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Prototype Model Design and Analysis of Hybrid Solar Backup System for Multi-Residential Applications

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Abstract: *The design and analysis of a hybrid solar energy system for residential buildings that supplies excess generated energy to the utility grid and provides backup power during grid outages are presented in this paper. Bidirectional energy meters, battery storage, rooftop solar photovoltaic panels, and grid connectivity are all integrated into the suggested system. Solar energy provides household loads during regular operation, and excess power is exported to the grid to generate income for company. The system operates in islanded mode to guarantee a continuous power supply in the event of a grid failure. The project also assesses the viability of selling solar energy to residential clients as a backup power source.*

Keywords: Hybrid Solar System; Rooftop Solar PV; Battery Energy Storage System; Bidirectional Energy Metering; Net Energy Export

I. INTRODUCTION

In many residential areas, frequent power cuts and increasing electricity demand have made reliable backup power a necessity. Conventional backup options such as diesel generators and inverter–battery systems are expensive to operate, noisy, and harmful to the environment [1]. Rooftop solar photovoltaic (PV) systems offer a clean and cost-effective alternative, as they can generate electricity close to the point of use and reduce dependence on the utility grid [2]. However, standard grid-connected solar systems stop supplying power during grid outages due to safety and anti-islanding requirements, which limits their usefulness as a complete backup solution [3].

To overcome this limitation, hybrid solar energy systems that combine solar PV, battery storage, and grid connectivity have gained significant attention. These systems store excess solar energy in batteries and supply power to essential household loads during grid failures, thereby improving reliability [4]. Proper calculation of solar power generation and battery capacity is essential to ensure that residential energy demand is met efficiently and economically [5], [6]. Additionally, when the grid is available, surplus solar energy can be exported through net-metering, helping consumers reduce electricity bills and supporting grid stability [7], [9]. The use of smart energy meters enables accurate monitoring of energy consumption and export at the household level, making hybrid solar systems a practical and sustainable solution for residential backup power and energy management [8], [10].

The proposed system is developed around a business model in which solar energy is offered as a paid backup power service. Solar panels installed on the rooftop generate electricity that is stored in a shared or dedicated battery system and supplied to homes during grid outages, improving power reliability and energy security [4], [5]. Consumers pay for backup power usage based on metered energy consumption, like conventional electricity billing, which enables fair and transparent energy accounting [8]. When the grid is available and solar generation exceeds local demand, surplus energy is exported to the utility grid through net-metering mechanisms, creating an additional revenue stream and improving system economics [7], [9]. Smart energy meters installed in each household measure backup energy usage, grid consumption, and exported power, ensuring transparent billing and effective energy management [8]. This approach not only enhances power reliability for residential consumers but also establishes a sustainable and scalable business opportunity for deploying hybrid solar energy systems in residential buildings [10].

II. LITERATURE REVIEW

Nagananthini et al. (2019) [11] evaluated the economic performance of bidirectional net metering in residential rooftop solar PV systems. The study showed that optimal panel orientation improves self-consumption, while exporting surplus energy to the grid significantly reduces electricity tariffs and enhances the viability of distributed solar generation.

Tabora et al. (2021) [12] assessed the technical and economic performance of hybrid photovoltaic systems with energy storage under both on-grid and off-grid operating conditions. The study demonstrated that hybrid systems effectively mitigate solar intermittency, reduce fossil fuel consumption, and lower energy costs, thereby enhancing operational flexibility and environmental sustainability for small- and medium-scale consumers.

Moorthy et al. (2023) [13] developed an IoT-based smart energy metering system for residential and industrial use using an ESP8266 and Wi-Fi communication. The system enables real-time monitoring and remote access, reduces manual meter reading, and improves energy management with lower operational costs.

III. SYSTEM ARCHITECTURE

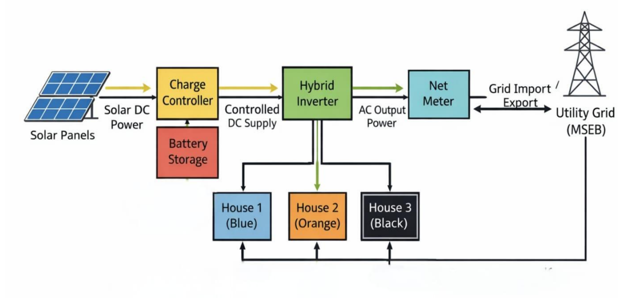

Fig.1: Block Diagram

System Block Diagram Explanation: Community Solar Microgrid

The Community Solar Microgrid is a distributed power generation system designed to supply clean and reliable electricity to multiple households using solar energy. The major components of the system include Solar Panels, Charge Controller, Battery Storage, Hybrid Inverter, Net Meter, and the Utility Grid (MSEB). The functional explanation of each block is as follows:

1. Solar Panels

Solar panels are the primary source of power generation in this system. They convert solar radiation into DC electricity using the photovoltaic effect. The generated DC power is then supplied to the Charge Controller for further regulation.

2. Charge Controller

The charge controller regulates the voltage and current coming from the solar panels to the Battery Storage and Hybrid Inverter.

Its main functions are:

To prevent overcharging and deep discharging of batteries.

To ensure a steady power supply to the inverter.

It acts as a protective and controlling unit between the solar array and storage system.

3. Battery Storage

The battery bank stores the excess DC energy generated during the daytime.

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This stored energy is used to supply power during nighttime or low sunlight conditions, ensuring 24×7 power availability to the community houses. It helps in maintaining system reliability and stability.

4. Hybrid Inverter

The hybrid inverter is the core of the system. It performs two major functions:

Converts DC power (from solar panels and batteries) into AC power suitable for household loads.

Manages bi-directional power flow between the solar source, battery, grid, and connected houses.

It automatically switches between solar, battery, and grid supply based on the availability of power sources.

5. Connected Houses (House 1, House 2, House 3)

The converted AC power from the hybrid inverter is distributed to multiple community houses.

In this diagram, three houses (House 1 – Blue, House 2 – Orange, House 3 – Violet) are connected to share the generated solar energy. Each house receives a stable and regulated power supply from the microgrid.

6. Net Meter

The Net Meter monitors the import and export of electricity between the community microgrid and the Utility Grid (MSEB).

If the solar system produces more power than consumed, the excess energy is exported to the grid. During a shortage, power can be imported from the grid.

This net metering system helps in reducing electricity bills and promotes efficient energy management.

7. Utility Grid (MSEB)

The utility grid acts as the backup source and energy exchange partner. It supports the microgrid during periods of high demand or low solar generation. In turn, the microgrid can supply surplus renewable energy back to the grid, contributing to the overall power system.

Working Summary

During the day, solar panels generate DC power that is regulated by the charge controller and used to supply loads through the hybrid inverter. Excess energy is stored in the battery and/or exported to the utility grid via the net meter. At night or during cloudy conditions, the stored battery energy or grid power supports the load demand, ensuring continuous electricity supply to all connected houses.

IV. METHODOLOGY

The design and analysis of a hybrid solar energy system for multi-residential buildings that supplies excess generated energy to the utility grid and provides backup power during grid outages are presented in this paper. Bidirectional energy meters, battery storage, rooftop solar photovoltaic panels, and grid connectivity are all integrated into the suggested system.

Solar energy provides household loads during regular operation, and excess power is exported to the grid to generate income for company such system should be studied by assuming based on minimum loads.

The proper formulas for sizing components in a small-scale off-grid or hybrid 12 V solar PV system (3 × 5 W LED) incorporate real-world losses, efficiencies, depth of discharge (DoD), autonomy, and local solar resource. These are standard in engineering guides and ensure reliable performance, especially for battery longevity and cloudy-day operation.

Here, We are assuming a minimal load according to our rating of PV system.

1. Load Estimation Formula: -

$E_{load} = P_{load} \times t$

Where:

E_{load} = daily energy demand (Wh/day)

P_{load} = total connected load (W)

t = operating hours per day (h)

Calculation: E_{load} = 15 W × 5 h = 75 Wh/day

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2. Battery Capacity Formula: -

$$C_{battery} = \frac{(E_{load} \times A)}{(V \times DoD \times \eta\_batt \times \eta\_inv)}$$

Where: $C_{battery}$ = required battery capacity (Ah)
E_{load}= daily energy demand (Wh/day)
A = autonomy (days of backup)
V = system voltage (V)
DoD = depth of discharge (typically 0.5 for lead-acid)
$\eta_{battery}$ = battery efficiency (≈ 0.85)
$\eta_{inverter}$ = inverter efficiency (≈ 0.85)
Calculation: $C_{battery} = \frac{75}{(12 \times 0.5 \times 0.85 \times 0.85)}$ ≈ 17.3 Ah
Select,
$\frac{12\ V}{20\ Ah}$ battery (for margin)

3. Solar PV Array Power Formula: -

$$P_{pv}\ (Wp) = \frac{E_{load}}{(PSH \times \eta\_sys)}$$

Where: P_{pv}= required PV panel rating (Wp)
PSH = peak sun hours (≈ 5 h/day)
η_{system} = overall system efficiency (≈ 0.75)
Calculation: $P_{pv} = \frac{75}{(5 \times 0.75)} = 20$ W
Select 1 × 20 W, 12 V solar panel

4. Charge Controller Sizing Formula: -

I_{cc} (A) = I_{sc},total × 1.25
Where: I_{cc} = controller current rating (A)
I_{sc}, total = sum of short-circuit currents of all panels (A) Example: For 20 W panel → I_{sc},≈ 1.5 A
I_{cc} = 1.5 × 1.25 = 1.9 A Select 10 A PWM controller (for future expansion)

5. Inverter Sizing Formula: -

$$P_{Inverter} \geq \left\{ \frac{P_{load}}{\eta\_inv} \right\} \times 1.25$$

Where: $P_{Inverter}$= required inverter power (W)
$\eta_{inverter}$ = inverter efficiency (≈ 0.85)
Calculation: $P_{Inverter} = \frac{15}{(0.85)} \times 1.25 \approx 22$ W
Select 100 W (12 V DC → 220 V AC)

Mathematical Calculations made up on prototype Model:

The Calculation Are Made as per Following Standards
(120W Solar | 12V 20Ah Battery | Backup Cost per unit = ₹9 | Grid Export ₹3.8/unit)

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1. Energy Flow Logic: xxx

Condition	*Solar Output*	*Battery*	*Consumer Supply*
Grid ON + Battery not full	*Charges battery*	*Charging*	*From Grid*
Grid ON + Battery full	*Export to grid*	*Full*	*From Grid*
Grid OFF	*Stops charging*	*Discharges*	*From Battery*

2. Battery Energy Available for Consumer Supply

Battery Rating: 12V, 20Ah Usable Capacity (DoD = 80%):

$$C_{usable} = 20 \times 0.80 = 16 \text{ Ah}$$

Total energy available per full discharge:

$$E_{battery} = V_b \times C_{usable} = 12 \times 16 = 192 \text{ Wh} = 0.192\text{kWh}$$

Load Power consumed by consumers:

$$P_{load} = 29.33W$$

Backup Duration per discharge cycle:

$$t_{backup} = \frac{192}{29.33} = 6.55 \text{ hours per outage}$$

3. Solar Charging Analysis

Daily Solar Energy Generated:

$$E_{solar/day} = 120 \times 5 = 600 \text{ Wh/day}$$

Energy required to fully charge battery from 80% DoD:

$$E_{charge} = \frac{C_{usable} \times V_b}{\eta_{cc}} = \frac{192}{0.95} = 202.1 \text{ Wh}$$

Time to fully charge battery from solar:

$$t_{charge} = \frac{E_{charge}}{P_{solar}} = \frac{202.1}{120} = 1.68 \text{ hours}$$

Remaining solar time after full charge:

$$t_{export} = PSH - t_{charge} = 5 - 1.68 = 3.32 \text{ hours}$$

4. Export Energy Calculation

Export occurs only after battery is fully charged:

$$P_{export} = P_{solar} = 120 \text{ W}$$

(Full solar output goes to grid since load is on grid during this time)

$$E_{export/day} = P_{export} \times t_{export} = 120 \times 3.32 = 398.4 \text{ Wh} = 0.3984 \text{ kWh/day}$$

5. Income Stream 1 — Consumer Supply During Grid Outage

Assumption: Grid outage occurs once per day and battery delivers one full discharge cycle

Energy supplied to consumers per outage:

$$E_{consumer} = 0.192 \text{ kWh per outage}$$

Income per outage:

$$Income_{consumer/outage} = 0.192 \times 9 = ₹1.728 \text{ per outage}$$

Assuming outage frequency scenarios:

Outage Frequency	Consumer Income/Month	Consumer Income/Year
Once every 2 days	₹25.92	₹311.04
Once per day	₹51.84	₹622.08
Twice per day	₹103.68	₹1,244.16

For thesis — taking standard assumption of 1 outage/day:

$$Income_{consumer/day} = ₹1.728/\text{day}$$
$$Income_{consumer/month} = 1.728 \times 30 = ₹51.84/\text{month}$$
$$Income_{consumer/year} = 1.728 \times 365 = ₹630.72/\text{year}$$

6. Income Stream 2 — Grid Export at ₹3.8/unit

$$\text{E}_{\text{export/day}} = 0.3984 \text{ kWh/day}$$
$$\text{Income}_{\text{export/day}} = 0.3984 \times 3.8 = ₹1.514/\text{day}$$
$$\text{Income}_{\text{export/month}} = 1.514 \times 30 = ₹45.43/\text{month}$$
$$\text{Income}_{\text{export/year}} = 1.514 \times 365 = ₹552.72/\text{year}$$

7. Total Income Analysis

Income Source	Daily	Monthly	Annual
Consumer Supply during outage (₹9/unit)	₹1.728	₹51.84	₹630.72
Grid Export (₹3.8/unit)	₹1.514	₹45.43	₹552.72
Total Income	₹3.242	₹97.27	₹1,183.44

$$R_{total/year} = 630.72 + 552.72 = ₹1{,}183.44/\text{year}$$

8. **Payback Period**

Total Capital Investment:

$$C_{total} = ₹8{,}400$$

Simple Payback Period:

$$Payback = \frac{C_{total}}{R_{total/year}} = \frac{8400}{1183.44} = 7.10 \text{ years} \approx 7 \text{ years } 1 \text{ month}$$

9. Cumulative Income & Payback Projection Table

Year	Annual Income (₹)	Cumulative Income (₹)	Investment Recovered (%)
1	1,183.44	1,183.44	14.09%
2	1,183.44	2,366.88	28.18%
3	1,183.44	3,550.32	42.27%
4	1,183.44	4,733.76	56.35%
5	1,183.44	5,917.20	70.44%
6	1,183.44	7,100.64	84.53%

Year	Annual Income (₹)	Cumulative Income (₹)	Investment Recovered (%)
7	1,183.44	8,284.08	98.62%
7.10	—	₹8,400 ✓	100% Break Even
10	1,183.44	11,834.40	140.89%
15	1,183.44	17,751.60	211.33%
20	1,183.44	23,668.80	281.77%
25	1,183.44	29,586.00	352.21%

10. 25-Year Financial Summary

Total Income over 25 years:

$$R_{25years} = 1183.44 \times 25 = ₹29{,}586$$

Net Profit after recovering investment:

$$Net_{profit} = 29{,}586 - 8{,}400 = ₹21{,}186$$

Return on Investment (ROI):

$$ROI = \frac{21{,}186}{8{,}400} \times 100 = 252.21\%$$

11. Complete Summary Table

Parameter	Value
Solar Panel Rating	120 W
Daily Solar Energy	600 Wh
Battery Charging Time	1.68 hours
Export Duration	3.32 hours/day
Daily Export Energy	0.3984 kWh
Energy to Consumers per Outage	0.192 kWh
Consumer Tariff	₹9/unit
Grid Export Tariff	₹3.8/unit
Daily Consumer Income	₹1.728
Daily Export Income	₹1.514
Daily Total Income	₹3.242
Monthly Total Income	₹97.27
Annual Total Income	₹1,183.44
Total Investment	₹8,400
Payback Period	7 years 1 month
25 Year Total Income	₹29,586
Net Profit (25 years)	₹21,186

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Parameter	Value
ROI	252.21%

12. Final Technical Conclusion

The hybrid solar backup system with a capital investment of **₹8,400** operates on a dual income model. During grid-connected operation, once the **12V 20Ah battery is fully charged within 1.68 hours**, the remaining **3.32 hours** of solar generation exports **0.3984 kWh daily** to the grid at ₹3.8/unit, earning **₹552.72/year**. During grid outages, the fully charged battery supplies consumers at **₹9/unit**, delivering **0.192 kWh per outage cycle** and earning **₹630.72/year** assuming one outage per day. Combined annual income stands at **₹1,183.44**, achieving a **payback period of 7 years and 1 month** within the 25-year panel lifespan. Over 25 years the system generates **₹29,586 in total income** with a **net profit of ₹21,186** and an **ROI of 252.21%**, firmly establishing the proposed system as a technically sound and economically profitable energy solution for multi-residential applications.

V. ADVANTAGES

***Uninterrupted Power Supply:* -** Provides continuous power by switching between solar, battery, and grid during outages.
***Reduced Electricity Bills:* -** Solar power usage and exporting excess energy to the grid lowers monthly energy costs.
Energy Trading Income: - Surplus solar energy can be sold to the utility grid through net-metering.
***Efficient Use of Renewable Energy:* -** Maximizes utilization of clean solar energy and reduces dependence on fossil fuels.
***Lower Carbon Emissions:* -** Helps in reducing greenhouse gas emissions and supports environmental sustainability.
***Improved Power Reliability:* -** Battery storage ensures stable supply during peak demand and grid failure.
***Scalable System:* -** Capacity can be easily expanded by adding more panels or batteries.

VI. RESULT AND CONCLUSION

The mathematical results confirm that the system achieves reliable day–night operation and effective energy storage, validating the correctness of the sizing and design formulas used. From the study it is concluded that the 12 V hybrid solar power system provides a technically feasible, cost-effective, and sustainable solution for domestic lighting applications.
The mathematical study shows how a small-scale solar system can operate independently or in hybrid mode with the grid, ensuring continuous power supply without manual intervention.
In future, The Design can be implemented for making a project depending upon resources available and the tools to be used considering small scale application in future expenditure.

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