\[ PR = \frac{\text{Actual Reading of Plant Output}}{\text{Calculated Plant Output}} \times 100 \]  

(2)

This ratio describes the quality of power, and it does not depend on incident solar isolation, orientation angle & location of the PV system. Greater the value of PR (close to 100%) indicates a higher efficiency of the PV system. High-performance PV systems work on PR close to 80% because of heating, and ohmic losses in the system.

(d) State of charge (SOC)

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![Figure 3. Performance analysis of LP-I type PV system.](image)

![Figure 4. Performance analysis of LP-II type PV system.](image)

![Figure 5. Performance analysis of LP-III Type PV system.](image)
In solar PV applications, SOC indicates the charging status of the battery bank. The SOC (State of Charge) is a sign of safe operations of batteries. It can be determined by measuring the specific gravity of acid or by terminal limit voltage. It is not an indication of the quality of battery (Capacity in Ah).

7.2. Performance Analysis

The performance of the specifically designed standalone photovoltaic system is investigated for all four kinds of load profiles. Figures 3–6 show yearly incident solar radiation and monthly power generation. PVSyst simulation tool predicts the percentage of SOC (state of charge) with system PR. Maximum PV power is generated in the month of March 1123.8 kWh with highest SOC 88% and minimum in July, i.e. 809.7 kWh for the LP-I type of load profile. However, the PR of the system shows high value 21.6% in August. Second and third kind of load profiles shows approximately same simulation results except for the SOC percentage and PR as observed in Figures 4 and 5.

Simulation results of optimized load profile are illustrated in the Table 12. Figure 6 describes the monthly availability of solar energy, user's need, average state of charge (SOC) of batteries and the average probability of loss of load. It is expected that the SOC for LP-II should
be less than LP-III because LP-II type profile operating
electrical equipment in daytime only. Average battery
SOC for LP-I, LP-II & LP-III are 48.8, 77.6, and 39.4%
respectively as shown in Figures 3–5. A lower value of
SOC in LP-I & LP-III profiles is because it requires power
at night time also. The average SOC of LP-IV type profile
is 50.9% with an average probability of loss 5.0%
shown in Figure 6.

8. Cost Analysis & Indian Policies for SPV
Systems

8.1. Cost Analysis

The optimum PV system rating with battery capacity for
each load profile is estimated and shown in Table 17. The
breakup of investment with each load profile is described
in Tables 13–16. It is observed that LP-I type load pro-
file requires a much higher amount of investment (Rs. 4,
90,000/-) compared to other profiles, because of large PV
power and battery bank size associated with this type of
PV system. LP-II type of profile based system needs the
least amount (Rs. 1,54,000/-) of investment as the battery
size is small. The investments on LP-III & LP-IV type of
profiles is comparable to each other and have a difference
of Rs. 4,000/- only as illustrated in Table 17; with this
negligible difference amount in the cost of LP-III & LP-IV
type profiles, there are several advantages of LP-IV type
profile over LP-III load profile such as availability of power
in the daytime as well as night time. It is also observed
that by an increase in load demand, the size of PV power
and battery bank increases, resulting in an increment in
the investment cost.

Component wise investment cost and a total invest-
ment of PV system for all four types of load profiles are
shown in Figures 7 and 8. The need for a large amount
of energy boost ups the investment cost. In component
investment cost analysis on increasing the size of PV
system structure cost also increases. However, inverter,
structure, and cable investment cost for LP-II, LP-III &
LP-IV type profiles are the same. The system cost of LP-IV
type profile is slightly higher than LP-III type (Rs. 4000/-)
load profile, but LP-IV type profile based systems are more
reliable and beneficial in terms of investment cost. The
slightly higher system cost of LP-IV type load profile sys-
tems can be a trade-off for using the facility of power in
the daytime as well as in night time.

8.2 Policies Supported by Government of India for
SPV Systems Installations

India is ranked 11th in production of solar energy based
power generation in the world. The Indian government is
now taking initiatives and implementing policies to pro-
mote the solar power. The Electricity act 2003 promotes
co-generation to generate electricity from renewable
energy sources. This act is also boosting the development
programmes of renewable energy throughout the coun-
try. The central government is also planning to propose
some tariff plans to make the sale and purchase of elec-
tricity transparently. The national electricity policy 2005
promotes distribution companies to increase the share
of non-conventional sources by competitive purchasing
process. The tariff policy 2006 directs that the distribution
companies shall purchase a minimum amount of electric-
ity from renewable energy based generation units in that
region on an appropriate tariff. In 2009, Jawaharlal Nehru
National Solar Mission (JNNSM) was launched with
the target to grid-connect twenty thousand megawatts
(20,000 MW) of solar powered energy by 2022 in three phases. In 2015, the Union Cabinet of India approved to scale up India’s solar power generating capacity by five times, i.e. 100 GW by 2022. The Indian government is also providing a subsidy of Indian rupees 150000 million to install rooftop solar PV systems in several cities of the country. However, the government of India does not have and tariff or other promoting policy to sell solar electrical power generated by rural or urban costumes. Unavailability of the grid is also a barrier to the implementation of grid-connected PV systems. Therefore, a standalone PV system is the best solution to provide electrical power in rural areas in the Indian scenario.

9. Conclusion

In this research work, the performance and cost analysis of standalone PV system is investigated. This work would help the interested solar researchers and PV system designers to optimize PV system size and analyze the investment cost considering the load profile conditions parameters. A standalone PV system is designed according to the load profile, and cost analysis is performed using PVsyst simulation. Four different types of load profiles are considered. The LP-I type load profile system is much expensive as expected. The only advantage of LP-II type based PV system is affordable to middle-class income group consumers residing in the rural areas of India, but it does not have an appreciable battery backup. LP-II type profile system is suitable for small shops, which do not require power in the night time. Similarly, LP-III type profile system is suitable for consumers who require power only at night time. LP-IV type profile system addresses the demands of the majority of the rural community because it could be used in the day as well as night time and can be tailor-made to suit any requirement with adequate storage energy facility. The cost of LP-IV type system is slightly higher than other load profiles type systems with an advantage that LP –IV type system is versatile in terms of energy availability to the consumers. The analysis can be used as a tool in the direction for rural electrification system design and is also in line with the policies of the government to promote solar energy based power generation.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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