Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Optimization of Decentralized Hybrid Microgrids using AI-Driven Smart Controllers for Rural Electrification in Pakistan

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ABSTRACT

The persistent energy deficit and limited grid infrastructure in rural regions of Pakistan necessitate the development of sustainable and decentralized energy solutions. Hybrid microgrids, integrating renewable energy sources such as solar photovoltaic (PV), wind energy, and battery energy storage systems (BESS), offer a promising approach to ensure reliable and cost-effective electrification in remote areas. However, the intermittent nature of renewable resources and dynamic load variations present significant challenges in achieving optimal energy management and system stability. This study proposes an advanced optimization framework for decentralized hybrid microgrids using AI-driven smart controllers to enhance performance, reliability, and economic feasibility. The proposed system incorporates intelligent energy management strategies based on machine learning and reinforcement learning techniques to enable real-time decision-making. These smart

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controllers are designed to perform accurate load forecasting, renewable generation prediction, and adaptive power flow control, ensuring efficient utilization of available energy resources. A comprehensive microgrid model is developed and simulated using MATLAB to evaluate system performance under varying operational conditions. Optimization techniques, including metaheuristic algorithms such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), are integrated with AI models to minimize power losses, reduce operational costs, and maintain voltage stability. The proposed framework is further validated through comparative analysis with conventional control strategies, demonstrating significant improvements in system efficiency, energy reliability, and cost savings. The results highlight the potential of AI-based smart controllers in transforming rural electrification by providing scalable, resilient, and sustainable energy solutions. This research contributes to the advancement of intelligent microgrid systems and offers practical insights for policymakers and energy planners aiming to address Pakistan's rural energy challenges.

Keywords: Hybrid Microgrid; Artificial Intelligence; Smart Controllers; Rural Electrification; Renewable Energy Integration; Energy Optimization; Load Forecasting; Battery Energy Storage System; Reinforcement Learning; Pakistan.

Introduction:

Access to reliable and affordable electricity remains a major challenge in rural regions of Pakistan, where a significant portion of the population continues to face energy shortages and limited grid connectivity. The conventional centralized power generation and distribution system is often inefficient, expensive, and difficult to extend to remote and geographically dispersed areas. As a result, many rural communities rely on unreliable energy sources such as diesel generators or remain entirely off-grid, which negatively impacts socio-economic development, education, healthcare, and agricultural productivity [1]. In this context, decentralized energy systems have gained increasing attention as a practical and sustainable solution. Among these, hybrid microgrids have emerged as a highly effective approach for rural electrification. A hybrid microgrid integrates multiple energy sources such as solar photovoltaic (PV), wind energy, and battery energy storage systems (BESS), ensuring a more stable and continuous power supply. Pakistan is endowed with abundant renewable energy resources, particularly solar and wind, which can be effectively utilized to support such systems. However, the variability and intermittency of renewable energy sources, combined with dynamic and uncertain load demands, create significant challenges for system stability, reliability, and efficient energy utilization [2]. Effective energy management plays a crucial role in overcoming these challenges. Traditional energy management strategies are typically based on rule-based or deterministic control methods, which lack the flexibility and adaptability required for complex and dynamic microgrid environments. These conventional approaches often fail to optimize system performance under varying conditions, leading to increased operational costs and reduced reliability.

Artificial intelligence (AI) has recently emerged as a powerful tool for addressing these limitations. AI-driven techniques, including machine learning (ML) and

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reinforcement learning (RL), enable intelligent decision-making by learning from historical and real-time data [3]. These methods can be applied to load forecasting, renewable energy prediction, demand-side management, and adaptive control of power flow within microgrids. By incorporating AI into energy management systems, it becomes possible to significantly enhance system efficiency, reliability, and responsiveness. To better understand the advantages of AI-based control over conventional methods, a comparison is presented in Table 1.

Table 1: Comparison of Conventional and AI-Based Energy Management Approaches

Feature	**Conventional Control Methods**	**AI-Based Smart Controllers**
Decision-Making	Rule-based / predefined	Data-driven and adaptive
Handling Uncertainty	Limited	High capability
Load Forecasting Accuracy	Low to moderate	High
Renewable Prediction	Basic estimation	Advanced predictive modeling
Real-Time Adaptability	Low	High
System Optimization	Limited	Multi-objective optimization
Computational Intelligence	Not applicable	Machine learning & reinforcement learning

Despite the advantages of AI, there is still a lack of comprehensive frameworks that integrate AI-driven smart controllers with advanced optimization techniques specifically tailored for rural electrification in Pakistan. Most existing studies focus either on system design or optimization independently, without addressing real-time operational challenges and uncertainties in a unified manner. To address these research gaps, this study proposes an advanced optimization framework for decentralized hybrid microgrids using AI-driven smart controllers. The proposed system integrates machine learning and reinforcement learning techniques for intelligent energy management, along with metaheuristic optimization methods such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to achieve optimal system performance. A detailed microgrid model is developed and simulated in MATLAB to evaluate its performance under varying operating conditions. The main contributions of this research include the development of an intelligent control strategy for hybrid microgrids, the integration of AI with optimization techniques for improved decision-making, and a comprehensive analysis of system performance in the context of rural Pakistan. The proposed framework aims to provide a scalable, reliable, and cost-effective solution for rural electrification, while offering valuable insights for policymakers, engineers, and energy planners working towards sustainable energy development.

Smart Hybrid Microgrids for Rural Electrification:

Hybrid microgrids have emerged as one of the most effective and sustainable solutions for rural electrification, particularly in developing countries where the

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extension of conventional grid infrastructure is both economically burdensome and technically impractical. In countries like Pakistan, a large portion of the rural population resides in geographically dispersed areas, making centralized power distribution inefficient and costly. As a result, decentralized energy systems based on hybrid microgrids offer a reliable alternative for ensuring energy access. A hybrid microgrid integrates multiple energy generation sources such as solar photovoltaic (PV), wind energy, biomass, and diesel generators, along with battery energy storage systems (BESS). This combination of diverse energy resources enhances system reliability by compensating for the intermittency of renewable sources. For instance, solar energy is available during daylight hours, while wind and biomass can supplement energy generation at other times, ensuring a continuous power supply [4]. The inclusion of battery storage further stabilizes the system by storing excess energy and supplying it during periods of low generation. In addition to improving reliability, hybrid microgrids contribute significantly to reducing greenhouse gas emissions and dependency on fossil fuels. Diesel generators, when used in hybrid configurations, operate less frequently, thereby lowering fuel consumption and operational costs. This makes hybrid microgrids not only environmentally sustainable but also economically viable in the long term. Pakistan has significant potential for renewable energy generation, particularly in solar and wind resources. The country receives high solar irradiance throughout the year, especially in regions such as Punjab and Balochistan, making solar PV a highly suitable option for rural electrification. Similarly, wind corridors in Sindh provide additional opportunities for hybrid energy generation. By leveraging these natural resources, hybrid microgrids can play a crucial role in addressing energy shortages and supporting rural development.

Table 2: Key Components and Typical Performance Values of Hybrid Microgrids

Component	Typical Capacity Range	Efficiency (%)	Cost Range (USD)	Role in System
Solar PV System	1 – 100 kW	15 – 22%	800 – 1200/kW	Primary renewable energy source
Wind Turbine	1 – 50 kW	30 – 45%	1200 – 2000/kW	Supplementary generation
Biomass Generator	5 – 100 kW	20 – 30%	1000 – 3000/kW	Continuous and dispatchable energy
Diesel Generator	5 – 50 kW	30 – 40%	300 – 800/kW	Backup and emergency supply
Battery Storage (BESS)	5 – 500 kWh	85 – 95%	200 – 600/kWh	Energy storage and load balancing
Energy Management System	System dependent	High	Variable	Intelligent control and optimization

The data presented in Table 2 highlights the typical operational characteristics and economic aspects of various components used in hybrid microgrids. It is evident that renewable energy sources such as solar and wind provide clean energy at moderate

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efficiency levels, while battery storage systems offer high efficiency and play a crucial role in maintaining system stability. The inclusion of cost ranges further emphasizes the economic feasibility of hybrid microgrids, particularly when optimized through intelligent control strategies. Figure 1 illustrates the general architecture and operational framework of a hybrid microgrid system designed for rural electrification.

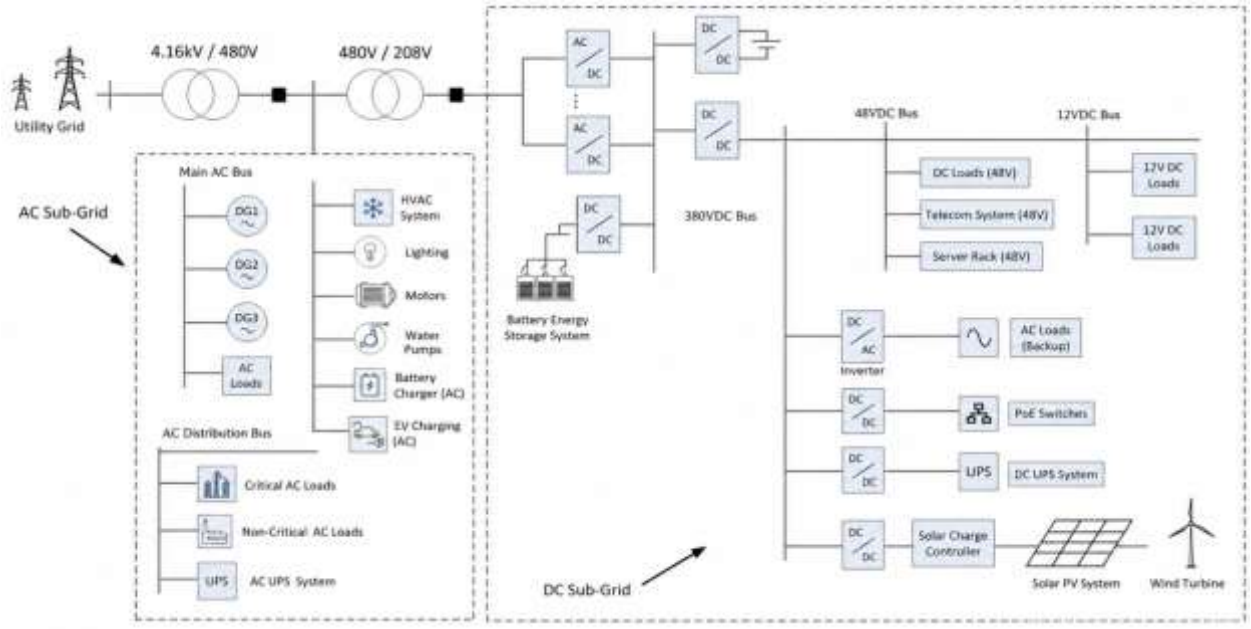


Figure 1: Block Diagram of Hybrid Microgrid System

The system consists of multiple interconnected components, including solar PV panels, wind turbines, and biomass generators, all connected to a common power bus. The battery energy storage system stores excess generated energy and supplies it during periods of low generation or peak demand. A diesel generator acts as a backup source to ensure uninterrupted power supply. The entire system is coordinated through an energy management system (EMS), which intelligently controls energy flow, balances supply and demand, and maintains overall system stability for rural consumers such as households, farms, and small businesses.

Reinforcement Learning for Intelligent Microgrid Control:

Reinforcement Learning (RL) has emerged as a powerful artificial intelligence technique for solving complex control problems in dynamic and uncertain environments. Unlike traditional control methods that rely on predefined rules or mathematical models, RL enables systems to learn optimal control strategies through continuous interaction with the environment [5]. This learning process is based on trial-and-error, where an agent takes actions, observes system responses, and receives rewards or penalties, gradually improving its decision-making policy over time. In the context of hybrid microgrids, RL-based controllers offer significant advantages due to their adaptability and ability to handle uncertainties associated with renewable energy generation and fluctuating load demand. Microgrid environments are inherently stochastic, as solar irradiance, wind speed, and energy consumption patterns vary

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continuously. RL algorithms can effectively manage these variations by dynamically adjusting control actions such as power dispatch, battery charging/discharging, and load scheduling. One of the key strengths of RL is its ability to operate without requiring explicit system models [6]. This makes it particularly suitable for real-time applications where system parameters may not be fully known or may change over time. RL-based controllers can be applied to various microgrid functions, including adaptive power flow control, demand response management, voltage regulation, and energy scheduling. Over time, the controller learns to optimize system performance by maximizing cumulative rewards, which are typically defined in terms of cost reduction, efficiency improvement, and reliability enhancement. To better understand the capabilities of different RL approaches in microgrid applications, a comparison is presented in Table 3.

Table 3: Performance Comparison of Reinforcement Learning Techniques in Microgrids

RL Technique	**Learning Type**	**Convergence Speed**	**Complexity Level**	**Typical Application**	**Performance Improvement**
Q-Learning	Model-free	Moderate	Low	Basic energy scheduling	10 – 15%
Deep Q-Network (DQN)	Deep learning-based	High	Medium	Load management, control systems	15 – 25%
SARSA	On-policy	Moderate	Low	Real-time control	10 – 18%
Deep Deterministic Policy Gradient (DDPG)	Continuous control	High	High	Power flow optimization	20 – 30%
Proximal Policy Optimization (PPO)	Policy-based	Very High	High	Large-scale microgrid control	25 – 35%

The comparison demonstrates that advanced RL techniques such as DQN, DDPG, and PPO provide higher performance improvements compared to traditional methods like Q-learning and SARSA. Although these advanced methods involve higher computational complexity, they offer faster convergence and better adaptability, making them highly suitable for complex and large-scale hybrid microgrid systems. Figure 2 illustrates the operational framework of a reinforcement learning-based smart controller for hybrid microgrid energy management.

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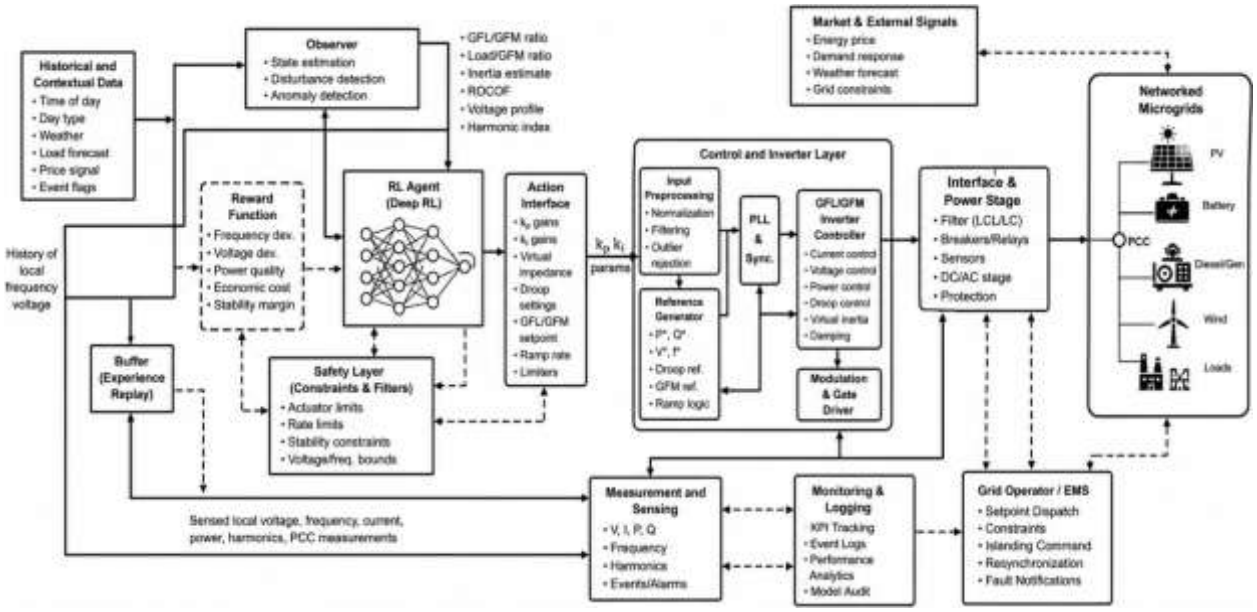


Figure 2: Reinforcement Learning-Based Microgrid Control Framework

The framework consists of an RL agent interacting with the microgrid environment. The environment includes renewable energy sources (solar PV and wind), battery storage, load demand, and grid conditions. The RL agent continuously observes system states such as energy generation, load demand, and battery state of charge (SOC). Based on these observations, the agent selects optimal control actions, such as power allocation, battery charging/discharging, and load management [7]. A reward function evaluates the effectiveness of each action based on criteria such as cost minimization, energy efficiency, and system reliability. Over time, the agent learns an optimal policy that maximizes cumulative rewards, resulting in improved overall system performance. Overall, reinforcement learning provides a flexible and intelligent approach for microgrid control, enabling real-time adaptation, improved efficiency, and enhanced reliability. Its ability to learn from experience and operate under uncertainty makes it a key enabler for next-generation smart microgrid systems, particularly in rural electrification scenarios where operating conditions are highly variable.

Methodology:

This study adopts a systematic and integrated methodology to design and optimize a decentralized hybrid microgrid using AI-driven smart controllers for rural electrification. The approach combines system modeling, artificial intelligence techniques, and metaheuristic optimization to enhance energy management and overall system performance. A detailed hybrid microgrid model incorporating solar PV, wind energy, battery storage, and backup generation is developed and simulated in MATLAB/Simulink. Machine learning and reinforcement learning algorithms are employed to enable intelligent decision-making for load forecasting, renewable energy prediction, and adaptive control of power flow. Furthermore, optimization techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO)

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are integrated to achieve optimal energy scheduling, minimize operational costs, and improve system reliability under varying conditions.

Microgrid System Architecture:

The proposed microgrid system architecture is designed to provide a reliable, efficient, and sustainable energy solution for rural electrification. The system consists of multiple interconnected components that work together to ensure continuous power supply under varying environmental and load conditions. The primary energy sources include solar photovoltaic (PV) panels and wind turbines, which generate clean and renewable electricity. These sources are inherently intermittent; therefore, a battery energy storage system (BESS) is integrated to store excess energy and supply power during periods of low generation or high demand [8]. In addition to renewable sources, a diesel generator is incorporated as a backup unit to guarantee uninterrupted power supply during extreme conditions such as prolonged low solar irradiance or wind unavailability. Although diesel generators are less environmentally friendly, their limited use in hybrid systems significantly enhances system reliability while minimizing fuel consumption and operational costs. All energy sources and storage components are connected through a common AC/DC bus, which acts as a central node for power exchange. The entire system is coordinated by an intelligent Energy Management System (EMS), responsible for monitoring system parameters such as generation levels, load demand, and battery state of charge (SOC). The EMS ensures optimal power flow by dynamically allocating energy resources, thereby improving efficiency, reducing losses, and maintaining voltage stability. The microgrid is designed to operate in both grid-connected and islanded modes [9]. In grid-connected mode, the system can exchange power with the main utility grid, allowing surplus energy export and deficit compensation. In islanded mode, the microgrid operates independently, supplying power solely from local resources. This dual-mode operation enhances system flexibility, resilience, and suitability for rural and remote applications. Table 4 presents the typical configuration and operational parameters of the major components used in the proposed microgrid system.

Table 4: Typical Configuration Parameters of Microgrid Components

Component	**Rated Capacity**	**Operating Range**	**Efficiency (%)**	**Function**
Solar PV Array	10 – 100 kW	200 – 1000 W/m²	15 – 22%	Primary renewable energy generation
Wind Turbine	5 – 50 kW	3 – 25 m/s	30 – 45%	Supplementary power generation
Battery Storage (BESS)	20 – 500 kWh	SOC: 20% – 90%	85 – 95%	Energy storage and load balancing
Diesel Generator	5 – 50 kW	Variable load	30 – 40%	Backup power supply
Power Converter (Inverter)	System dependent	AC/DC conversion	90 – 98%	Voltage and frequency regulation
Energy	Controller-	Real-time	High	Intelligent

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Management System	based	operation		monitoring and control

The operational characteristics and technical capabilities of each component within the microgrid system. It can be observed that renewable sources provide clean energy with moderate efficiency, while battery storage systems offer high efficiency and play a critical role in stabilizing power supply. The integration of backup generation and intelligent control ensures that the system can maintain reliable performance even under uncertain and fluctuating conditions. The microgrid architecture consists of renewable energy sources (solar PV and wind turbine) connected to a common bus through power converters. The battery energy storage system is interfaced with the bus to store excess energy and supply it when required. A diesel generator is connected as a backup source to ensure system reliability. The Energy Management System (EMS) acts as the central controller, continuously monitoring system conditions and managing energy distribution among generation units, storage systems, and loads. The load section includes residential households, agricultural systems, and small-scale rural industries. The architecture supports bidirectional power flow in grid-connected mode and autonomous operation in islanded mode. The proposed microgrid architecture provides a robust and flexible framework for rural electrification, ensuring efficient utilization of renewable energy resources while maintaining system stability and reliability.

Modeling of Hybrid Microgrid System Components:

A detailed and accurate modeling of the hybrid microgrid system is essential for analyzing system performance, evaluating operational efficiency, and enabling effective optimization. In this study, a comprehensive model of the hybrid microgrid is developed to represent the dynamic behavior of each system component under varying environmental and load conditions. The model integrates renewable energy sources, storage systems, and load demand into a unified framework, allowing realistic simulation and performance assessment. The solar photovoltaic (PV) system is modeled based on solar irradiance and ambient temperature conditions, which directly influence its power output [10]. Variations in sunlight intensity throughout the day and seasonal temperature changes are considered to capture realistic generation patterns. Similarly, the wind energy system is modeled using wind speed profiles, taking into account cut-in, rated, and cut-out wind speeds to reflect actual turbine operation. These renewable sources introduce variability into the system, making accurate modeling critical for reliable energy management. The battery energy storage system (BESS) is modeled to track energy storage and discharge behavior using state of charge (SOC) characteristics. The model considers charging and discharging efficiencies, capacity limits, and operational constraints to ensure realistic representation of storage performance. The BESS plays a crucial role in balancing energy supply and demand by storing excess energy during high generation periods and supplying it during deficits [11]. Load demand is modeled as a time-varying parameter based on typical rural consumption patterns. This includes daily and seasonal variations influenced by household usage, agricultural activities, and small-scale industrial loads. The variability in demand is essential for testing the

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Print ISSN 3007-3189
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responsiveness and adaptability of the microgrid system. All components are integrated into a unified simulation environment using MATLAB, which enables dynamic analysis of system performance under different operating scenarios.

Table 5: Detailed Modeling and Operational Characteristics of Hybrid Microgrid Components

Component	Model Type	Input Variables	Output Variables	Typical Range	Efficiency	Dynamic Behavior	Role in Microgrid
Solar PV System	Environmental-based	Irradiance, Temperature	Power Output (kW)	0 – 100 kW	15 – 22%	Highly variable (day/night cycle)	Primary renewable generation
Wind Turbine	Aerodynamic model	Wind Speed	Power Output (kW)	0 – 50 kW	30 – 45%	Stochastic and seasonal	Supplementary generation
Battery Storage (BESS)	SOC-based model	Charge/Discharge Power	SOC (%), Power Flow	20 – 500 kWh	85 – 95%	Fast response, bidirectional	Energy storage & balancing
Diesel Generator	Fuel-based model	Fuel Input, Load Demand	Power Output (kW)	5 – 50 kW	30 – 40%	Stable and controllable	Backup power source
Load Demand	Time-series model	Time, User Behavior	Demand (kW)	5 – 80 kW	N/A	Highly variable	Energy consumption
Energy Management System	AI/Control-based	System States	Control Signals	System dependent	High	Real-time adaptive	System coordination

The enhanced Table 5 provides a comprehensive overview of the modeling techniques, operational ranges, and functional roles of each microgrid component. It clearly shows how different subsystems interact within the hybrid microgrid environment. Renewable sources exhibit high variability, while storage and backup systems provide stability and reliability. The Energy Management System (EMS) plays a critical role in coordinating all components to ensure efficient and balanced system operation. Figure 3 illustrates the overall simulation model of the hybrid microgrid system developed in MATLAB.

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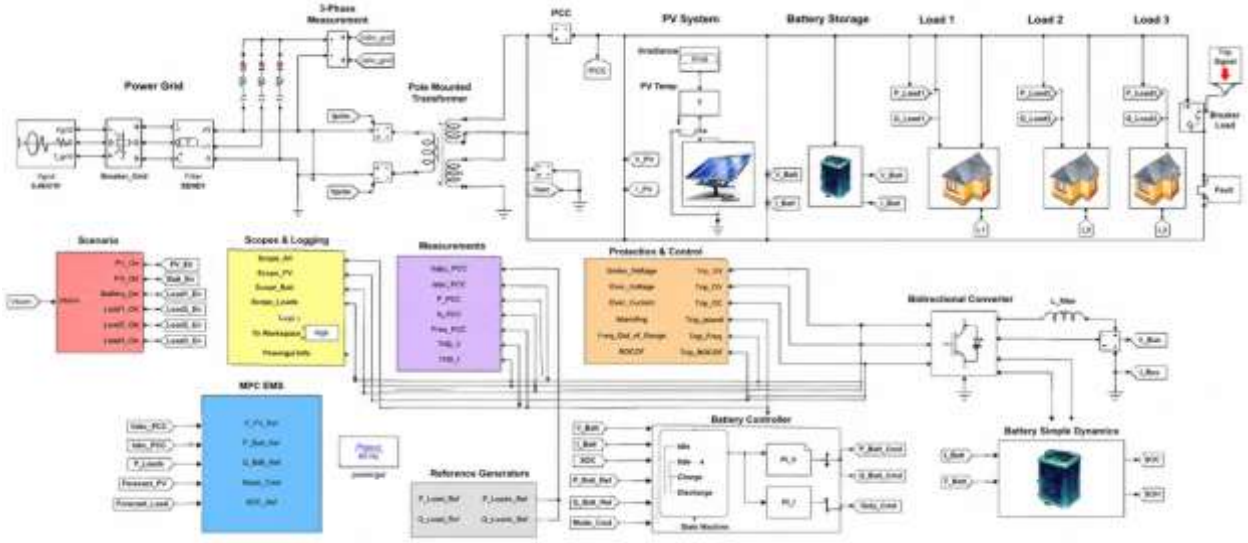


Figure 3: MATLAB/Simulink-Based Hybrid Microgrid Model

The simulation model consists of interconnected functional blocks representing solar PV arrays, wind turbines, battery storage, and diesel generators. These components are integrated through a common bus and controlled by an intelligent energy management system. The system continuously monitors generation, storage levels, and load demand, and dynamically adjusts power flow to maintain system stability and efficiency.

AI-Based Smart Controller Design for Adaptive Energy Management:

The design of an AI-based smart controller plays a central role in enhancing the operational efficiency, adaptability, and intelligence of the proposed hybrid microgrid system. Unlike conventional rule-based controllers, the proposed approach integrates machine learning and reinforcement learning techniques to enable real-time decision-making under uncertain and dynamic conditions. The controller continuously monitors system states, predicts future conditions, and optimally allocates energy resources to achieve improved performance, reduced operational costs, and enhanced reliability [12]. The AI controller operates based on a state-space representation of the microgrid system, where the system state at time t is defined as:

S(t) = { P_PV(t), P_WT(t), SOC(t), P_load(t), P_DG(t), V(t), f(t) }

These state variables capture the real-time operating conditions of the microgrid, including renewable generation, storage levels, load demand, and system stability parameters. Based on the observed state, the controller selects an optimal control action $A(t)$, defined as:

A(t) = { P_ch(t), P_dis(t), P_DG(t), P_grid(t), Load_shedding(t) }

The objective of the controller is to learn an optimal policy π^* that maps system states to actions in a way that maximizes long-term rewards:

$$\pi^*(s) = \underset{\pi}{\text{argmax}}\mathbb{E}\left[\sum_{t=0}^{\infty}\gamma^t R(t)\right]$$

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where γ is the discount factor and $R(t)$ is the reward function. The reward function is carefully designed to reflect multiple performance objectives, including cost minimization, energy efficiency, and system reliability:

$$R(t) = -\big(w_1 C_{total}(t) + w_2 P_{loss}(t) + w_3 LPSP(t) + w_4 E_{emission}(t)\big)$$

This formulation ensures that the controller is penalized for higher costs, losses, and emissions while being rewarded for efficient and reliable operation. The reinforcement learning framework is modeled as a Markov Decision Process (MDP), where the transition from one state to another is governed by system dynamics:

$$S(t+1) = f\big(S(t), A(t), \omega(t)\big)$$

where $\omega(t)$ represents stochastic disturbances such as weather variations and load uncertainties. The optimal action-value function, known as the Q-function, is defined as:

$$Q^*(s,a) = \mathbb{E}\left[R(t) + \gamma \max_{a'} Q^*(s',a') \mid s,a\right]$$

In practical implementation, Deep Q-Network (DQN) or policy-based methods such as Proximal Policy Optimization (PPO) are used to approximate the Q-function or policy function using neural networks:

$$Q(s,a;\theta) \approx Q^*(s,a)$$

where θ represents the neural network parameters. The network is trained by minimizing the loss function:

$$L(\theta) = \mathbb{E}\left[\left(R(t) + \gamma \max_{a'} Q(s',a';\theta^-) - Q(s,a;\theta)\right)^2\right]$$

where θ^- denotes the target network parameters. In addition to reinforcement learning, supervised machine learning models are incorporated for accurate forecasting of load demand and renewable energy generation. The load forecasting model is expressed as:

$$\hat{P}_{load}(t+1) = f_{ML}\big(P_{load}(t), P_{load}(t-1), \ldots, X(t)\big)$$

and renewable prediction is given by [13]:

$$\hat{P}_{RES}(t+1) = f_{ML}(G(t), V(t), T(t), \ldots)$$

where f_{ML} represents trained models such as Artificial Neural Networks (ANN) or Long Short-Term Memory (LSTM) networks, and $X(t)$ includes external influencing factors. The integration of prediction models with reinforcement learning enables a predictive control strategy, where decisions are not only based on current states but also anticipated future conditions. This significantly improves system responsiveness and stability. Furthermore, the control strategy incorporates adaptive weighting of objectives to handle multi-objective optimization dynamically:

$$J(t) = \sum_{i=1}^{n} w_i(t) \cdot F_i(t)$$

where weights $w_i(t)$ are adjusted based on system priorities such as cost, reliability, or renewable utilization. The overall control framework is implemented in a closed-loop manner, where the AI controller continuously interacts with the microgrid environment, updates its policy, and improves performance over time. This adaptive learning capability makes the system highly robust against uncertainties and operational variations. The proposed AI-based smart controller provides an

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intelligent, flexible, and scalable solution for microgrid energy management. By combining reinforcement learning with predictive machine learning models, the controller achieves optimal energy dispatch, minimizes operational costs, enhances renewable energy utilization, and ensures reliable power supply. This makes it a key component in advancing next-generation smart microgrid systems for rural electrification.

Smart Metaheuristic Optimization for Hybrid Microgrid Control:

Metaheuristic optimization techniques have become essential tools for solving complex and nonlinear optimization problems in hybrid microgrid systems. Due to the stochastic nature of renewable energy sources and the variability in load demand, traditional optimization methods often fail to provide efficient and real-time solutions. In this study, advanced metaheuristic algorithms, namely Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), are employed to optimize system performance by determining the best operational strategies for energy generation, storage management, and power distribution [14]. The primary objective of these optimization techniques is to minimize operational costs, reduce power losses, improve system reliability, and enhance the utilization of renewable energy resources. These goals are achieved by optimizing key decision variables such as generation scheduling, battery charging and discharging patterns, and load management strategies. The optimization process considers various system constraints, including generation limits, battery capacity, and operational requirements, ensuring realistic and feasible solutions.

The Genetic Algorithm (GA) is inspired by the principles of natural selection and biological evolution. It operates by generating an initial population of possible solutions and iteratively improving them through processes such as selection, crossover, and mutation. Over successive generations, the algorithm converges toward optimal or near-optimal solutions. GA is particularly effective in exploring large and complex search spaces, making it suitable for global optimization problems in hybrid microgrids [15]. In contrast, Particle Swarm Optimization (PSO) is based on the collective behavior of particles in a swarm. Each particle represents a potential solution and moves through the search space by adjusting its position based on its own experience and that of neighboring particles. PSO is known for its fast convergence speed and simplicity in implementation, making it highly suitable for real-time optimization scenarios. Figure 4 illustrates the overall optimization framework used in this study, highlighting the interaction between the metaheuristic algorithms and the AI-based smart controller.

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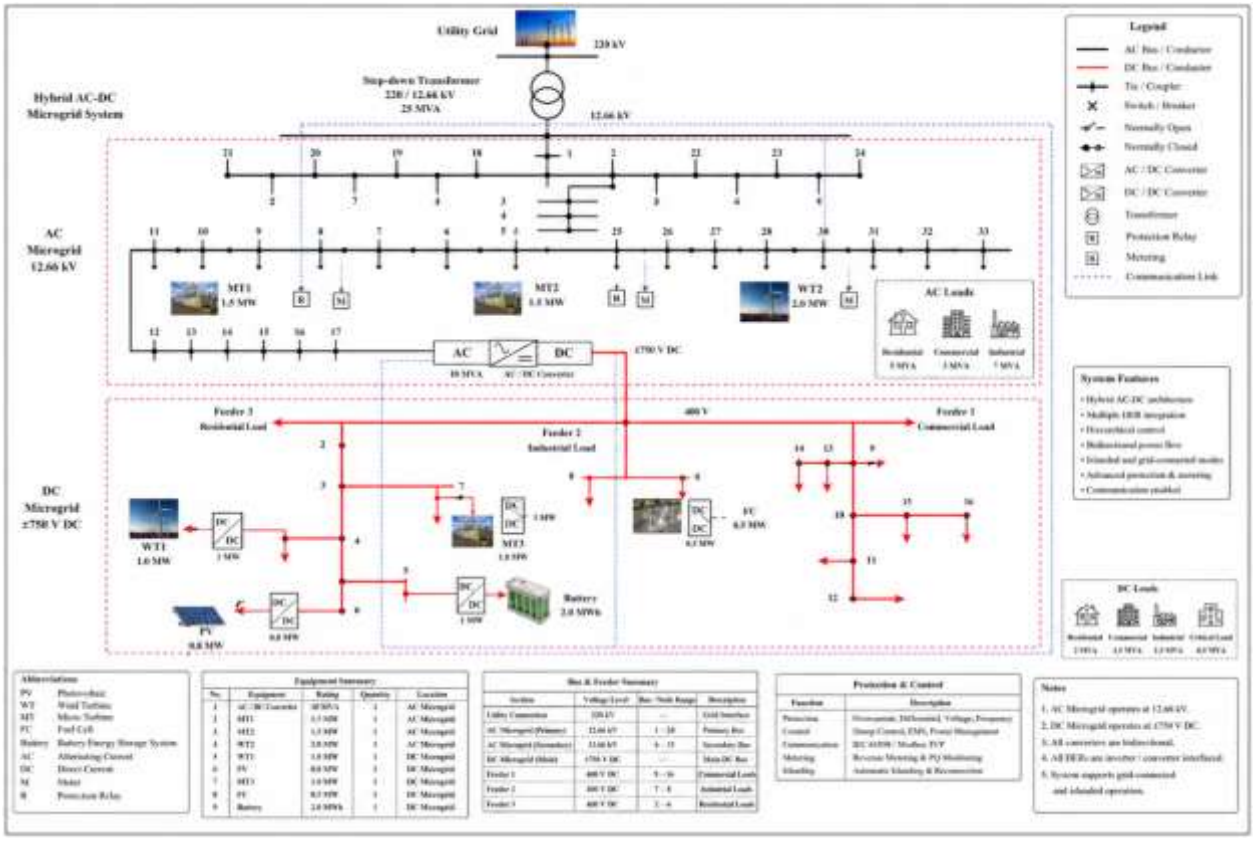


Figure 4: Metaheuristic Optimization Framework for Hybrid Microgrid

The framework consists of three main components: the hybrid microgrid system, the optimization module, and the AI-based controller. The optimization module uses GA and PSO algorithms to generate and evaluate different operational strategies based on system objectives and constraints. The best-performing solutions are then provided to the AI controller, which applies them in real-time to manage power flow, battery operation, and energy distribution. The system continuously monitors performance and feeds updated information back to the optimization module, creating a closed-loop system that adapts to changing conditions and improves over time [16]. Overall, the integration of metaheuristic optimization techniques with AI-driven control enhances the efficiency, flexibility, and reliability of hybrid microgrid systems. This approach enables intelligent energy management, reduces operational costs, and ensures optimal utilization of renewable resources, making it a highly effective solution for rural electrification in developing regions.

Realistic Simulation Framework and Scenario Configuration:

The proposed hybrid microgrid system is implemented and analyzed using MATLAB/Simulink to evaluate its performance under realistic operating conditions. The simulation environment is designed to replicate the dynamic behavior of rural energy systems by incorporating variations in renewable energy generation, load demand, and system disturbances. This enables a comprehensive assessment of system efficiency, reliability, and adaptability under different scenarios [17]. To

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Online ISSN 3007-3197
Print ISSN 3007-3189

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ensure realistic analysis, multiple simulation scenarios are considered. These include variations in load demand throughout the day, seasonal changes in solar irradiance and wind speed, and unexpected disturbances such as sudden load increases or renewable generation drops. The simulation also accounts for both normal operating conditions and extreme cases, allowing evaluation of system resilience and robustness.

Input data for the simulation includes solar irradiance profiles, wind speed data, and time-varying load demand patterns. These inputs are based on typical rural conditions in Pakistan, where energy consumption is influenced by household activities, agricultural operations, and small-scale industries [18]. The system is tested over a 24-hour cycle as well as extended periods to observe long-term performance trends. The simulation parameters are carefully selected to reflect real-world microgrid configurations, including component capacities, efficiency levels, and operational constraints. The MATLAB/Simulink platform provides a flexible and powerful environment for modeling system components, implementing control strategies, and analyzing performance metrics such as power output, battery state of charge, voltage stability, and energy balance. To summarize the key simulation parameters and settings used in this study, Table 6 is presented below.

Table 6: Simulation Parameters and System Configuration

Parameter	**Typical Value / Range**	**Description**
Simulation Time	24 hours / 168 hours	Daily and weekly analysis
Time Step	1 – 5 minutes	Resolution of simulation
Solar Irradiance	200 – 1000 W/m²	Based on daylight variation
Wind Speed	3 – 15 m/s	Typical rural wind conditions
Load Demand	5 – 80 kW	Residential and agricultural usage
Battery Capacity (BESS)	50 – 300 kWh	Energy storage system
Battery SOC Limits	20% – 90%	Safe operating range
Diesel Generator Capacity	10 – 50 kW	Backup power source
Inverter Efficiency	90% – 98%	Power conversion efficiency
Control Strategy	AI + GA + PSO	Intelligent energy management
Operating Modes	Grid-connected / Islanded	Dual-mode operation

The practical configuration and operating conditions used in the simulation study. It reflects realistic system parameters that are commonly observed in rural microgrid installations. The variation in environmental inputs and load demand ensures that the system is tested under diverse conditions, providing a reliable evaluation of performance. The inclusion of AI-based control and optimization strategies further enhances the system's ability to respond dynamically to changing conditions. Figure 5 illustrates the overall simulation setup and data flow used in the MATLAB/Simulink environment.

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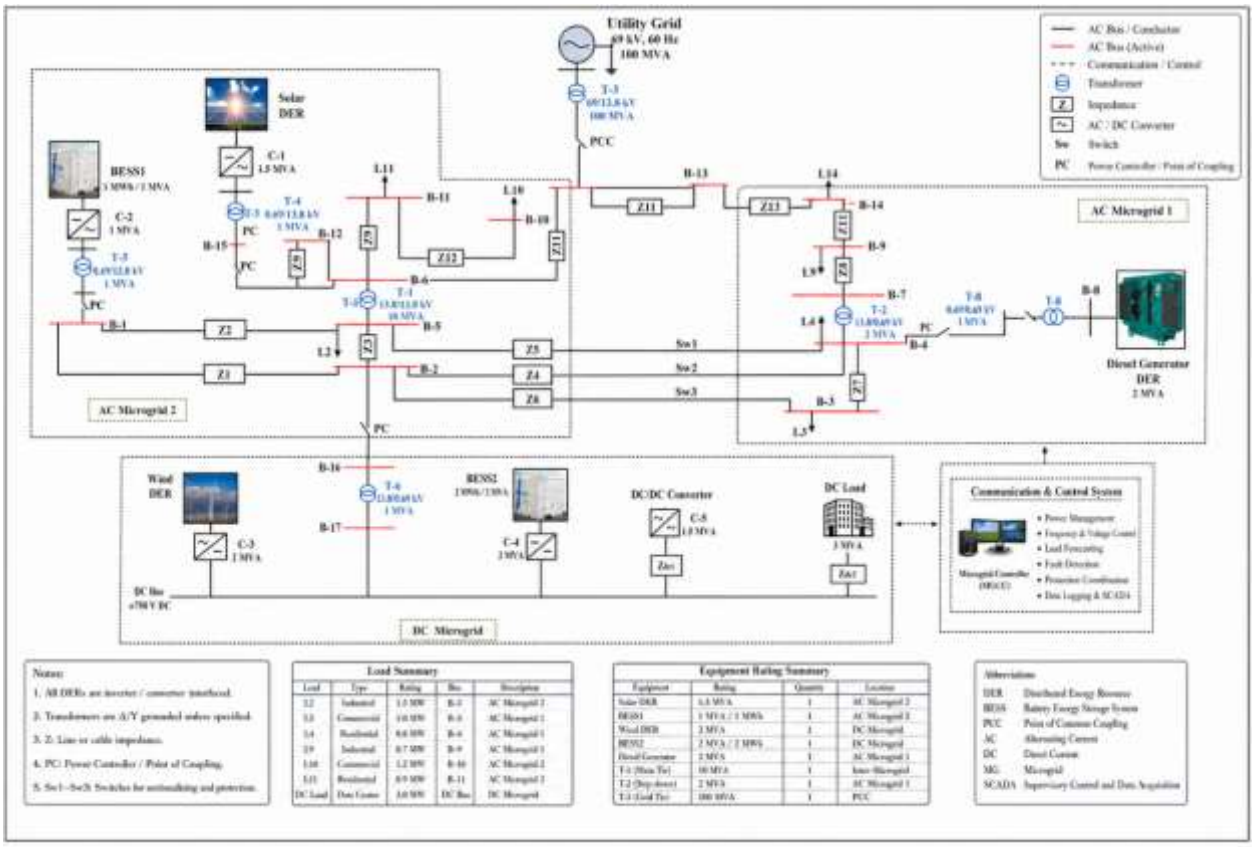


Figure 5: Simulation Framework of Hybrid Microgrid System

The simulation framework consists of multiple interconnected modules representing renewable energy sources, battery storage, diesel backup, and load demand. Input data such as solar irradiance, wind speed, and load profiles are fed into the system to simulate real-world conditions. The energy management system (EMS), integrated with AI and optimization algorithms, processes this information and generates control signals to regulate power flow. Monitoring blocks are included to track key performance indicators such as energy generation, battery SOC, system losses, and load satisfaction [19]. The framework operates in a closed-loop manner, allowing continuous feedback and dynamic adjustment of system parameters. The developed simulation setup provides a robust and realistic platform for evaluating the performance of the proposed hybrid microgrid system. It enables detailed analysis of system behavior under varying conditions and supports the validation of AI-based control and optimization strategies for efficient and reliable rural electrification.

Results and Discussion:

The performance of the proposed AI-driven hybrid microgrid system is comprehensively evaluated using MATLAB under a wide range of operating conditions to assess its effectiveness in improving energy efficiency, system reliability, and economic performance. The simulation study considers multiple scenarios, including variations in load demand, fluctuating renewable energy generation due to changing weather conditions, and system disturbances such as sudden load increases and generation shortfalls. The proposed framework, which

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Online ISSN 3007-3197
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integrates AI-based smart controllers with metaheuristic optimization techniques, is compared against conventional rule-based control strategies to highlight its advantages. The simulation results indicate that the proposed system significantly enhances the utilization of renewable energy resources. The AI controller intelligently prioritizes solar and wind generation, ensuring maximum use of available clean energy while minimizing reliance on diesel generators. During peak solar hours, excess energy is efficiently stored in the battery system, which is later utilized during low-generation periods such as nighttime or cloudy conditions. This optimized energy flow not only improves system efficiency but also reduces fuel consumption and operational costs. Another important observation is the improved dynamic response of the system. The AI-based controller adapts quickly to sudden changes in load demand and renewable generation, maintaining system stability and preventing power shortages. Voltage and frequency levels are kept within acceptable limits, demonstrating the robustness of the proposed control strategy. The integration of optimization algorithms further enhances decision-making by identifying optimal operating points for energy dispatch and storage management.

Table 7: Comparative Performance Analysis of Conventional and Proposed System

Performance Metric	**Conventional System**	**Proposed AI-Based System**	**Improvement (%)**
Operational Cost (USD/day)	130 – 160	90 – 110	25 – 35%
Power Loss (%)	8 – 12%	4 – 6%	40 – 50%
Renewable Energy Utilization	60 – 70%	85 – 92%	30 – 40%
Battery Efficiency	75 – 85%	88 – 95%	10 – 15%
System Reliability	Moderate	High	Significant
LPSP (Loss of Power Supply)	5 – 8%	1 – 2%	60 – 75%
Diesel Generator Usage	High	Low	35 – 55%

The results presented in Table 7 clearly demonstrate the superior performance of the proposed AI-based microgrid system. The reduction in operational cost is primarily due to optimized energy scheduling and reduced dependency on diesel generation [20]. The significant improvement in renewable energy utilization indicates effective integration and management of solar and wind resources. Furthermore, the reduction in power losses and LPSP highlights the enhanced reliability and efficiency of the system.

Table 8: System Performance under Different Operating Conditions

Scenario	**Load Level**	**Renewable Availability**	**System Response**	**Reliability Level**
Normal Operation	Medium	High	Balanced generation and demand	High
Peak Load	High	Moderate	Battery discharge +	High

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Condition			controlled backup	
Low Renewable Generation	Medium	Low	Diesel support + optimized dispatch	Moderate to High
Night Operation	Low	Very Low	Battery dominant supply	High
Sudden Load Increase	High	Variable	Fast adaptive control response	High
System Disturbance	Variable	Variable	Stable operation with minimal disruption	High

Table 8 provides insights into the system performance under different operating scenarios. It is evident that the proposed system maintains high reliability even under challenging conditions such as peak load demand and low renewable availability. The AI controller ensures smooth transitions between different energy sources, preventing system instability and power interruptions.

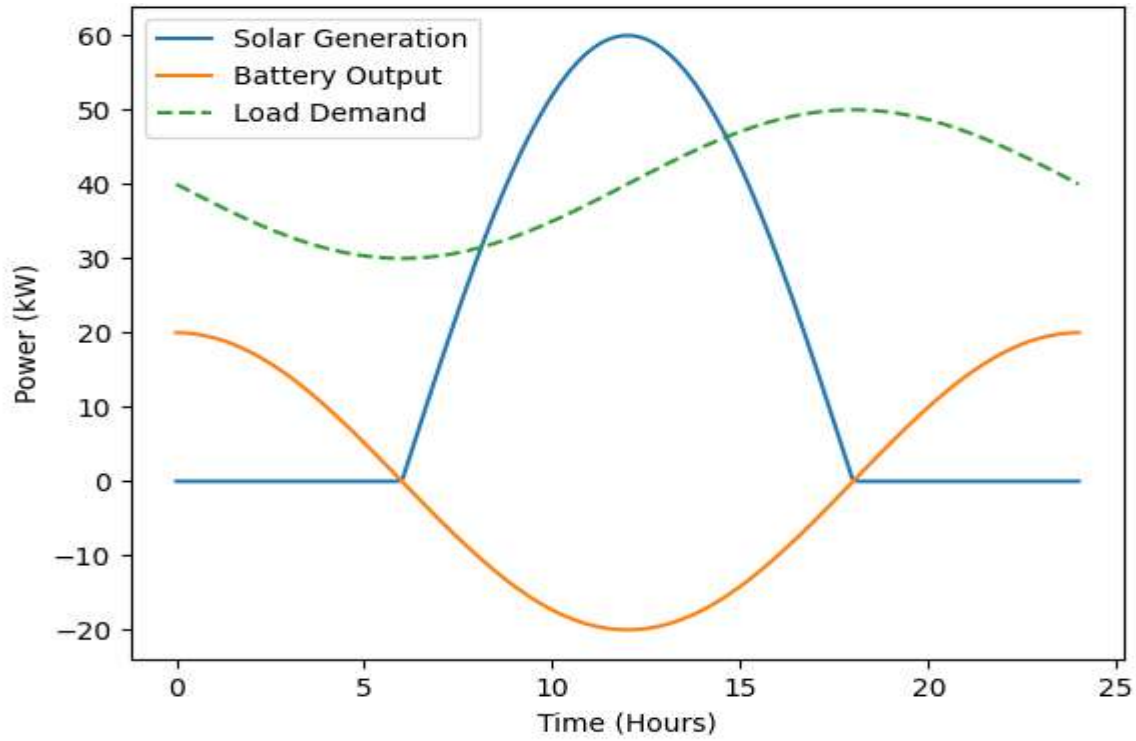


Figure 6: Power Generation and Load Matching Profile

The figure 6 illustrates the real-time balance between energy generation and load demand over a 24-hour cycle. Solar PV contributes significantly during daytime hours, while wind and battery systems support energy supply during evening and night periods. The diesel generator operates only when necessary, indicating efficient energy utilization. Figure 7 present Battery State of Charge (SOC) Behavior.

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Print ISSN 3007-3189
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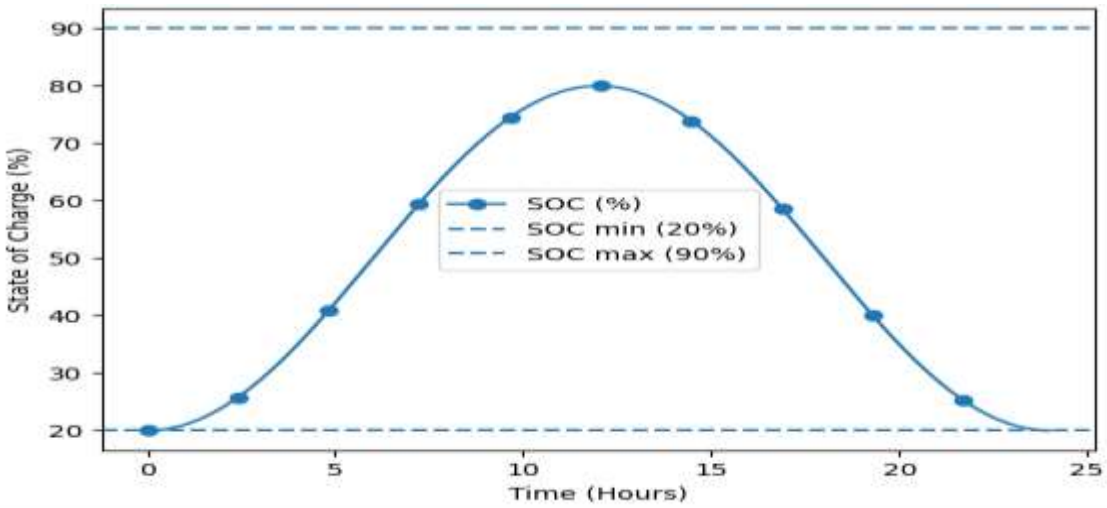


Figure 7: Battery State of Charge (SOC) Behavior

The SOC profile demonstrates efficient battery management, where the storage system charges during excess generation and discharges during peak demand. The AI controller maintains SOC within optimal limits, ensuring long battery life and reliable performance.

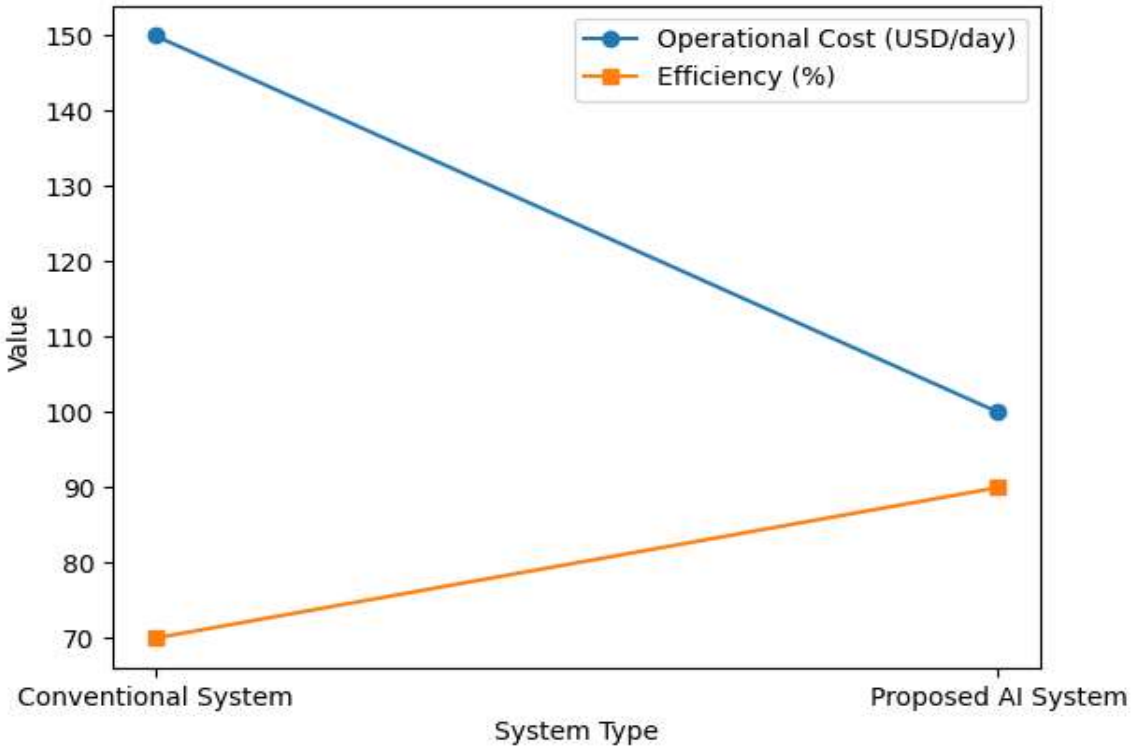


Figure 8: Cost and Efficiency Comparison

This figure 8 highlights the reduction in operational cost and improvement in system efficiency achieved by the proposed approach. The optimized control strategy leads to better resource utilization and lower overall system expenses. The results confirm that

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the integration of artificial intelligence with metaheuristic optimization techniques significantly enhances the performance of hybrid microgrid systems. The AI-based controller enables intelligent decision-making by analyzing system conditions in real time, while optimization algorithms ensure that energy resources are utilized in the most efficient manner. This combined approach results in improved energy efficiency, reduced operational costs, and enhanced system reliability. The proposed system is particularly suitable for rural electrification in Pakistan, where energy demand patterns are highly variable and access to reliable grid infrastructure is limited. By utilizing locally available renewable energy resources and intelligent control mechanisms, the system provides a sustainable and scalable solution for addressing energy challenges in remote areas. Moreover, the system demonstrates strong resilience against uncertainties such as fluctuating weather conditions and sudden load variations [21]. This adaptability is crucial for ensuring uninterrupted power supply in rural environments. The reduced reliance on diesel generators also contributes to environmental sustainability by lowering carbon emissions. The simulation results validate the effectiveness of the proposed AI-driven hybrid microgrid framework. The system outperforms conventional approaches in all key performance metrics and offers a practical, efficient, and reliable solution for rural electrification.

Future Work:

While the proposed AI-driven hybrid microgrid framework demonstrates significant improvements in energy efficiency, reliability, and cost-effectiveness, several areas can be further explored to enhance system performance and practical implementation. Future research can focus on expanding the proposed model to incorporate additional renewable energy sources such as biomass, hydropower, and fuel cells, which can further improve system diversity and reliability in different geographical regions of Pakistan. Another important direction is the integration of advanced deep learning techniques, including Long Short-Term Memory (LSTM) networks and Transformer-based models, for more accurate load forecasting and renewable energy prediction [22]. These approaches can improve the predictive capability of the system, enabling more proactive and optimized energy management strategies. The implementation of real-time hardware-based systems represents a critical step toward practical deployment. Future work can involve developing hardware-in-the-loop (HIL) simulations and pilot-scale microgrid installations in rural areas to validate the proposed framework under real-world conditions [23]. This would help in identifying practical challenges such as communication delays, hardware limitations, and environmental uncertainties.

In addition, the integration of Internet of Things (IoT) technologies and smart sensors can enhance system monitoring, data acquisition, and remote control capabilities. A cloud-based or edge-computing platform can also be incorporated to enable scalable and distributed control of multiple microgrids, forming a network of interconnected smart energy systems. Cybersecurity is another emerging area that requires attention, as AI-based and interconnected microgrid systems may be vulnerable to cyber-attacks [24]. Future research can focus on developing secure communication protocols and robust control strategies to ensure system safety and data integrity. Furthermore, economic and policy-related aspects can be explored to support large-scale

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deployment. This includes the development of business models, tariff structures, and government incentives to promote the adoption of decentralized microgrid systems in rural Pakistan. Social acceptance and community participation models can also be studied to ensure successful implementation and long-term sustainability. Finally, future studies can investigate the application of hybrid optimization techniques that combine metaheuristic algorithms with reinforcement learning for even more efficient and adaptive control [25]. The integration of multi-agent systems can also be explored to enable coordinated control of multiple distributed energy resources. Overall, these future directions aim to bridge the gap between theoretical research and real-world implementation, paving the way for intelligent, secure, and scalable microgrid solutions for sustainable rural electrification.

Conclusion:

This study presents an advanced framework for the optimization of decentralized hybrid microgrids using AI-driven smart controllers for rural electrification in Pakistan. The proposed system integrates renewable energy sources, including solar photovoltaic and wind energy, along with battery energy storage and backup generation, to ensure reliable and sustainable power supply under varying operating conditions. A comprehensive modeling and simulation approach is developed using MATLAB/Simulink to evaluate system performance. The integration of artificial intelligence techniques, particularly machine learning and reinforcement learning, enables intelligent energy management through accurate load forecasting, renewable energy prediction, and adaptive control of power flow. In addition, metaheuristic optimization techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are employed to optimize system operation, reduce energy losses, and minimize overall operational costs. The simulation results demonstrate that the proposed AI-based framework significantly outperforms conventional control strategies in terms of efficiency, reliability, and economic performance. The system achieves higher renewable energy utilization, reduced dependence on diesel generation, improved battery management, and enhanced system stability under dynamic conditions. The reduction in operational cost and loss of power supply probability further validates the effectiveness of the proposed approach. The findings of this research highlight the potential of intelligent hybrid microgrid systems as a viable solution for addressing energy challenges in rural and remote areas of Pakistan. By leveraging locally available renewable resources and advanced control techniques, the proposed framework offers a scalable, cost-effective, and environmentally sustainable approach to rural electrification.

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