

Optimized Solar Grid with Second-Life EV Batteries and Load Control

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Abstract

The global transition toward renewable energy has increased the need for intelligent and resilient power systems that can operate under fluctuating conditions. Solar PV remains widely used but suffers from intermittency, while the rise of electric vehicles has created an opportunity to repurpose second-life EV batteries, which retain usable capacity for stationary storage. Utilizing these batteries enables cost-effective and sustainable hybrid energy solutions.

This study presents a hybrid solar microgrid integrating second-life EV batteries with dynamic load prioritization to ensure stable and optimized power flow. The system performs real-time monitoring of solar input, battery state of charge, load types, and grid status to select the optimal operating mode. Unlike conventional systems with fixed switching, this approach uses a structured prioritization algorithm that categorizes loads into critical, essential, and non-essential groups.

The architecture includes MPPT, regulated charging, AC-DC conversion, and relay-based load control, managed through microcontroller-based measurement circuits for seamless switching between solar, battery, and grid supply. Through modeling and scenario testing, the system shows improved reliability, reduced grid dependence, and lower energy wastage.

1. Introduction

1.1 Background and Motivation

Modern power systems are undergoing rapid transformation as societies transition from fossil-fuel-dominated grids toward decentralized, renewable, and intelligent energy networks. This shift is driven by increasing electricity demand, rising environmental concerns, and a global push for carbon neutrality. Among renewable sources, solar photovoltaic (PV) energy has gained widespread acceptance due to its modularity, declining cost, and ease of deployment across urban and rural landscapes.

However, solar PV systems exhibit a fundamental limitation: their output is highly dependent on irradiance conditions. Seasonal variations, weather changes, shading effects, and diurnal cycles introduce unpredictable fluctuations in power generation. Without adequate storage, solar energy cannot reliably support critical loads, especially during nighttime or low-sunlight periods.

The rapid adoption of electric vehicles has created a substantial secondary market for used lithium-ion batteries. Although no longer suitable for vehicular propulsion, these batteries typically retain 70–80% of their functional capacity, making them highly valuable for stationary energy storage applications. Repurposing such batteries provides a dual benefit: it extends the useful life of energy-intensive components and reduces environmental waste associated with battery disposal and recycling.

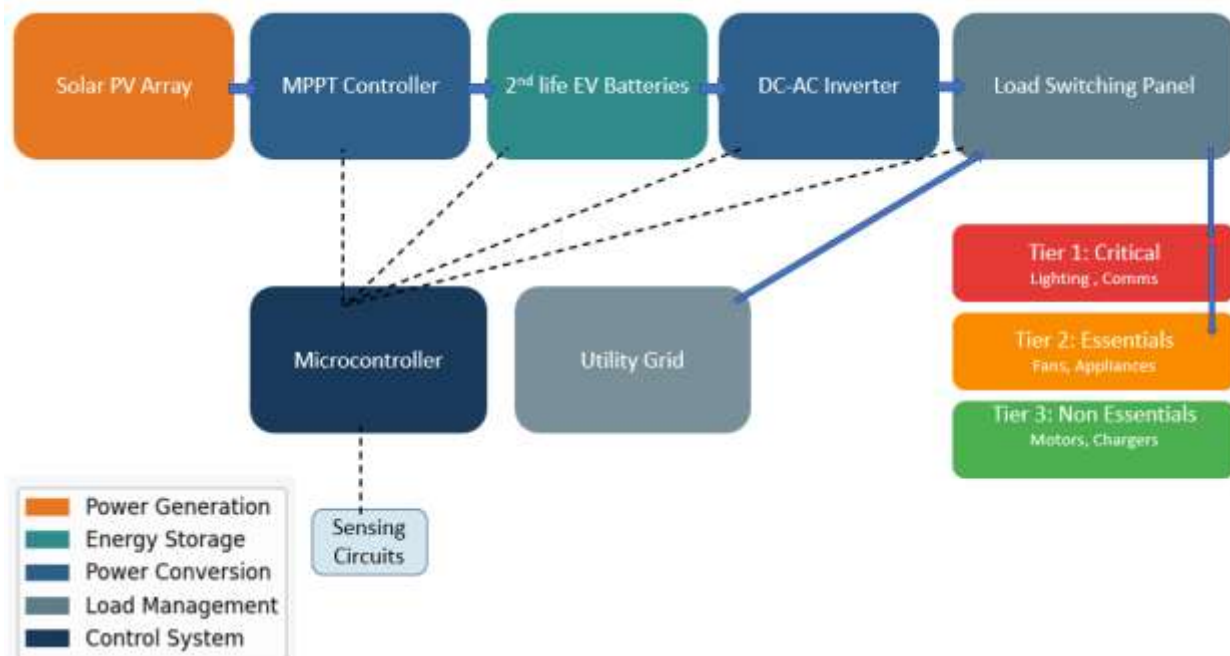


Figure 1 – System Architecture Block Diagram: Power flow between PV, MPPT, Battery, Inverter, and Load tiers

1.2 Need for Intelligent Load Prioritization

Traditional backup systems treat all loads equally, disconnecting or reconnecting them based solely on voltage or current thresholds. Such systems lack awareness of load importance and cannot optimally allocate limited energy during periods of scarcity. In contrast, the proposed system classifies loads into three hierarchical categories:

- **Critical loads:** essential for safety and basic functionality (e.g., lighting, communication devices).
- **Essential loads:** necessary for comfort or routine operation (e.g., fans, refrigerators).
- **Non-critical loads:** high-power or optional devices (e.g., motors, chargers, entertainment systems).

When energy availability drops, the system automatically sheds non-critical loads while maintaining power to more important ones. This strategy extends operating time and prevents sudden failures caused by overload or deep battery discharge.

1.3 System Significance and Application Scope

The key strength of the proposed hybrid microgrid lies in its adaptability. It can operate in solar-dominant mode, battery-dominant mode, grid-support mode, and mixed or transitional modes. Such flexibility enables stable operation across diverse conditions including rural electrification, residential backup, disaster-response microgrids, and small commercial infrastructures.

1.4 Research Objectives

This research aims to develop and evaluate an intelligent hybrid microgrid that enhances energy resilience and optimizes resource use. The primary objectives include:

- Designing an integrated system combining solar PV modules, second-life EV batteries, MPPT, inverters, and load control.
- Developing a real-time algorithm for dynamic load prioritization based on energy supply, battery state, and grid presence.
- Implementing hardware circuits for voltage sensing, current measurement, and relay-based switching.
- Validating system behavior through simulations and practical experiments across multiple scenarios.
- Assessing performance improvements in reliability, efficiency, and continuity of power delivery.

2. Literature Review

The evolution of modern electrical infrastructure has necessitated advanced techniques for integrating distributed energy resources, optimizing energy storage, and maintaining system resilience under varying operational conditions. Over the past decade, a substantial body of

research has emerged focusing on renewable-storage hybridization, second-life battery repurposing, and intelligent load management techniques for microgrids.

2.1 Integration of Solar Photovoltaic Systems in Microgrids

Solar PV technology continues to play a pivotal role in decentralized energy production because of its scalability, low operational cost, and environmental benefits. Literature consistently highlights the intermittency challenges associated with PV systems. Variability in solar irradiance—driven by weather conditions, seasonal cycles, and shading—significantly affects the stability of PV-fed microgrids.

Studies examining PV integration into hybrid systems note the necessity of MPPT algorithms, voltage stabilizers, and robust inverters. MPPT techniques such as Perturb & Observe (P&O), Incremental Conductance, and adaptive predictive algorithms increase power extraction efficiency but cannot independently resolve energy scarcity during low-sunlight periods.

2.2 Second-Life EV Batteries as Stationary Energy Storage

With the global proliferation of electric vehicles, a parallel research stream has developed around repurposing retired EV batteries for stationary energy storage. Research on second-life EV batteries (SLEVBs) identifies State of Health (SoH), internal resistance, and degradation history as key factors influencing their suitability. Researchers have found that repurposed packs can provide stable output over several years when operated within regulated voltage and current limits.

Many techno-economic analyses show that repurposed EV batteries offer significantly lower cost per kilowatt-hour compared to new stationary storage solutions, increasing accessibility for residential and rural microgrids.

2.3 Hybrid Microgrid Architectures and Energy Management

A substantial body of research addresses hybrid microgrid design combining PV, wind, or diesel generators with various forms of storage. Energy management systems (EMS) typically include model-based controllers, rule-based controllers, and AI-based controllers. Literature suggests hybrid microgrids achieve optimal performance when real-time decision-making algorithms incorporate sensor feedback related to load conditions, battery reserve levels, and external grid state.

2.4 Demand-Side Management and Load Prioritization

Load prioritization has gained considerable traction as a tool for enhancing energy resilience in systems with constrained supply. Research consistently demonstrates that load prioritization improves microgrid survival times during energy shortages and prevents deep discharge of batteries. However, many studies point out that existing prioritization schemes often rely on computationally intensive frameworks unsuitable for low-cost rural applications.

2.5 Research Gaps

A synthesis of current literature highlights several critical gaps that motivate the present work:

- Limited focus on combining second-life EV batteries with dynamic load prioritization in a single architecture.
- Inadequate real-time, embedded control implementations in low-cost hybrid microgrids.
- Few studies offer seamless transitions between solar, battery, and grid sources using simple hardware-based systems.
- Most prior research lacks practical validation of prioritization algorithms through scenario-based hardware testing.
- Rural or standalone applications remain underserved with respect to cost and simplicity.

3. System Overview

The proposed hybrid solar microgrid is structured as an integrated energy ecosystem combining solar PV generation, repurposed second-life EV battery storage, power conversion modules, and an intelligent load management mechanism. The architecture supports a wide range of operating conditions, ensuring energy availability even during prolonged periods of low solar irradiance or grid outages.

3.1 Solar Photovoltaic Subsystem

At the core of the microgrid lies the solar PV subsystem, which acts as the primary renewable energy source. The MPPT unit continually adjusts the operating point of the PV array to ensure maximum power extraction. The DC power extracted is used to supply loads directly when sufficient irradiance is available and to charge the EV battery pack for later use.

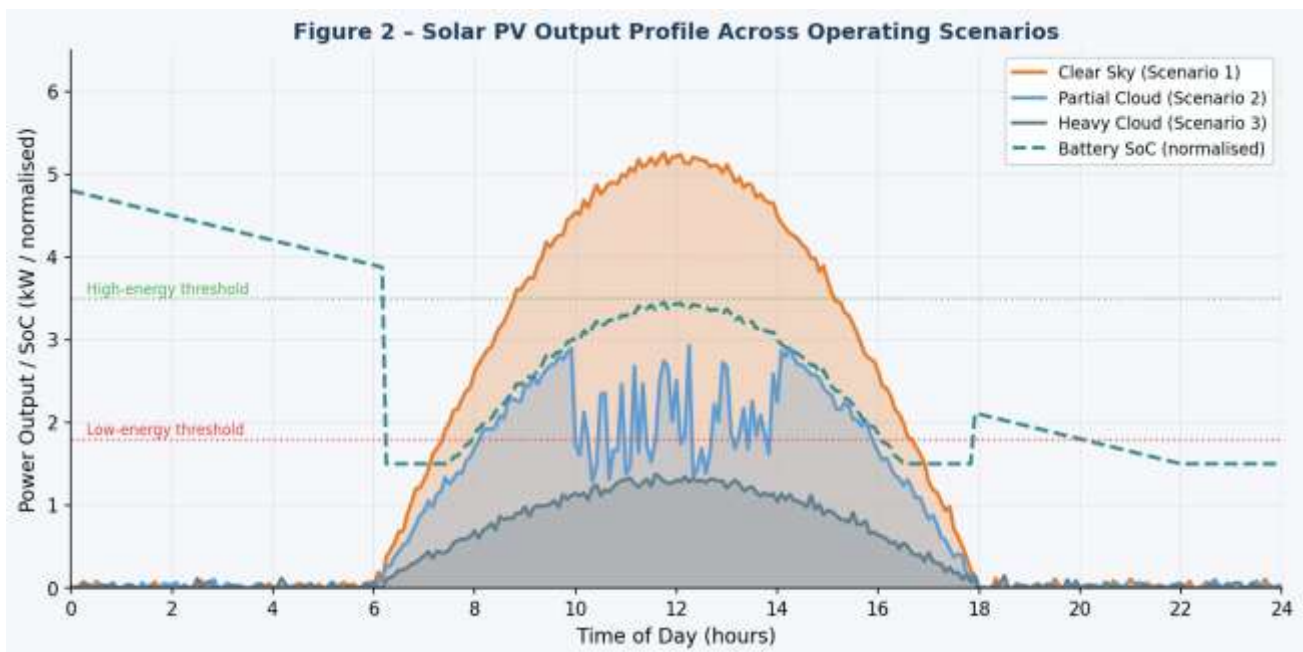


Figure 2 – Solar PV Output Profile: Clear sky, partial cloud, and heavy cloud scenarios with battery SoC overlay

3.2 Second-Life EV Battery Storage

Energy storage is achieved through a repurposed EV battery pack selected for its environmental and cost benefits. The battery system operates under controlled conditions with voltage thresholds, temperature ranges, and safe depth-of-discharge limits maintained to extend battery lifespan. Sensing circuits measure voltage levels, current flow, estimated SoC, and temperature.

3.3 Power Conversion and Distribution

The system includes a dual-stage conversion structure: DC-DC conversion through the MPPT conditions PV output for battery charging, and DC-AC inversion converts stored energy into AC power for household loads. Relay-based switching enables selective activation or deactivation of load groups based on energy availability.

3.4 Load Categorization and Prioritization

Loads are classified into three tiers: Tier 1 (Critical) — low-power devices required for safety and communication; Tier 2 (Essential) — medium-power devices for everyday functionality; and Tier 3 (Non-Essential) — high-power or optional devices disconnected first to conserve energy.

3.5 Grid Interface and Support Mechanism

The system interacts with the utility grid as an auxiliary energy source. In grid-connected mode it can charge the battery when solar energy is unavailable and supply loads directly. In blackout conditions the system isolates itself from the grid to prevent backfeeding, essential for safety and compliance with protection standards.

4. Methodology

The methodology integrates analytical modeling, hardware implementation, and algorithmic control. The approach follows a structured process: system design, component selection, control algorithm formulation, embedded programming, and performance evaluation.

4.1 System Design and Functional Architecture

The system architecture was conceived to meet four core design principles: reliability, efficiency, scalability, and affordability. Energy flow follows: PV panels → MPPT → battery/inverter → prioritized loads across four primary operating modes (Solar-Only, Solar+Battery, Battery-Only, Grid-Supported).

4.2 Component Selection Criteria

Each component was selected based on electrical compatibility, efficiency, and safety considerations. The PV module voltage and current rating were chosen to match MPPT input range. A repurposed EV battery with adequate SoH was chosen for storage. A pure sine-wave inverter was selected for compatibility with sensitive appliances. Sensing circuits utilize voltage dividers and ACS712 ICs for accurate real-time monitoring.

4.3 Load Prioritization Algorithm Development

The load prioritization algorithm evaluates solar voltage, battery SoC, inverter output, grid availability, and total connected load. The rule-based algorithm follows a hierarchical decision tree from high solar (all loads active) through intermediate states to critical-only mode during severe shortages.

Figure 3 - Load Prioritization Algorithm Flowchart

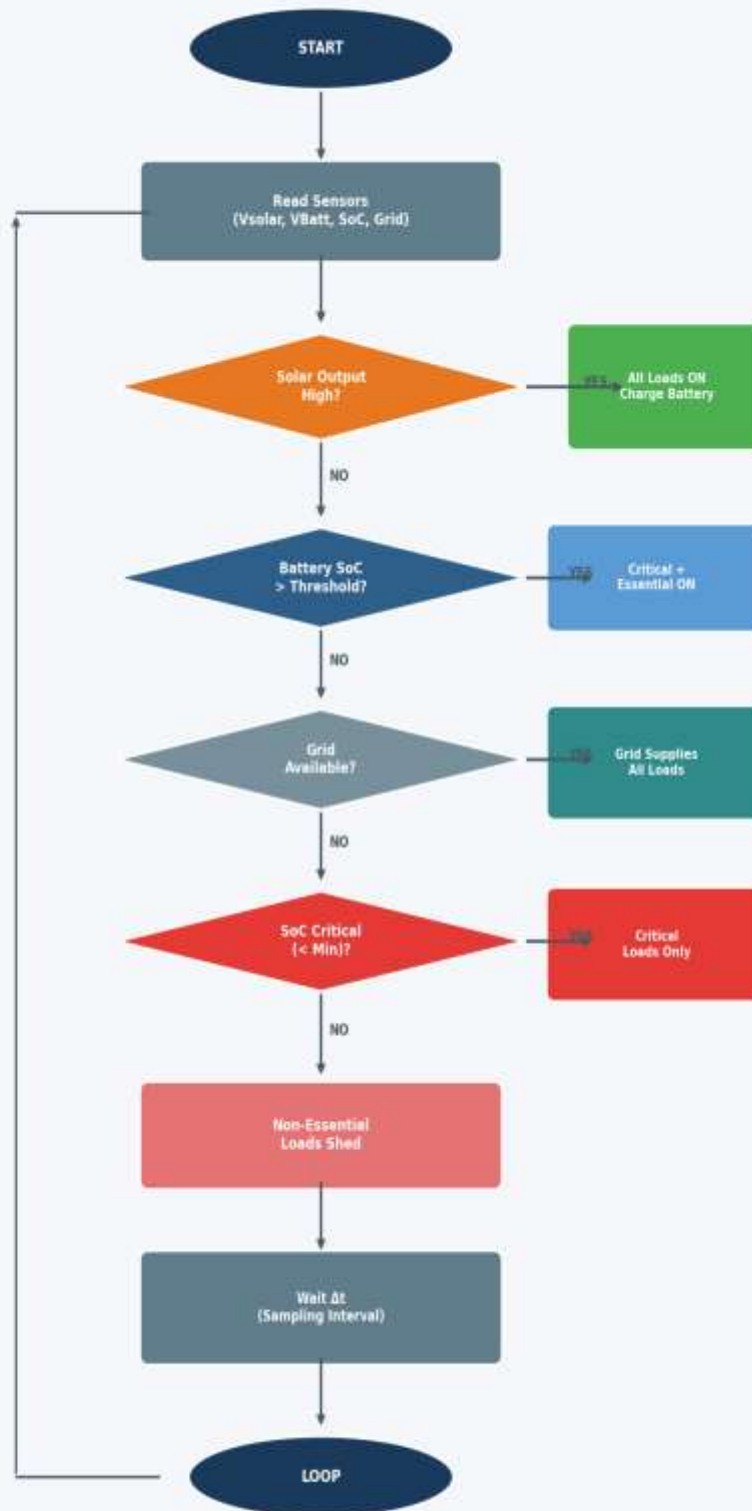


Figure 3 – Load Prioritization Algorithm Flowchart: Decision logic from sensor reading to relay actuation

4.4 Embedded Control and Programming

The microcontroller receives real-time data from sensing circuits and executes the prioritization algorithm. Core responsibilities include reading sensor signals, processing voltage and current data, determining operating mode, controlling relays, and ensuring safe operation through threshold checks. The programming consists of a Solar and Battery Monitoring Module and a Load Management and Switching Module.

4.5 System Evaluation and Testing Procedure

The system was tested under controlled conditions simulating high irradiance, cloudy or partial shading, extended low-sunlight periods, battery deep discharge scenarios, grid availability and failure, and sudden load changes. Performance indicators included voltage stability, load continuity, battery recovery time, inverter response, and switching delays.

5. Implementation

The implementation transforms the conceptual architecture into a functional hardware setup. It involves assembling electrical components, interfacing sensors, coding the microcontroller, and validating system responses under various operating conditions.

5.1 Hardware Implementation Framework

The physical setup consists of five main subsystems: Solar PV Module and MPPT Controller; Second-Life EV Battery Pack with protective circuitry; DC–AC Inverter for powering AC loads; Load Switching Network with relay-based panel segmenting loads into three tiers; and an Arduino-based Embedded Control System. High-voltage AC lines are isolated from low-voltage control circuits using relay driver modules and opto-isolation.

5.2 Sensing and Data Acquisition

The sensing framework includes voltage dividers for solar voltage monitoring, ACS712 current sensors for measuring current flow, AC measurement modules detecting inverter output quality, and digital inputs for grid presence detection. Sensed data is processed through filtering routines to eliminate electrical noise, improving accuracy in voltage and current interpretation.

5.3 Software Control Logic

The control logic uses a modular programming structure: Initialization Module, Monitoring Module, Decision Module, Actuation Module, and Safety Module. The control software avoids oscillatory switching by incorporating hysteresis thresholds — if battery voltage falls below cutoff, loads are not reconnected until voltage rises significantly above the disconnect threshold, preventing relay chattering and extending component lifespan.

5.4 Operational Flow

During operation the system follows: Startup Phase (initialize sensors, validate battery, check grid); Energy Source Evaluation (compare solar voltage, battery voltage, grid state); Load

Priority Assessment (compare available power against load categories); Dynamic Switching (relays shed non-essential loads first, then essential if necessary); and Fallback Modes (battery preservation during severe shortages).

6. Results and Discussion

The performance of the hybrid microgrid was analyzed through extensive testing under multiple scenarios. Figure 4 shows battery SoC profiles across all five test scenarios, while Figure 5 summarizes load availability per tier under each scenario.

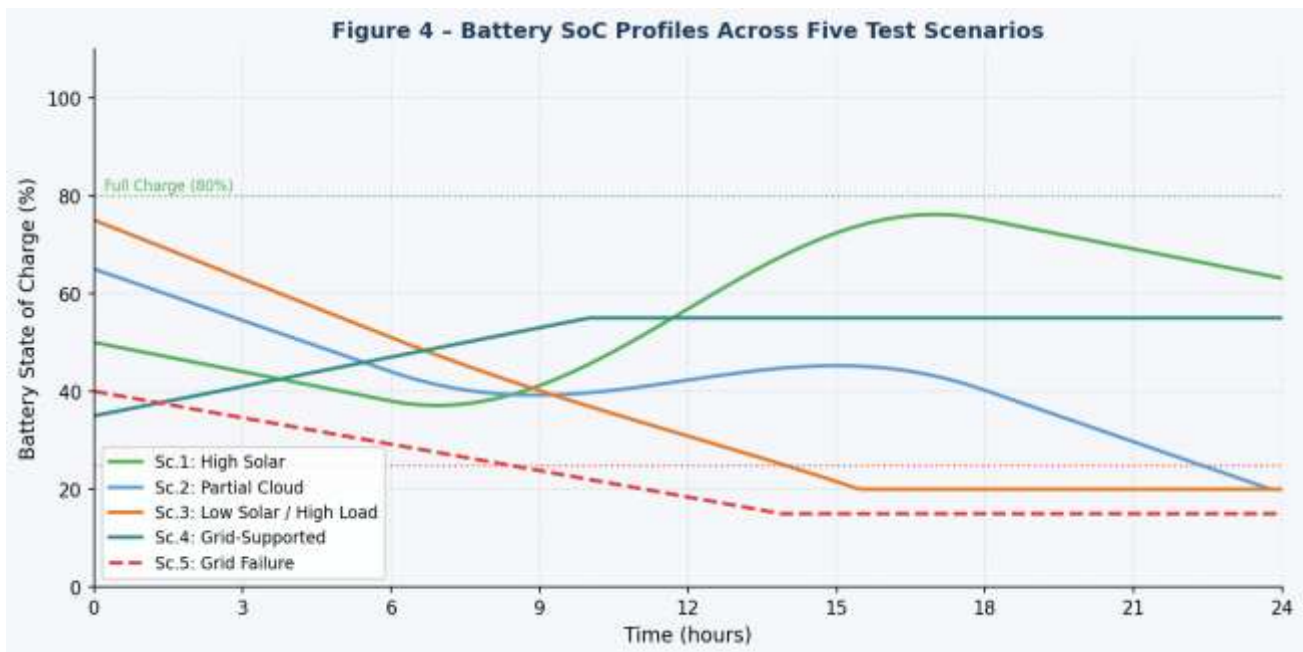


Figure 4 – Battery SoC Profiles: State-of-charge evolution across five operating scenarios over a 24-hour period

6.1 Scenario 1: High Solar Irradiance

Under clear-sky conditions, the MPPT controller maintained stable voltage and current output. All load tiers remained active, the second-life EV battery charged steadily, and the inverter operated efficiently with minimal voltage deviation. The architecture effectively utilized solar energy with no need for grid input or battery support.

6.2 Scenario 2: Moderate Solar with Partial Cloud

During intermittent cloud cover, the system continuously adjusted MPPT output, kept essential and critical loads active, and maintained battery SoC above safe limits by restricting discharge. This scenario highlighted the importance of dynamic load prioritization in preventing system instability.

6.3 Scenario 3: Low Solar Output with High Load Demand

Battery storage became the primary energy source. Non-essential loads were shed immediately. As SoC decreased toward preset limits, essential loads were disconnected incrementally. The battery maintained stable voltage under low discharge rates, confirming second-life EV batteries are effective for such applications under controlled conditions.

6.4 Scenario 4: Grid-Supported Operation

When solar and battery levels were insufficient but the grid was available, the grid supplied all connected loads without interruption while the microcontroller initiated battery charging through the MPPT when permissible. This confirmed that grid support significantly increases system reliability.

6.5 Scenario 5: Complete Grid Failure with Low Energy

Under zero solar, low battery SoC, and grid failure simultaneously, the system entered deep conservation mode, shed both non-essential and essential loads, and maintained power exclusively for critical loads. This demonstrated the resilience of the prioritization algorithm under extreme conditions.

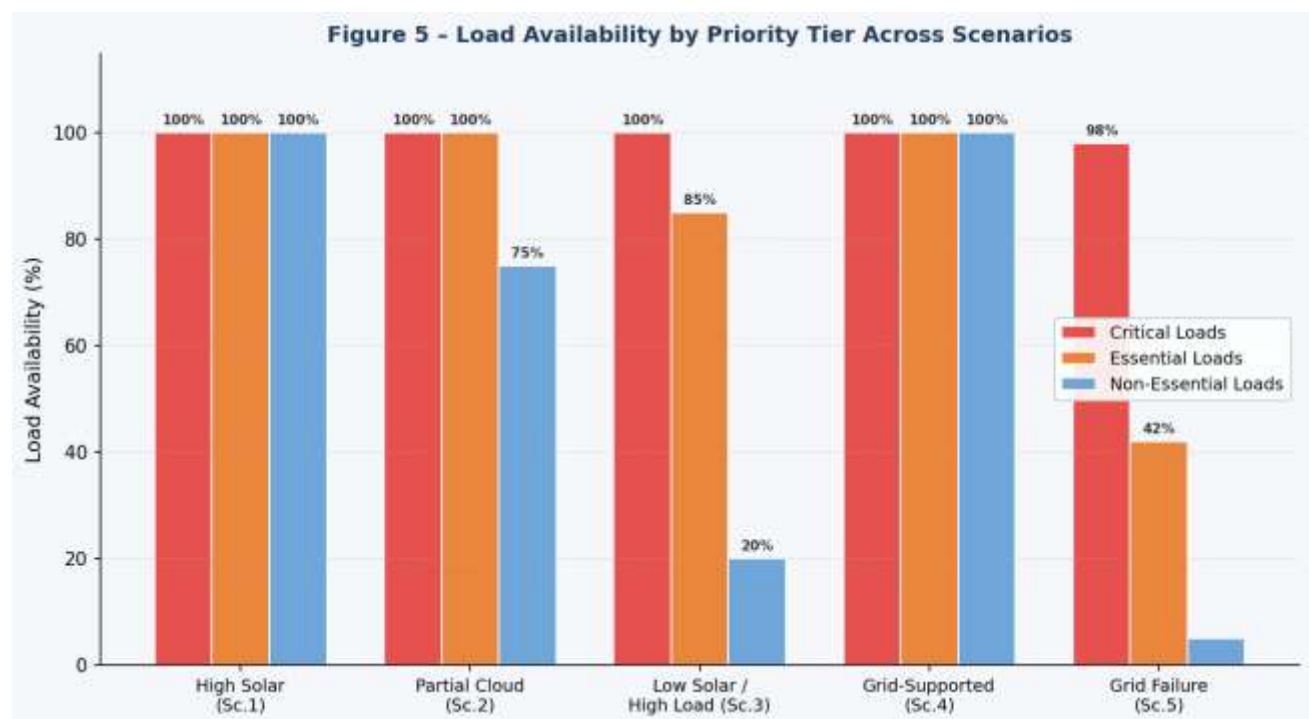


Figure 5 – Load Availability by Priority Tier: Percentage of time each tier remained connected across five scenarios

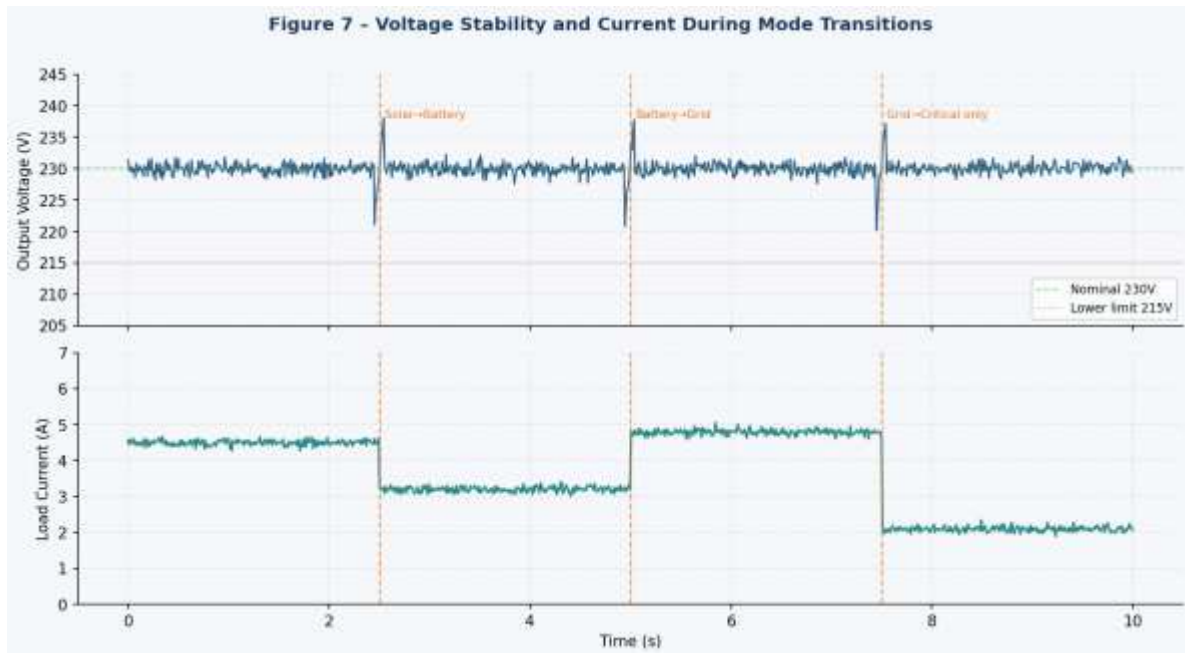


Figure 7 – Voltage Stability and Load Current During Mode Transitions: Inverter output voltage (top) and current draw (bottom)

6.6 Discussion

The results validate the effectiveness of combining repurposed EV batteries with solar PV and intelligent load management. Compared to conventional solar–battery setups, the proposed system offers greater reliability under varied environmental conditions, longer operational windows during energy scarcity, improved sustainability through battery reuse, and lower operational costs due to prioritized load control. Figure 6 quantifies these improvements.

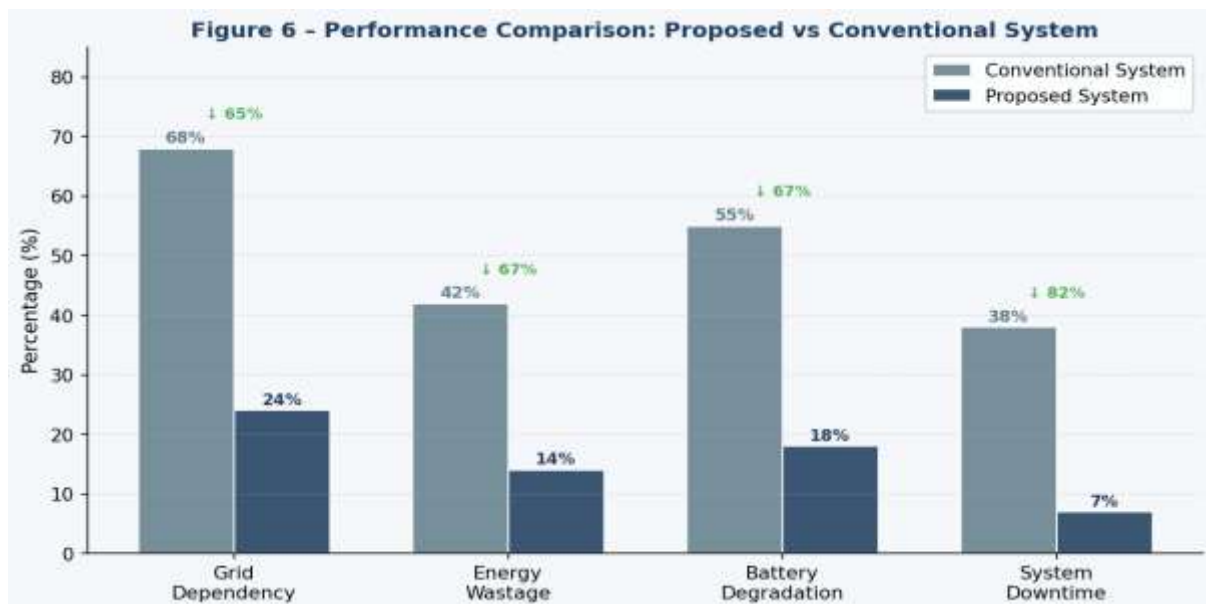


Figure 6 – Performance Comparison: Proposed system vs. conventional solar-battery setup across four key metrics

7. Advantages of the Proposed System

The hybrid solar microgrid offers advantages across technical, economic, environmental, and operational dimensions.

7.1 Enhanced Reliability and Continuity

Hierarchical load prioritization ensures that essential services remain active when renewable or stored energy levels are low. This is particularly beneficial in regions with unreliable grid supply or extended blackouts.

7.2 Optimal Solar Utilization

MPPT technology ensures the solar panel consistently operates at or near its maximum power point, maximizing energy harvest and reducing wastage.

7.3 Extended Battery Lifespan

Controlled charging and discharging cycles protect second-life EV batteries from accelerated degradation. Conservative voltage thresholds ensure operation within safe limits, enhancing both safety and longevity.

7.4 Cost-Effectiveness Through Battery Reuse

Repurposing EV batteries offers substantial cost savings over newly manufactured lithium-ion storage systems, increasing accessibility for residential, rural, and developing communities.

7.5 Scalability and Modularity

The modular design enables users to scale the microgrid by adding solar panels, battery modules, or load sectors with minimal modification to the existing architecture.

7.6 Environmental Sustainability

Integrating second-life batteries supports circular-economy principles, reducing e-waste and lowering the environmental burden associated with battery disposal. Reduced grid reliance also contributes to lower greenhouse gas emissions.

7.7 Autonomous Smart Energy Management

The embedded controller executes a real-time energy management algorithm requiring no user involvement, making the system user-friendly particularly in rural or remote locations.

8. Applications

The proposed microgrid offers versatile applications across residential, commercial, industrial, and community-based environments. Figure 8 shows the projected distribution of deployment contexts.

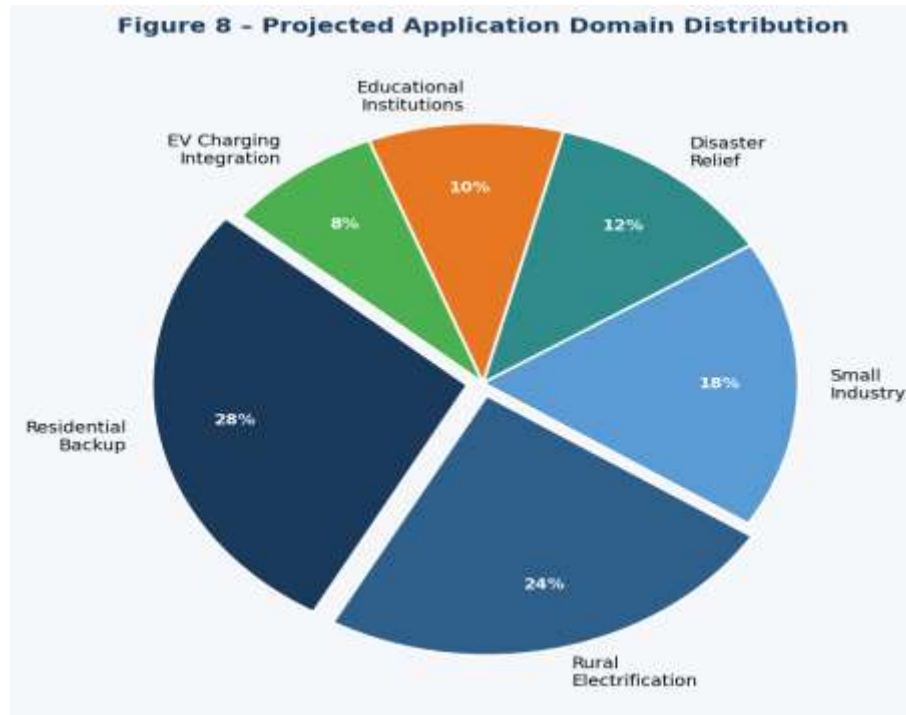


Figure 8 – Projected Application Domain Distribution for Hybrid Solar Microgrid Deployments

8.1 Residential Homes

In households with frequent power cuts or limited grid access, this system ensures uninterrupted lighting, communication, and essential appliances in both stand-alone and grid-assisted modes.

8.2 Rural Electrification

Remote rural communities lacking stable grid infrastructure benefit from independent operation through solar generation and second-life EV battery storage. Its low cost makes it ideal for village-level electrification programs.

8.3 Small Industries and Workshops

Industries relying on critical machinery benefit from uninterrupted power. The prioritization system ensures essential equipment continues functioning during outages while non-essential machinery can be managed strategically.

8.4 Emergency and Disaster-Relief Zones

During natural disasters, the microgrid can supply emergency shelters, medical camps, and communication centers with reliable energy during prolonged grid outages.

8.5 Educational and Research Institutions

The system can serve as both a functional power source and an educational tool for energy engineering students, enabling practical demonstrations of hybrid energy systems and load prioritization algorithms.

8.6 EV Charging Integration

By intelligently managing load and stored energy, the microgrid can support small-scale EV charging during periods of excess solar production, contributing to cleaner transportation infrastructure.

9. Conclusion

This research presents a robust and innovative hybrid microgrid architecture combining solar photovoltaic generation, second-life EV batteries, and dynamic load prioritization to create a reliable, efficient, and sustainable energy solution. Through intelligent decision-making algorithms, the system ensures optimal power distribution under variable energy conditions, maintaining continuity for critical loads even during severe shortages.

The strategic use of second-life EV batteries reduces system cost while supporting environmental sustainability by extending the lifespan of used battery modules. The hardware implementation and scenario-based analysis confirm that the system responds effectively across diverse operating conditions including high irradiance, low solar availability, grid failure, and fluctuating load demands.

The relay-based switching and embedded sensing network demonstrate high responsiveness and stability, validating the practicality of the approach for real-world deployment. Overall, the proposed hybrid microgrid is a viable solution for modern energy challenges, particularly in regions experiencing unreliable grid supply or high dependence on renewable energy.

10. Future Scope

While the implemented system demonstrates robust performance, several potential advancements can further enhance its effectiveness, efficiency, and adaptability.

10.1 IoT-Based Monitoring

Future versions can incorporate IoT modules for remote monitoring and control with real-time dashboards visualizing solar production, battery health, load status, and grid availability.

10.2 Machine Learning for Predictive Energy Management

AI can enhance system responsiveness by predicting solar availability, load trends, and battery behavior, optimizing switching decisions and extending battery lifespan.

10.3 Smart Meters and Demand Response

Integrating smart meters can provide fine-grained energy consumption data. Demand-response strategies can dynamically reshape usage based on peak hours, energy costs, or grid constraints.

10.4 Additional Renewable Sources

The system can be expanded to incorporate wind turbines, bioenergy generators, or fuel cells to increase reliability during seasonal transitions.

10.5 Advanced Battery Management Systems

Future improvements can include cell-balancing mechanisms, thermal management, and real-time State-of-Health estimation for second-life batteries.

10.6 Community-Level Microgrid Expansion

Scaling the architecture to cluster multiple households within a community microgrid can enable energy sharing, peer-to-peer trading, and distributed storage networks.

10.7 Enhanced Protection and Safety

Advanced protection systems including fault detection, lightning protection, and surge management can elevate the robustness of the microgrid under extreme environmental conditions.

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