

Design and Optimization of an Off-Grid Solar Home Energy System Based on Residential Load Analysis

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DOI: 10.5281/zenodo.20645844

ABSTRACT

The increasing demand for electrical energy in residential buildings and frequent power interruptions has accelerated the adoption of rooftop solar photovoltaic (PV) systems. However, improper system sizing without detailed load analysis often leads to higher costs, reduced efficiency, and unreliable performance. This paper presents the design and optimization of a solar home energy system based on detailed residential load analysis. The proposed methodology involves evaluating household electrical consumption, categorizing loads, and determining appropriate ratings for the inverter, solar PV panels, and battery storage system. A design-oriented optimization approach is employed to identify the most suitable system configuration by evaluating performance and cost trade-offs under practical residential constraints. A case study of a typical residential home is considered to demonstrate the system design, considering factors such as daily energy demand, roof area availability, backup requirements, and safety aspects. The optimized system configuration ensures reliable power supply, improved energy utilization, and cost effectiveness. The results highlight the importance of load-based design in enhancing the performance and economic feasibility of residential solar energy systems, particularly under Indian climatic and operating conditions.

Keywords: Solar Home Energy System, Load Analysis, Off-Grid Solar PV, Inverter Sizing, Battery Storage.

1. INTRODUCTION

The rapid growth in residential electricity consumption, driven by increased usage of household appliances, has created a strong demand for reliable and sustainable energy solutions. In India, frequent power outages, rising electricity tariffs and environmental concerns have accelerated the adoption of rooftop solar photovoltaic (PV) systems for residential applications. Solar energy offers a clean, renewable, and economically viable alternative to conventional grid-based electricity. Despite the growing installation of residential solar systems, improper system sizing remains a major challenge. Many solar installations are designed based on assumed or generalized load values without a detailed analysis of actual household energy consumption. Such approaches often result in oversized systems that increase initial investment or undersized systems that fail to meet backup and energy requirements. Therefore, accurate load assessment and system optimization are essential for achieving reliable performance and cost effectiveness. This paper focuses on the design and optimization of a solar home energy system based on detailed residential load analysis. A typical 2 BHK residential home is considered as a case study to demonstrate the methodology for load calculation, inverter selection, solar PV sizing, and battery storage design. Practical installation constraints, safety considerations, and economic aspects are also discussed to ensure a realistic and implementable system design under Indian operating conditions.

2. METHODOLOGY

The methodology the methodology adopted for designing the off-grid solar home energy system is illustrated. The design process begins with residential load assessment, in which all household electrical appliances are identified and their daily energy consumption is estimated based on rated power and duration of usage. The total daily energy requirement of the household is then calculated in watt-hours (Wh) and kilowatt-hours (kWh).

Based on the estimated energy demand and peak load conditions, the inverter rating is selected by considering the maximum simultaneous load and the starting current requirements of appliances such as refrigerators and water pumps. Subsequently, the required solar photovoltaic (PV) array capacity is determined using the daily energy demand, average peak sun hours, and system losses. Battery storage capacity is designed to meet the specified backup duration while accounting for inverter efficiency and allowable depth of discharge of the batteries. Finally, installation and safety considerations, including cable sizing, earthing, and protection devices, are incorporated to ensure reliable and safe system operation. An economic analysis is also carried out to

evaluate the initial system cost and estimate the payback period, thereby assessing the overall feasibility of the proposed solar home energy system.

Table-1 : Daily load assessment for 2-bhk residential home

Appliance	Quantity	Power (W)	Usage (hrs/day)	Energy (Wh/day)
LED Lights	10	9	6	540
Ceiling Fans	4	75	10	3000
LED TV	1	120	5	600
Refrigerator	1	180	10	1800
Washing Machine	1	500	1	500
Laptop	2	65	5	650
Water Pump	1	750	0.5	375
Total		2070		7465 Wh/day

3. OFF-GRID SOLAR HOME ENERGY SYSTEM DESCRIPTION

An off-grid solar home energy system operates independently of the utility grid and supplies electrical power using solar photovoltaic (PV) panels, battery storage, and an inverter. Such systems are widely adopted in regions with unreliable grid supply or frequent power outages. The basic configuration of an off-grid solar system consists of a solar PV array, an integrated charge controller and inverter, a battery bank, and appropriate protection devices. In this study, an off-grid solar energy system is designed for a typical 2-BHK residential home to ensure uninterrupted power supply for essential household loads. The system design is based on residential energy consumption patterns and considers daily energy demand, peak power requirements, backup duration, and safety standards applicable to residential installations. The design is carried out under the following assumptions: the system is assumed to be located in India with average solar insolation conditions; the average peak sun hours are considered to be 5 hours per day; the DC system voltage is selected as 48 V; the inverter efficiency is assumed to be 90%; the allowable depth of discharge of the battery bank is limited to 80% to enhance battery life; the required backup duration is set to 8 hours; and only essential household loads are considered for system design. Based on the residential load assessment presented in Table I, the total daily energy requirement of the household is calculated as 7465Wh/day, which is approximately equal to 7.5kWh/day. The peak load under simultaneous operation of household appliances is estimated to be in the range of 2.5–3.0 kW.

4. INVERTER SIZING

The inverter rating is selected based on the maximum connected load and the starting current requirements of household appliances such as refrigerators and water pumps. To ensure reliable operation and avoid overloading during peak demand conditions, a safety factor is applied to the estimated peak load.

The required inverter power rating is calculated using

$$P_{inverter} = 1.25 \times P_{peak}$$

Where P_{peak} represents the maximum simultaneous load demand. For the considered residential load, the peak demand is estimated to be approximately 3.0 kW. Accordingly, the inverter rating is obtained as

$$P_{inverter} = 1.25 \times 3.0 = 3.75k$$

Based on the calculated value, a commercially available off-grid solar inverter with a rated capacity of 4 kW is selected. The selected inverter operates at a DC input voltage of 48 V and provides a standard AC output voltage of 230 V with a pure sine wave output, ensuring compatibility with residential electrical appliances and improved power quality.

5. BATTERY CAPACITY CALCULATION

The battery bank is designed to meet the specified backup duration requirement during periods when solar generation is unavailable. For the proposed off-grid solar home energy system, a backup duration of 8 hours is considered. Based on the total daily energy consumption of 7.5 kWh, the energy required during the backup period is calculated as

$$E_{backup} = 7.5/24 \times 8 = 2.5 kWh$$

To account for inverter losses and to limit battery degradation, the inverter efficiency and allowable depth of discharge (DoD) of the battery bank are considered. The required battery energy capacity is therefore calculated as

$$E_{battery} = E_{backup} / \eta_{inv} \times DoD = 2.5/0.9 \times 0.8 = 3.47 kWh$$

For a DC system voltage of 48 V, the corresponding battery capacity in ampere-hours (Ah) is obtained as

$$C_{battery} = 3470/48 = 72.3 \text{ Ah}$$

Based on the calculated requirement and to provide adequate margin for battery aging and future load variations, a battery bank consisting of four 12 V batteries connected in series is selected. Each battery is rated at 150 Ah, resulting in a total battery bank capacity of 48 V and 150 Ah, which ensures reliable backup performance for the designed residential system.

6. SOLAR PV ARRAY DESIGN

The solar photovoltaic (PV) array is designed to generate sufficient energy to meet the daily electrical demand of the residential load while accounting for system losses such as inverter inefficiency, wiring losses, and temperature effects. Based on the total daily energy requirement of 7.5 kWh, the effective energy that must be generated by the PV system is calculated by considering an overall system efficiency of 75%.

The required daily energy generation from the PV array is given by

$$E_{PV} = 7.5/0.75 = 10 \text{ kWh/day}$$

Assuming an average of 5 peak sun hours per day, the required PV array capacity is calculated as

$$P_{PV} = E_{PV}/5 = 10/5 = 2 \text{ kW}$$

Based on the calculated PV capacity and availability of commercially rated solar modules, the PV array is configured using five solar panels, each rated at 400 W. This configuration results in a total installed PV capacity of 2 kW, which is sufficient to meet the daily energy demand of the 2-BHK residential home under the considered operating conditions.

7. INSTALLATION AND SAFETY CONSIDERATIONS

Proper installation and safety measures are essential to ensure reliable and long-term operation of off-grid solar home energy systems. In the proposed system, effective earthing is provided for the solar PV array, inverter, and battery bank to protect equipment and users from electrical faults and lightning-induced surges. Appropriate DC isolators and circuit breakers are incorporated on both the DC and AC sides of the system to enable safe disconnection during maintenance and fault conditions.

Adequate cable sizing is selected based on current-carrying capacity and permissible voltage drop limits in order to minimize power losses and improve system efficiency. The battery bank is housed in a well-ventilated enclosure to prevent heat accumulation and ensure safe operation, particularly during charging and discharging cycles. Furthermore, the overall system installation is designed in compliance with the guidelines and safety standards prescribed by the Ministry of New and Renewable Energy (MNRE) and relevant International Electrotechnical Commission (IEC) standards to enhance system reliability and operational safety.

8. OPTIMIZATION OF SYSTEM CONFIGURATION

Optimization of the off-grid solar home energy system is carried out to achieve a balance between system reliability, energy availability, and overall cost. Rather than relying on complex computational algorithms, a design-oriented optimization approach based on residential load characteristics is adopted. The objective is to avoid under-sizing, which leads to unreliable performance, and over-sizing, which increases system cost unnecessarily.

8.1 Optimization Objective

The primary objective of optimization is to minimize the total system cost while satisfying residential energy demand and backup requirements. This objective can be expressed as

$$\text{Minimize: } C_{total} = C_{PV} + C_{battery} + C_{inverter}$$

Subject to the following constraints:

- Daily energy generated \geq Daily energy demand
- Backup duration \geq 8 hours
- Battery depth of discharge (DoD) \leq 80%
- Inverter capacity \geq Peak load demand

This constrained optimization ensures system reliability, longer battery life, and economic feasibility.

8.2 Comparative Design Scenarios

To evaluate the optimized system configuration, three different design scenarios are analyzed based on variations in PV array capacity, battery storage, and inverter rating. These configurations are summarized in Table 2.

Table-2 : Comparative analysis of system configurations

Case	PV Capacity	Battery Bank	Inverter Rating	Backup Duration	Remarks

Case I (Under-sized)	1.5 kW	48 V, 100 Ah	3 kW	~5 hours	Insufficient backup, inverter overload
Case II (Optimized)	2.0 kW	48 V, 150 Ah	4 kW	~8 hours	✓ Optimal balance
Case III (Over-sized)	2.5 kW	48 V, 200 Ah	5 kW	~10 hours	High initial cost

Case I fails to meet the required backup duration and peak load conditions, leading to frequent system stress and reduced reliability. Case III satisfies energy and backup requirements but results in higher capital cost with marginal improvement in performance. Case II provides the most suitable compromise between energy availability, backup duration, and system cost, and is therefore selected as the optimized system configuration.

8.3 Optimized System Selection

Based on the comparative analysis, the configuration consisting of a 2 kW solar PV array, 48 V, 150 Ah battery bank, and a 4 kW inverter is identified as the optimized solution for the considered 2-BHK residential home. This configuration satisfies all design constraints while minimizing unnecessary oversizing of system components.

The optimization results demonstrate that load-based system sizing combined with constraint-driven comparison is an effective approach for residential solar energy system optimization, particularly in regions with limited roof area and cost sensitivity.

9. RESULTS AND DISCUSSIONS

The designed off-grid solar home energy system successfully meets the daily energy demand of a typical 2-BHK residential home under the considered operating conditions. The total daily energy requirement of the household is 7.465 kWh, which is fully supplied by the proposed 2 kW PV array in combination with the battery storage system. The inverter, rated at 3.75 kW, ensures smooth operation of household appliances even during peak simultaneous loads. The battery bank, with a total capacity of 150 Ah at 48 V, provides up to 8 hours of backup during periods of low solar generation or grid unavailability.

Table-3 : summarizes the optimized system components and their performance against the calculated requirements.

Component	Requirement / Demand	Selected / Optimized	Remarks
Daily Energy (kWh)	7.465	7.5	Meets demand
Peak Load (kW)	3.0	3.75	Includes 25% safety factor
Battery Capacity (Ah)	72.3	150	Provides 8-hour backup
PV Array Capacity (kW)	2.0	2.0	Meets daily energy

The daily load profile, as considered in the design, shows that energy consumption peaks occur in the morning and evening hours due to lighting, fan, and appliance usage. The battery state-of-charge (SOC) analysis indicates that the system maintains sufficient energy during nighttime operation, ensuring uninterrupted power supply. During the day, the PV array generates slightly more energy than the daily demand, which provides a margin for cloudy days or minor load variations.

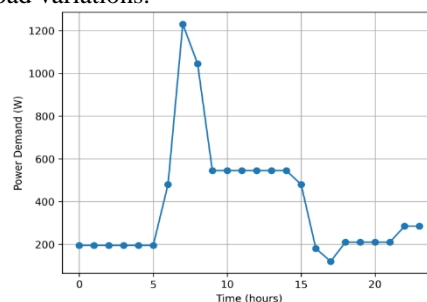


Fig -2 : Daily Load Profile of a 2-BHK Residential Home

The results confirm that systematic residential load analysis combined with proper component sizing significantly enhances system reliability and operational efficiency. The optimized selection of inverter and battery capacities prevents unnecessary oversizing, thereby reducing the overall system cost. Moreover, the off-grid configuration enables complete energy independence from the utility grid, making the proposed system suitable for regions experiencing frequent power outages or unreliable grid infrastructure.

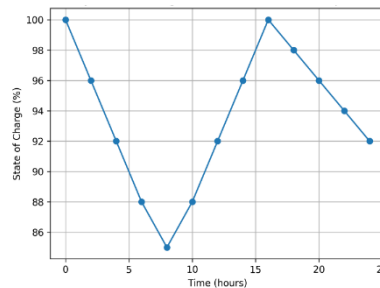


Fig -3 : Battery State-of-Charge (SOC) vs Time

A sensitivity analysis shows that a 10% increase in daily energy demand can be accommodated with minor adjustments to battery usage without affecting inverter operation, demonstrating the robustness of the proposed design. Overall, the results highlight the effectiveness of a load-based, design-oriented optimization approach for residential solar home energy systems, ensuring both economic feasibility and reliable performance.

Furthermore, the off-grid configuration enables complete energy independence from the utility grid, making the proposed system particularly suitable for regions experiencing frequent power outages or unreliable grid infrastructure. The results demonstrate that systematic residential load analysis combined with proper component sizing can significantly enhance system reliability, performance, and economic feasibility.

10 CONCLUSIONS

This paper presented the design and optimization of an off-grid solar home energy system based on detailed residential load analysis. The proposed methodology highlights the importance of accurate load assessment in selecting suitable inverter ratings, battery storage capacity, and solar PV array size. By incorporating system losses, backup requirements, and safety considerations, the designed system provides a reliable and efficient power solution for residential applications. The optimization results demonstrate that evaluating multiple system configurations using load-driven constraints enables the selection of an economically viable and dependable off-grid solar solution.

The study demonstrates that off-grid solar systems can effectively improve energy utilization and ensure uninterrupted power supply in areas with unreliable or unavailable grid infrastructure. The presented design approach can serve as a practical guideline for homeowners, engineers, and practitioners seeking to design and implement cost-effective.

11. REFERENCES

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