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SUSTAINABLE ENERGY SOLUTIONS: PEAK LOAD MANAGEMENT IN DC MICROGRIDS EMPOWERED BY PV AND BESS

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Abstract

A study explores how a PV generation coupled with battery energy storage system (BESS) forms a hybrid DC microgrid to achieve peak load sustainability while improving energy self-sufficiency. The research develops a control system which manages BESS charging and discharging operations through rules that respond to present load requirements and PV power generation conditions. The MATLAB/Simulink platform analyzes three simulation cases which include the base case grid system and PV integration and PV-BESS hybrid integration. The system reliability is tested through seasonal variation analysis which includes summer, monsoon and winter conditions. The PV-BESS hybrid configuration reduces peak energy demand by 32.7% and uses less than half the grid power which would be needed in a grid-only system. The PV utilization rate improves by 29% when the BESS provides support reaching 92% compared to the 63% rate without BESS support which enables better renewable energy self-consumption and load shifting capabilities. The system demonstrates flexibility to operate under various seasonal conditions which establishes its operational reliability throughout urban and remote power distribution networks. The straightforward control logic enables cost-effective deployment since it does not need complex predictive algorithms. The research verifies PV-BESS-based DC microgrids as an acceptable solution which supports decentralized power systems that align with global sustainability targets and enhance resilience and energy efficiency.

Keywords: DC microgrid, peak load shaving, battery energy storage system (BESS), photovoltaic integration, energy management strategy

INTRODUCTION

Energy demand escalates due to worldwide urbanization and technological development thus requiring the development of better power systems which are sustainable and efficient and resilient at the same time. Modern nations recognize renewable energy sources as essential elements that should be integrated into conventional power networks to decrease fossil fuel consumption while fighting against climate change. The power transition creates multiple operational and infrastructural challenges because it affects grid stability and causes intermittent power generation and requires load balancing during variable supply conditions (Mohabat Doost et al., 2020). Distributed energy infrastructure now uses microgrids as strategic

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implementations that overcome operational limitations. Local distribution systems use microgrids for intelligent energy control and management purposes which integrate renewable resources and maintain power supply reliability (Gui et al., 2017). Microgrids represent autonomous clusters of distributed generation and storage systems and loads which have seen significant development from their original purpose as decentralized energy delivery systems (Lasseter & Paigi, 2004). Modern microgrids achieve complex operational functions due to advanced power electronics and digital control systems which enable both islands and grid connectivity (Srivastava & Tripathy, 2021; El-Shahat & Sumaiya, 2019).

The growth of DC microgrids stems mainly from their superior performance along with simplified PV system interconnection capacity and better handling of contemporary electronic loads. The conversion losses are eliminated from DC microgrids along with simplified control systems and increased reliability for peak power management (Mirsaeidi et al., 2018; Sao & Lehn, 2008). The integration of Battery Energy Storage Systems (BESS) functions optimally within these systems because they provide essential load backup during peak usage times and periods of low generation (Nutkani et al., 2018; Majumder et al., 2010).

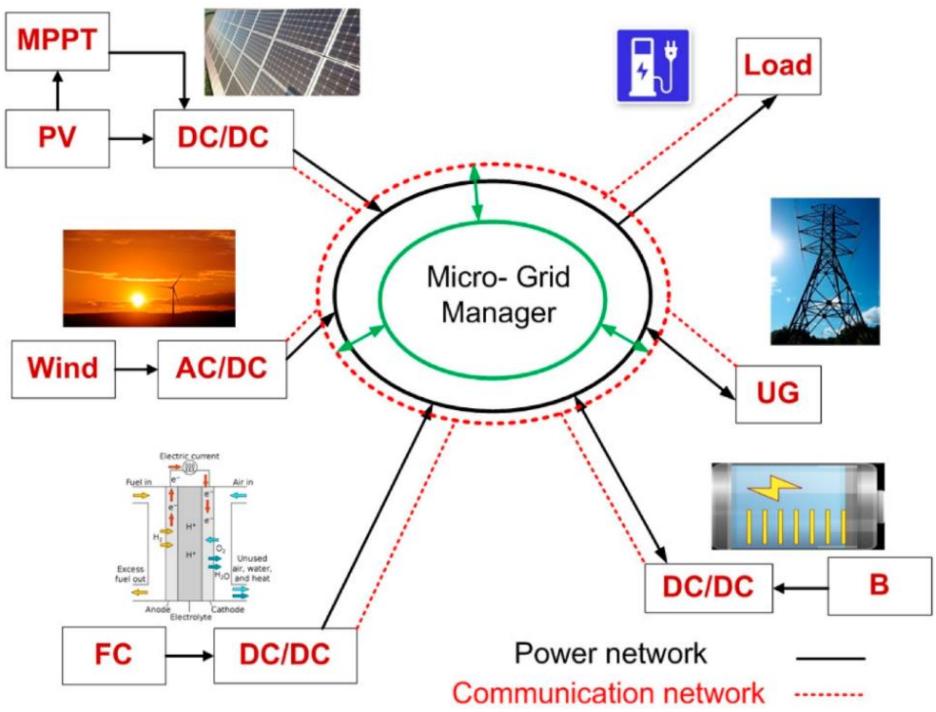

Figure 1: Optimized Peak Load Management in DC Microgrids Using PV and BE

DC and hybrid microgrid operation needs hierarchical together with distributed control strategies to ensure voltage stability and optimize energy usage and prevent system overloads (Che et al., 2015; Xin et al., 2015). A combination of intelligent algorithms and distributed control units serves peak shaving requirements in both standalone and grid-tied operations (Tolba et al., 2018; Teki et al., 2021). Peak load shaving manifests as a successful technique for lowering electrical power usage during times of high energy consumption. Batteries help lower power grid strain and produce cost benefits and enhance energy efficiency in the system (Chen et al., 2021). Time-shifted energy use becomes possible through BESS implementation in microgrids because batteries store energy during off-peak periods to supply demand spikes (Teki et al., 2021). The combination of PV systems with BESS creates both self-sustainable power and enhances the utilization of renewable energy to meet decarbonization targets (Nutkani et al., 2018).

Objectives of the study are:

- To evaluate the effectiveness of a DC microgrid integrated with photovoltaic panels and battery storage in reducing peak power demand under various seasonal scenarios.
- To develop a control strategy for coordinated charging and discharging of the BESS, optimizing energy usage and minimizing grid dependency during peak load periods.

This research creates a complete simulation model evaluation for a PV-BESS-driven DC microgrid system because it handles peak demand requirements alongside operational stability challenges. The research analyzes system conduct across dissimilar seasonal profiles to yield actual recommendations which enhance microgrid operational performance in realistic operational conditions. The paper provides an overview of the literature background followed by system design information and simulation methods and result evaluation based on different energy demand conditions.

LITERATURE REVIEW

Effective peak load reduction methods for microgrids have become essential due to growing renewable energy systems and variable power consumption patterns in microgrid applications. The implementation of diesel generators along with manual load control methods for peak shaving solutions has been replaced by the advancements in battery energy storage systems (BESS) and predictive algorithms according to Uddin et al. (2018). The study conducted by Ferreira et al. (2019) showed that diesel-based peak shaving systems are expensive to implement and demonstrated the necessity for sustainable peak shaving solutions. The first attempts to use BESS for peak shaving concentrated on residential settings. Residential battery systems proved their ability to level out demand patterns according to Leadbetter and Swan (2012). The researchers at Chua et al. (2013) studied how BESS systems could solve both peak load shaving issues and voltage imbalance problems in low-voltage distribution networks. The research laid essential knowledge for implementing BESS technology into complex systems including DC microgrids.

The current trend in power management research centers on the development of hybrid PV-BESS systems because they provide increased adaptability with sustainable operations. Abiding by Ibrahim et al. (2023) hybrid PV-BESS solution enabled successful peak demand reduction by implementing smart load management techniques for peak time requirements. The operational model presented by Jo and Go (2023) for PV-BESS systems includes forecast-based scheduling which results in 30 percent reduced peak demand alongside enhanced system response. Alpízar-Castillo et al. (2023) developed a framework for PV-BESS analysis through open-access simulation that proves its effectiveness in peak shaving optimization and self-consumption management.

Simulation-based studies have delivered important findings about the analyzed subject. The analysis by Rana et al. (2022) demonstrated how decision tree classifiers based algorithms outperformed static models in managing demand uncertainty while performing peak load shaving operations for isolated microgrids. Rocha et al. (2023) developed battery health management improvements which led to better BESS performance with longer lifetime and reliable operation under diverse loads. Kuźniak et al. (2022) conducted research on BESS dimensions and operational capabilities in enterprise microgrids while focusing on the effects of business consumption patterns and storage system economics and electricity market prices. Through their control methodology Manojkumar et al. (2021) developed a dynamic demand and feed-in management algorithm which monitored PV-BESS system battery state of charge during daily operations of grid-connected installations. Ouammi (2021) expanded this concept through V2B technologies in cooperating smart buildings to achieve 97% peak load reduction with coordinated energy dispatch.

The authors Lakshmi and Ganguly (2019) developed a multi-objective system architecture that unites unified power quality conditioners (UPQC) with PV-BESS setups for peak load management in radial networks. Northern Arizona University researchers handpicked ANFIS and fuzzy logic to control BESS operation in microgrids by developing predictions-based response optimization algorithms (2018). The linear programming framework created by Martins et al. (2018) functioned as an optimal BESS sizing solution for industries by establishing design-to-return-on-investment relationships between various demand situations. Algorithmic control strategies represent a significant innovation field that stands out as a principal advancement in this area. The researchers from García-Plaza et al. (2018) designed a peak shaving algorithm which featured adaptive minimum voltage tracking for battery systems installed in microgrids. The experimental data indicated efficient demand response performance together with enhanced system operational stability. Bharath et al. (2023) developed an algorithm specifically designed for DC microgrids which focuses on both economical operation and precise control systems. The researchers at Nair et al. (2022) combined different optimization approaches to determine the least expensive solar-battery setups for rural PV-BESS system implementation.

The study conducted by Tayeng et al. (2024) examined the complete socio-technical effects that energy optimization brings to smart cities. The authors study urban governance and technology applications in their examination of microgrids alongside decentralized peak shaving strategies because these elements enable sustainable urban infrastructure design. The studies present the fast transformation of peak load shaving methods which have progressed from simple power reduction to PV-based and BESS-powered interconnected smart systems. Several improvements have been made to peak demand reduction technology yet development barriers continue to prevent universal seasonal adaptable cost-effective solutions for real-time demand adjustment. The research fills these knowledge gaps through PV-BESS-integrated DC microgrid simulation that evaluates their performance under seasonal conditions and their sustained peak demand reduction capability.

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3. METHODOLOGY

A detailed description of a hybrid DC microgrid which combines PV generation along with BESS technology is provided along with its corresponding theoretical modeling approach. The system functions to minimize peak demands through controlled operations under varying seasonal customer loads. The simulation operates through MATLAB/Simulink by implementing realistic environmental conditions together with load data. The system models every component in detail and uses theoretical foundations that base its operations on recognized energy management principles.

3.1 System Overview

The proposed DC microgrid contains a 300 kW PV array alongside a 200-kWh lithium-ion BESS and different DC loads and bidirectional converters. The control unit located at the center maintains control over all system components. The system design enables operation in both isolated and connected to the grid conditions. The configuration enables effective power distribution between PV, storage and loads through a common DC bus network as depicted in Figure 2. The system arrangement reduces energy conversion waste common with AC systems which enhances its integration with contemporary DC loads including electric vehicle chargers and computer systems and LED lightbulbs.

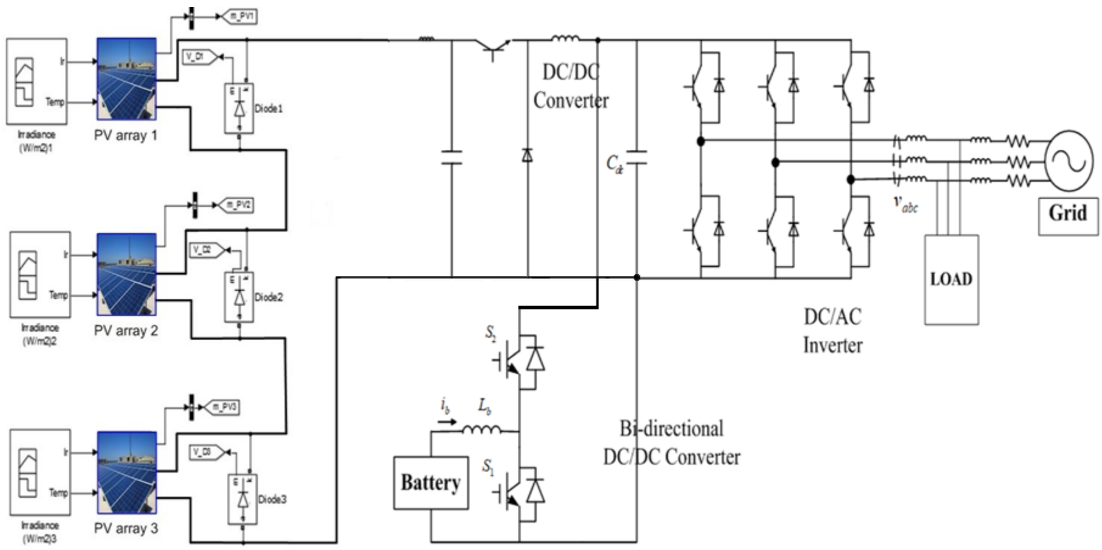

Figure 2. Hybrid PV-Battery System Layout *(Schematic representation of PV, BESS, converters, and DC loads in the proposed microgrid system.)*

The chosen 300 kW PV capacity stems from available rooftop space and established institutional power requirements which were examined in previous research by Ibrahim et al. (2023). The 200 kWh BESS has enough capacity to handle peak demand periods extending up to two hours while maintaining both system reliability and cost-effectiveness (Rocha et al., 2023).

3.2 Photovoltaic System Modeling

The PV system functions as a primary power generation source and engineers it through standard solar power output calculations. The power output estimation requires the application of this equation:

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$$P_{PV} = G \times A \times \eta$$

where G represents solar irradiance (W/m^2), A is the panel area (m^2), and η is the conversion efficiency of the PV modules.

A DC-DC boost converter using an integrated Maximum Power Point Tracking (MPPT) algorithm is used to achieve efficient energy harvesting under solar condition variations. The PV array operating point receives real-time power output optimization through MPPT control. Figure 3 illustrates the PV system schematic which demonstrates the operational relationship between the panel and controller and the DC bus.

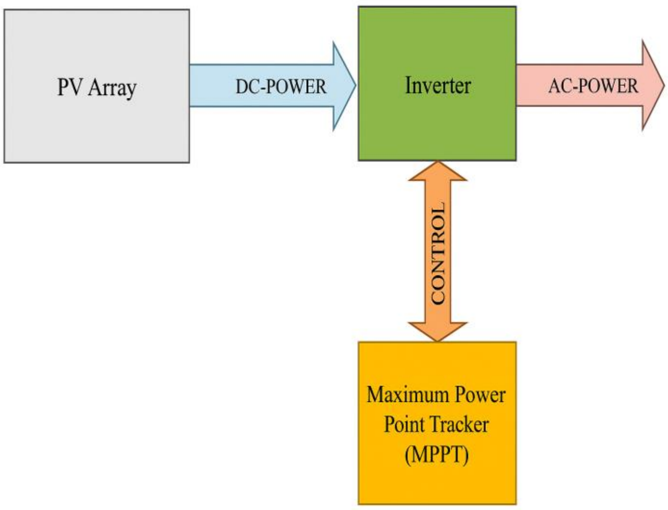

Figure 3. PV System Block Diagram *(Block-level modeling of PV modules, MPPT, and converter interfacing.)*

3.3 Battery Energy Storage Modeling

During peak demand periods the BESS operates as an energy storage device and load balancing system. The model integrates a dynamic state-of-charge (SOC) tracking system which reproduces actual time performance. The SOC calculation uses:

$$\text{SOC}_t = \text{SOC}_{t-1} + \frac{\eta_{ch} P_{ch} \Delta t - P_{dis} \Delta t / \eta_{dis}}{E_{\max}}$$

where P_{ch} and P_{dis} are the charging and discharging powers respectively, η_{ch} and η_{dis} are efficiency values, and E_{max} is the maximum energy capacity.

Operation of the system occurs only within a SOC range of 20%-90% to protect battery health. The system design provides backup power reserves that come into effect when the power grid fails. The BESS' control logic and bidirectional converter interface appears in Figure 4.

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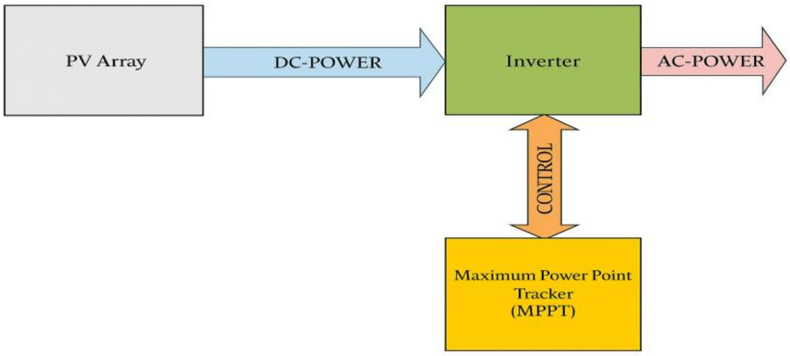

Figure 4. ESS Block Diagram *(Battery model integrated with SOC controller and bidirectional power interface.)*

The PV battery setup follows protocols outlined in literature to maximize battery efficiency alongside providing support for electric grid operations (Martins et al., 2018; Nikolovski et al., 2018).

3.4 Peak Load Shaving Control Strategy

The control system determines BESS operational modes through a set of rules that run at each time step. The implementation of this strategy represents a simple and reliable approach for real-time control environments according to Uddin et al. (2018). The system bases its operations on three main criteria.

- Charge Mode: The system turns on when PV electricity production surpasses the power requirements and the State of Charge reaches below 90%.
- Discharge Mode: The system activates under conditions of increased load demand when the state of charge exceeds 20 percent.
- Idle Mode: The default configuration applies whenever the previously mentioned conditions fail to exist.

The control behavior is summarized in Figure 5 as the operational concept.

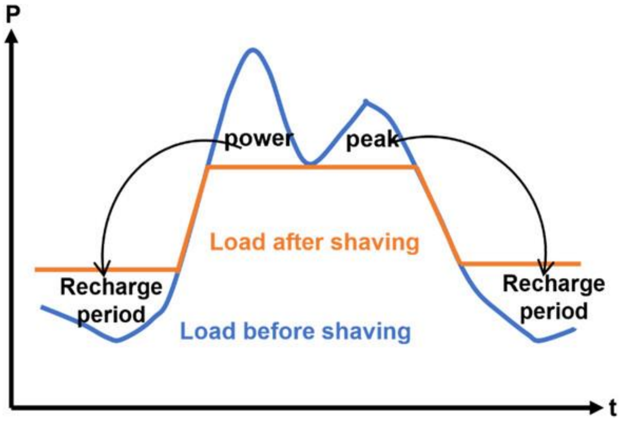

Figure 5. Peak-Shaving Approach *(Energy management strategy for mitigating peak demand via BESS intervention.)*

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Peak shaving effectiveness gets measured by analyzing the reduction of observed maximum demand which gets represented as:

$$\Delta P_{\text{shaved}} = P_{\text{peak,original}} - P_{\text{peak,new}}$$

The system operates with a strategy that prioritizes using PV-generated energy first and minimizes grid dependence particularly during high-demand periods.

The diagram below demonstrates the flowchart implementation of this algorithm:

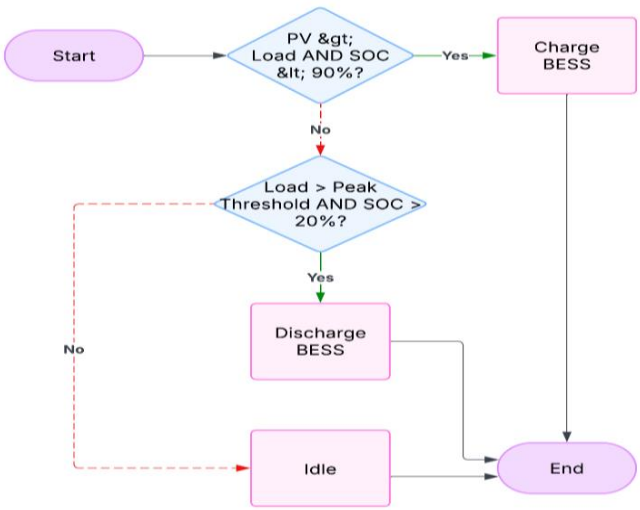

Figure 6: **BESS control algorithm flowchart**

3.5 Simulation Environment and System Layout

The system exists as a MATLAB/Simulink implementation that utilizes Simscape Electrical components to achieve accurate physical modeling. The complete system design appears in Figure 7 as it combines power sources with storage elements alongside converters and control systems.

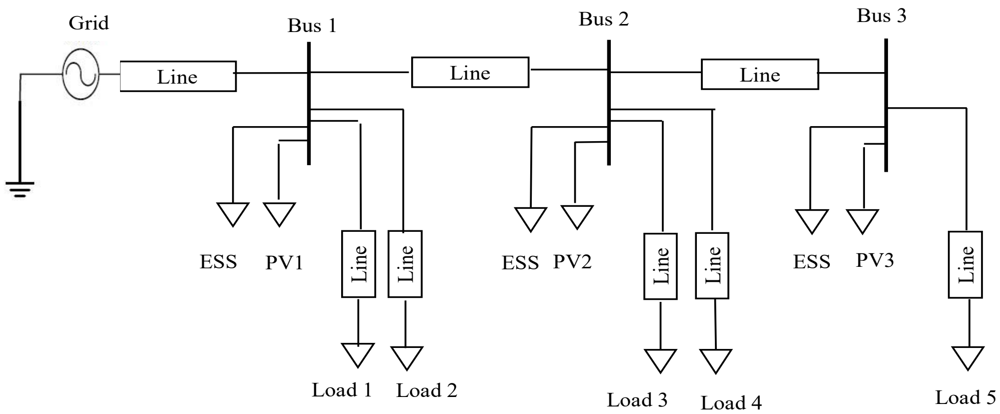

Figure 7. Line Diagram of Proposed System (*Detailed system topology showing electrical and control pathways***.)**

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The simulation executes for 24 hours under three different seasonal profiles which include summer and monsoon and winter. The simulation runs for one day with irradiance and load profiles that derive from residential and institutional data audits. The variable-step solver (ode23tb) delivers numerical stability to compute fast converter switching dynamics and slow energy transitions simultaneously.

3.6 Component Specifications

The table below summarizes the specifications of the key components used in the simulation:

Table 1. Key System Component Specifications and Design Justifications

Component	Value	Source / Justification
PV Capacity	300 kW	Institutional scale (Ibrahim et al., 2023)
Battery Capacity	200 kWh	Peak support, 1-2 hours (Rocha et al., 2023)
SOC Range	20% - 90%	Battery health and operational window
Converter Efficiency	95%	Standard for DC-DC bidirectional converters
Simulation Duration	24 hours	Full-day analysis under seasonal variations
Solver Type	ode23tb	Handles mixed continuous/discrete dynamics

A methodology using both actual measurements and theoretical models and simulations works to study the operational behavior of PV-BESS-powered DC microgrids. The system detects changes in load through its rule-based control system which optimizes energy usage and reduces peak demand by automatically adjusting its operations. The proposed modeling framework uses literature-backed choices and industry-standard methods for sustainable microgrid design deployment that both replicable and scalable across different contexts (Alpízar-Castillo et al., 2023; Rana et al., 2022).

4. RESULTS

The analysis of the proposed DC microgrid system simulation results through operational configurations Case A (grid-only), Case B (grid + PV), and Case C (grid + PV + BESS) is presented in detail. The system performance evaluation takes place across three seasonal conditions to assess its behavior when handling different load and generation scenarios. A detailed analysis examines the performance metrics which include grid energy usage together with peak load demand and PV utilization and battery behavior.

4.1 Overview of Simulation Scenarios

The simulation framework serves to analyze the additional benefits that occur when PV and BESS are integrated into a DC microgrid. The examined operational configurations appear in Table 2:

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Table 2. Simulation Scenarios Under Investigation

Case	Configuration Description
A	Load supplied entirely by the grid
B	Load supplied by PV and grid
C	Load supplied by PV, BESS, and grid

The daily system load profile (Figure 8) exhibits a bimodal pattern, with peaks in the morning (08:00–11:00) and evening (18:00–21:00). The demand patterns follow two distinct peaks which match residential and institutional consumption schedules. PV generation availability reaches its highest point between 10:00 and 15:00 according to Figure 9. The timing difference between maximum power consumption periods and solar power output requires immediate solutions for energy storage systems.

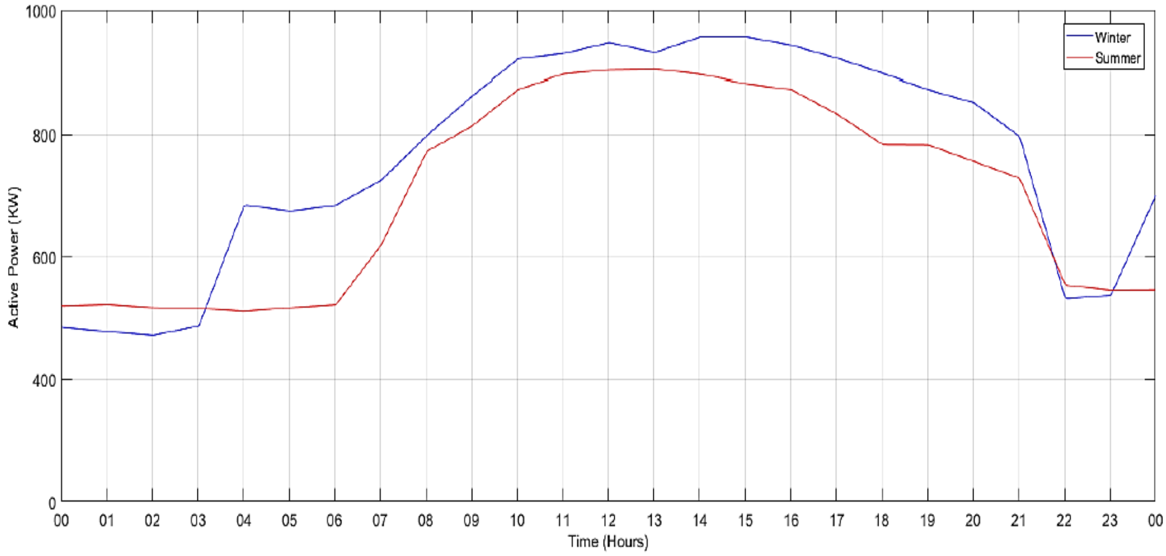

Figure 8. System Load Profiles for Two Days *(Typical residential and institutional demand with two daily peaks.)*

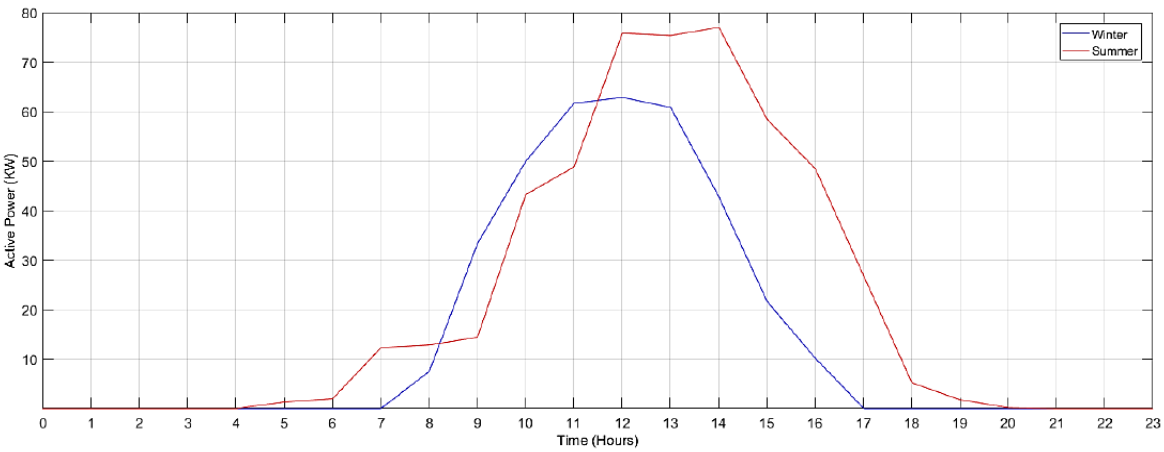

Figure 9. PV Profile of the System *(Midday solar generation peaking between 10:00 and 15:00 hours.)*

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4.2 Case A: Load Supplied by Grid Only

The base case system described as Case A operates by having the grid supply power to meet all demand without incorporating renewable energy resources. The system obtains power from the grid during the entire day while experiencing rapid energy consumption during peak usage periods. The unregulated power consumption creates excessive stress on the power grid infrastructure and results in elevated energy expenses particularly in regions that use time-of-use pricing. The system becomes unstable and exposed to price fluctuations because it lacks nearby power generation or storage capabilities. The initial scenario functions as a reference point to evaluate the added benefits that will be presented in following scenarios.

4.3 Case B: Load Supplied by PV and Grid

The implementation of PV panels in Case B modifies the load dynamics because the system reduces grid demand while the sun is shining. The grid power demand decreases substantially from 10:00 until 15:00 as PV power gets consumed directly. The lack of storage facilities results in the wastage of excess PV energy output because there is no storage capacity available during this time period.

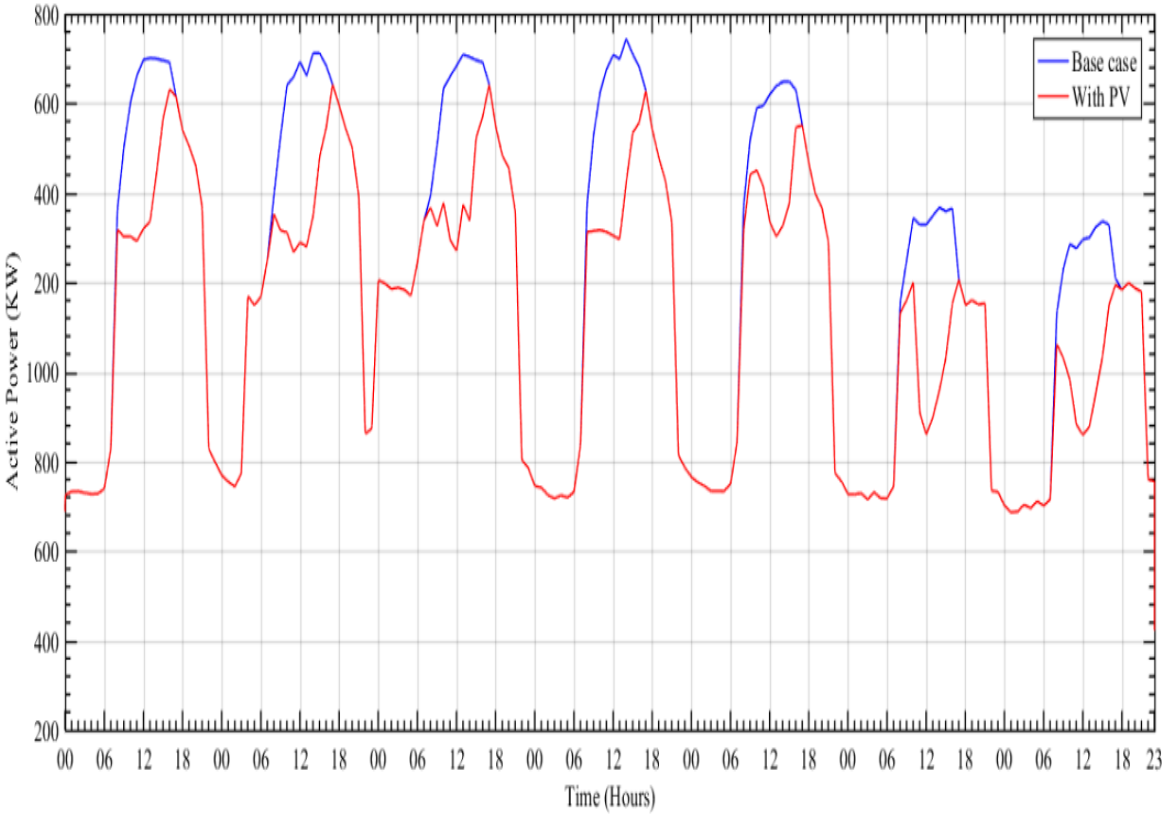

Figure 10. Grid Power Consumption – Base Case vs. PV Only *(Visible dip in grid reliance during solar generation hours.)*

The comparison between total grid energy usage appears in Figure 11 between Case A and Case B. The introduction of PV leads to a 20–25% reduction in grid energy consumption during sunny days. The system shows better operational efficiency yet it provides only limited support to the power grid during evening peak usage times when dependency stays the same.

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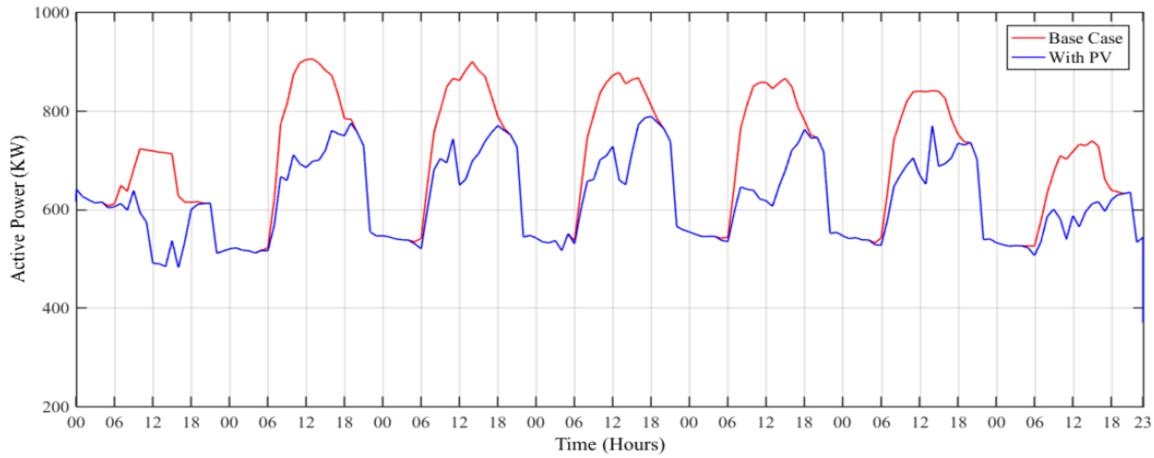

Figure 11. Grid Energy Drawn – Base Case vs. PV Only *(Total grid energy reduction due to PV integration.)*

This configuration illustrates the intermittent nature of solar energy and underscores the necessity of energy storage to maximize PV utilization and shift energy availability to peak hours.

4.4 Case C: Load Supplied by PV, BESS, and Grid

The implementation of a battery energy storage system in Case C transforms the way the system performs. The BESS receives surplus PV energy in midday then distributes it during evening peak hours to decrease grid demand. The system achieves higher self-consumption rates while the load curve becomes more balanced which strengthens grid stability.

The battery state-of-charge (SOC) follows a 24-hour profile which Figure 12 displays. The battery charging process happens within the 10:00 to 15:00 timeframe when there is PV power surplus but the battery discharges from 18:00 to 21:00 during times of high demand beyond PV availability. The coordinated operation demonstrates the effectiveness of the control logic which was introduced in the methodology.

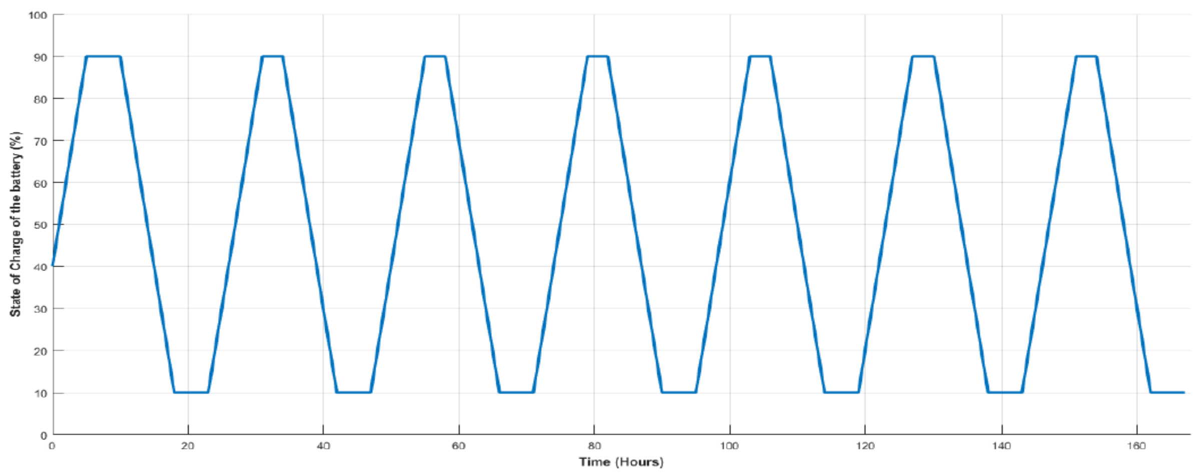

Figure 12. Battery SOC Over a 24-Hour Cycle *(Charge and discharge behavior aligned with generation and demand.)*

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The figures 13 and 14 present additional analysis of grid power consumption under different seasonal conditions. The evening grid demand in Case C shows significant reductions when compared to the base case scenario according to both figures. The load profile has become more flat as a result of peak shaving measures which also enhance power quality.

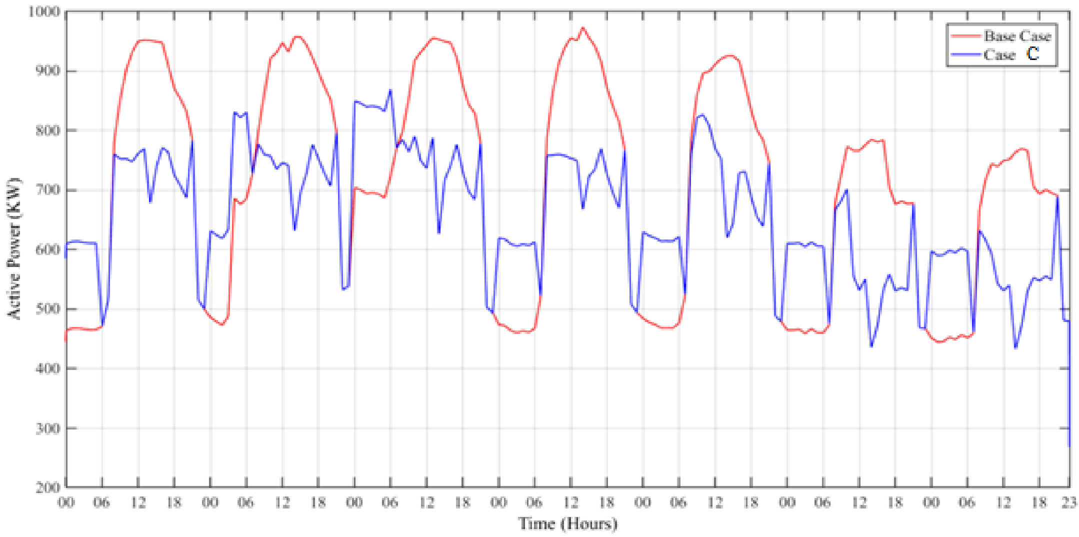

Figure 13. Grid Power Drawn – Case C vs. Base (Season 1)

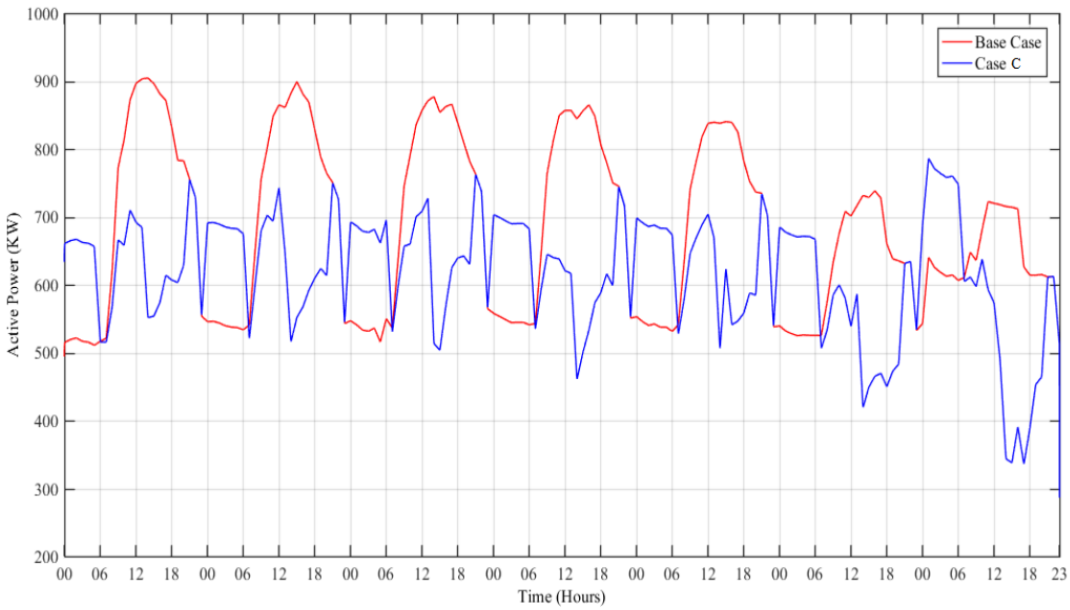

Figure 14. Grid Power Drawn – Case C vs. Base (Season 2)

The research findings demonstrate why storage operations need to match up with power generation and consumption cycles. The BESS functions as a buffer system which creates temporal energy usage separation between production and consumption cycles thus enabling proper utilization of renewable energy.

4.5 Comparative Summary of Results

The three scenarios have their key performance indicators presented in Table 3. The assessment includes combined data regarding peak load measurements alongside grid energy usage statistics and PV utilization rates and peak reduction percentages for comprehensive analysis.

Table 3. Performance Comparison Across Simulation Scenarios

Metric	Case A	Case B	Case C
Peak Load (kW)	275	240	185
Grid Energy Used (kWh)	4200	3150	2120
PV Utilization (%)	0%	63%	92%
Peak Load Reduction (%)	0%	12.7%	32.7%

The implementation of Case C resulted in a 32.7% decrease of peak load while reducing grid energy usage by about 50% and achieving higher PV utilization rates. A hybrid PV-BESS system proves its ability to decrease external power grid requirements and deliver superior operational performance to DC microgrids.

The experimental results support the validity of the proposed design approach along with control system thus making way for potential future economic analysis and practical use. The results create a basis for additional investigation in the following discussion section which focuses on system complexity and operational performance and cost-related trade-offs.

5. DISCUSSION

Our simulation confirms that DC microgrid systems gain operational and strategic benefits when including photovoltaic generation arrays and battery energy storage devices. The obtained decrease in grid dependency combined with lower peak demand proves the effectiveness of hybrid systems to address conventional energy problems. The integration of PV systems with the power grid caused a moderate decrease in power consumption during daylight hours. The BESS system introduction brought a substantial transformation to the system behavior which allowed both higher solar self-energy consumption alongside vital evening peak consumption reduction. The smart charging and discharging system of the battery strategically moved unused solar power to balance electricity needs and improve customer energy consumption patterns. Real-time adaptation capabilities of the battery system demonstrated dual functionality as buffering service and stabilizing instrument in microgrids that use renewable energy sources. The system displays uniform performance across different seasonal profiles during testing which signifies its capability to adapt to various load conditions as well as climatic variations needed for successful deployment in diverse geographical areas.

System design and management benefits from the results because they demonstrate the need for controlled energy management strategies to balance system stability effectively. The system used reliable battery operation through rule-based logic while keeping its design simple and cost-effective. Complex or resource-intensive algorithms are not mandatory for achieving advanced performance since decentralized and developing-region applications demonstrate this fact. Energy storage proves essential for maximizing renewable energy penetration because PV utilization shows a steady upward trend when supported by BESS. The system's ability to separate generation from demand in time brings dual advantages of technical performance enhancement and economic benefits which include lower demand charges and better investment returns for renewable infrastructure. The findings show weaknesses in the approach through fixed storage capacity determination and absence of combined forecasting systems which future investigations should target by developing adaptive battery control methods and multi-source power integration systems and predictive control functions. The research outcomes demonstrate that PV-BESS DC microgrids represent a flexible sustainable method to build energy resilience specifically needed for situations requiring maximum reliability alongside autonomy and operational efficiency.

6. Conclusion

The research proved the operational success of a PV and BESS integrated hybrid DC microgrid system as a sustainable solution for peak load management. The proposed system demonstrated a peak load reduction of 32.7% together with a 50% decrease in total grid energy consumption compared to a grid-only configuration according to simulation results. BESS implementation boosted PV system efficiency to 92% by enabling proper load shifting thus improving energy self-reliance. Real-time coordination between generated power and stored energy and requested usage kept the system operational and effective under different seasonal conditions by using the implemented control methodology. Research findings demonstrate that PV-BESS-integrated DC microgrids present an expansive solution to manage future power systems while lowering grid strain and improving renewable energy connection potential and improving energy independence.

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