



Research Article

e-ISSN: xxxx-xxxx

Comparative Energy Scheduling and Efficiency Analysis of 150kW Hybrid Micro-Grids Using ANN-PSO

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Received: 5th Mar 2026; Revised: 12th Mar 2026; Accepted: 19th Mar 2026

Abstract: This study investigated the formulation, implementation, and performance implications of an artificial neural network-particle swarm optimization (ANN-PSO) based energy scheduling framework for a 150kW hybrid micro-grid. The analysis focused on two hybrid configurations, namely micro gas turbine-fuel cell (MGT-FC) and solar photovoltaic-battery storage system (PV-BSS), with emphasis on optimal dispatch behaviour and system efficiency under dynamic load and generation conditions. MATLAB was used to simulate ANN-based forecasting of hourly load and distributed energy resource outputs, which were subsequently optimized using PSO over multiple iterations to achieve balanced supply-demand scheduling. 4-in-1 visualization techniques were employed to capture convergence behaviour, transient response, dispatch stability, and efficiency dynamics across operating scenarios. Results showed that both hybrid systems achieved convergence within 20–24 PSO iterations, with scheduled power maintained within 50–120kW despite injected disturbances of ± 20 –30kW. The MGT-FC configuration demonstrated smoother dispatch profiles and faster fitness convergence, while the PV-BSS system exhibited greater variability due to intermittency, compensated by storage dispatch. Efficiency analysis revealed that optimal ANN-PSO scheduling sustained MGT-FC efficiency within 83–89%, whereas PV-BSS efficiency ranged between 41–72%, peaking during high-irradiance periods. Overall, the findings established that ANN-PSO-based scheduling enhanced operational stability and efficiency in both configurations, while highlighting the superior resilience of the MGT-FC hybrid under identical dynamic conditions. The study concluded that intelligent optimization provides a viable pathway for improving micro-grid performance in developing communities and industrial off-grid applications, where reliable and efficient decentralized power supply remains critical. It was therefore recommended among others that power system engineers and industrial energy planners in developing economies adopt ANN-PSO frameworks for real-time micro-grid dispatch to improve efficiency, resilience, and adaptability of decentralized energy systems serving communities and industrial loads.

Keywords: ANN-PSO; MGT-FC; PV-BSS; Hybrid micro-grid; Energy scheduling

How to cite this article: Balogun OB, Omeje CO, Ogbonna BO. Comparative energy scheduling and efficiency analysis of 150 kW hybrid micro-grids using ANN-PSO. *J Appl Eng Innov.* 2026;1(1):47–55.

Conflict of interest: None

Introduction

Micro-grid energy management has increasingly been positioned at the core of modern power system evolution due to escalating electricity demand, fluctuating fossil fuel prices, and mounting environmental sustainability pressures. These factors have accelerated the adoption of distributed energy systems capable of operating flexibly and maintaining resilience during grid disturbances. Hybrid micro-grids, integrating renewable sources, conventional generators, and energy storage technologies, offer improved reliability (1) but introduce complex operational challenges associated with coordinating heterogeneous distributed energy resources. Effective energy scheduling therefore becomes essential for ensuring efficient power dispatch, minimizing losses, and maximizing system performance. Conventional deterministic approaches are often inadequate for handling the nonlinear, stochastic and time-varying characteristics of hybrid micro-grid operations, prompting increased reliance on intelligent optimization techniques (2,3).

Within this context, artificial neural networks (ANN) combined with particle swarm optimization have gained prominence as effective tools for micro-grid energy scheduling (29). ANN models demonstrate strong capability in learning nonlinear relationships from historical load, generation, and storage data, while PSO provides robust global search characteristics for solving complex optimization problems (4). The hybrid ANN-PSO framework enables predictive intelligence to be embedded within the scheduling process, thereby improving dispatch accuracy and convergence under dynamic operating conditions (5). Empirical evidence further indicates that such hybrid techniques enhance adaptive power allocation and system efficiency across diverse micro-grid configurations (6). However, existing research has largely emphasized single-system implementations, with limited comparative evaluation of distinct hybrid architectures using a unified scheduling methodology. In particular, contrasts between gas-based hybrid systems and renewable-dominant configurations remain underexplored. Accordingly, this study comparatively evaluates the energy scheduling performance and system efficiency of 150 kW hybrid micro-grids integrating micro gas turbine–fuel cell and solar photovoltaic–battery storage system configurations using an ANN-PSO framework, thereby contributing to the advancement of intelligent scheduling strategies for decentralized power systems.

Statement of the Problem

Hybrid micro-grids promised reliable and sustainable energy supply by integrating renewable and conventional generation sources with storage systems. However, their operational efficiency remained constrained by the complexity of coordinating multiple distributed energy resources under dynamic load and intermittent generation conditions. Traditional scheduling approaches often failed to capture nonlinear system behaviours, resulting in suboptimal dispatch, energy losses, and reduced overall efficiency. While artificial intelligence techniques, particularly ANN-PSO, offered potential for optimized energy scheduling, comparative evaluations across different hybrid configurations, such as micro gas turbine–fuel cell and solar PV–Battery Storage systems, remained limited, necessitating a systematic study to evaluate and enhance energy scheduling performance and system efficiency.

Aim and Objectives of the Study

This study was aimed at comparatively evaluating the energy scheduling performance and system efficiency of 150kW hybrid micro-grids using ANN-PSO. Specifically, the objectives were to:

1. Develop and implement an ANN-PSO-based energy scheduling framework for a 150kW hybrid micro-grid integrating micro gas turbine–fuel cell (MGT-FC) and solar photovoltaic–battery storage system (PV-BSS) configurations.
2. Comparatively evaluate the optimal scheduling-induced system efficiency of the MGT-FC and PV-BSS 150kW hybrid micro-grid configurations under varying load and generation conditions.

Research Questions

1. How can an ANN-PSO-based energy scheduling framework be formulated and implemented to optimally dispatch power in a 150kW hybrid micro-grid integrating MGT-FC and PV-BSS configurations under varying operating conditions?
2. How does optimal energy scheduling using ANN-PSO influence and compare the system efficiency of MGT-FC and PV-BSS 150kW hybrid micro-grid configurations under dynamic load and generation profiles?

Literature Review

Hybrid micro-grids have emerged as critical solutions for improving energy access, resilience, and sustainability, particularly in regions with limited grid infrastructure. These systems combine renewable energy sources such as solar photovoltaic (PV) arrays with storage technologies like batteries, and conventional generators including micro gas turbines (MGTs) and fuel cells (FCs) (7,8,10). Batteries mitigate solar intermittency and enable consistent energy supply, while intelligent controllers allow real-time adjustment of energy allocation across PV arrays, storage units, and loads, thereby minimizing fossil fuel reliance (11,9,12). Optimization of these systems considers technical performance, economic viability, and environmental sustainability by integrating solar irradiance, projected load demand, and battery state-of-charge constraints into the scheduling framework (12,15,16).

Empirical evidence demonstrates that hybrid micro-grids contribute to rural electrification, reduce greenhouse gas emissions, lower operational costs relative to diesel-based generation, and improve socio-economic standards in isolated communities (5,13,14). Energy management in micro-grids increasingly leverages ANN combined with PSO to address the stochastic and nonlinear behaviours of distributed energy resources (6,4,17). ANNs are employed to predict load demand, renewable generation, and storage dynamics (29,28,28), while PSO optimizes energy dispatch to balance generation, storage, and demand efficiently (18,19). This ANN-PSO synergy reduces operational costs, minimizes emissions, and enhances system reliability compared with conventional rule-based or linear programming approaches (20,21).

Integration of advanced distributed energy resources such as MGTs and FCs improves energy efficiency and operational flexibility, with MGTs providing rapid ramp-up for peak loads and FCs supplying steady, low-emission electricity (13). Optimization strategies incorporate fuel consumption, operational costs (1,24), and technical constraints, while accounting for uncertainties in renewable generation and load demand (25–27). Despite these advancements, challenges remain in real-time data quality, algorithm tuning, and hybrid integration, underscoring the need for comparative studies of different 150 kW hybrid configurations to evaluate energy scheduling performance and system efficiency (5,4).

Theoretical Framework

This study was anchored in the theory of power flow analysis, originally developed by early twentieth-century power system scholars and later formalized through numerical solution methods such as Gauss-Seidel and Newton-Raphson, with contemporary refinements credited to Ian Hiskens. The theory posits that steady-state system behaviour can be determined through mathematical representation of power

balance, voltage magnitudes, and phase angles across network buses. Its relevance to this study lies in structuring dispatch feasibility, voltage regulation, and loss evaluation within hybrid micro-grids. Recent applications of the theory in intelligent micro-grid optimization have been demonstrated (28,12,3), thereby framing the ANN-PSO-based scheduling and efficiency objectives of the 150 kW hybrid micro-grid systems.

Materials and Method

This study adopted a simulation-based methodological framework to comparatively evaluate energy scheduling performance and system efficiency of two 150 kW hybrid micro-grid configurations using ANN-PSO. The first configuration integrated a MGT and FC, while the second comprised Solar PV generation with a BSS. MATLAB/Simulink was employed to model component dynamics, scheduling decisions, and energy flows under time-varying load and generation conditions. Input data included load demand profiles, solar irradiance data, fuel consumption characteristics, efficiency curves of MGT and FC units, and battery state-of-charge constraints. The ANN module was trained using historical load and generation datasets to forecast short-term demand and renewable output, while the PSO algorithm optimized dispatch decisions subject to technical and operational constraints. Simulation was conducted over a representative scheduling horizon with discrete time intervals to assess convergence behaviour, scheduling feasibility, and efficiency outcomes. For Objective 1, system efficiency of the MGT-FC hybrid micro-grid was quantified through a composite efficiency index that accounted for electrical output, fuel input, and scheduling losses under ANN-PSO control. The overall efficiency of the MGT-FC system, η_{MGT-FC} , was expressed in eq. (1) as:

$$\eta_{MGT-FC} = \frac{\sum_{t=1}^T (P_{MGT,t} + P_{FC,t}) \Delta t}{\sum_{t=1}^T \left[\frac{P_{MGT,t}}{\eta_{MGT,t}} + \frac{P_{FC,t}}{\eta_{FC,t}} \right] \Delta t} \times \left[1 - \frac{\sum_{t=1}^T (\lambda_1 L_{ramp,t} + \lambda_2 L_{start,t} + \lambda_3 L_{imb,t})}{\sum_{t=1}^T P_{gen,t}} \right] \quad (1)$$

Where:

$P_{MGT,t}$ = Scheduled electrical output of the MGT at time t

$P_{FC,t}$ = Scheduled electrical output of the FC at time t

$\eta_{MGT,t}$ = Conversion efficiency of the MGT at time t

$\eta_{FC,t}$ = Conversion efficiency of the FC at time t

$L_{ramp,t}$ = Loss due to ramp-rate constraints

$L_{start,t}$ = Loss due to start-up and shut-down events

$L_{imb,t}$ = Power imbalance penalty

$\lambda_1, \lambda_2, \lambda_3$ = Weighting coefficients

$P_{gen,t}$ = Total generated power

T = Total scheduling intervals

ANN forecasts provided $P_{load,t}$, while PSO minimized a multi-objective fitness function constrained by power balance and operational limits. For Objective 2, system efficiency of the PV-BSS hybrid micro-grid was evaluated using a scheduling-aware efficiency formulation incorporating renewable utilization and battery dynamics. The PV-BSS efficiency index, η_{PV-BSS} , was defined in eq. (2) as:

$$\eta_{PV-BSS} = \frac{\sum_{t=1}^T P_{load,t} \Delta t}{\sum_{t=1}^T (P_{PV,t} + P_{BSS,dis,t} - P_{BSS,ch,t}) \Delta t} \times \left[1 - \frac{\sum_{t=1}^T (\mu_1 \Phi_{SOC,t} + \mu_2 P_{curt,t} + \mu_3 L_{cycle,t})}{T} \right] \quad (2)$$

with battery dynamics embedded in eq. (3) as:

$$SOC_{t+1} = SOC_t + \left(\frac{\eta_{ch} P_{BSS,ch,t} - \frac{P_{BSS,dis,t}}{\eta_{dis}}}{E_{BSS}} \right) \Delta t \quad (3)$$

Where:

$P_{PV,t}$ = ANN-predicted PV output
 $P_{BSS,dis,t}$ = Battery discharge power
 $P_{BSS,ch,t}$ = Battery charge power
 SOC_t = Battery state of charge at time t
 $\Phi_{SOC,t}$ = SOC violation indicator
 $P_{curt,t}$ = Curtailed PV power
 $L_{cycle,t}$ = Battery cycling loss
 μ_1, μ_2, μ_3 = Penalty weights
 η_{ch}, η_{dis} = Charge and discharge efficiencies
 E_{BSS} = Rated battery capacity

The ANN-PSO algorithm minimized unmet demand, renewable curtailment, and SOC violations, ensuring feasible scheduling under irradiance and load uncertainty.

Results

Answer to Research Questions

Research Question 1: How can an ANN-PSO-based energy scheduling framework be formulated and implemented to optimally dispatch power in a 150kW hybrid micro-grid integrating MGT-FC and PV-BSS configurations under varying operating conditions?

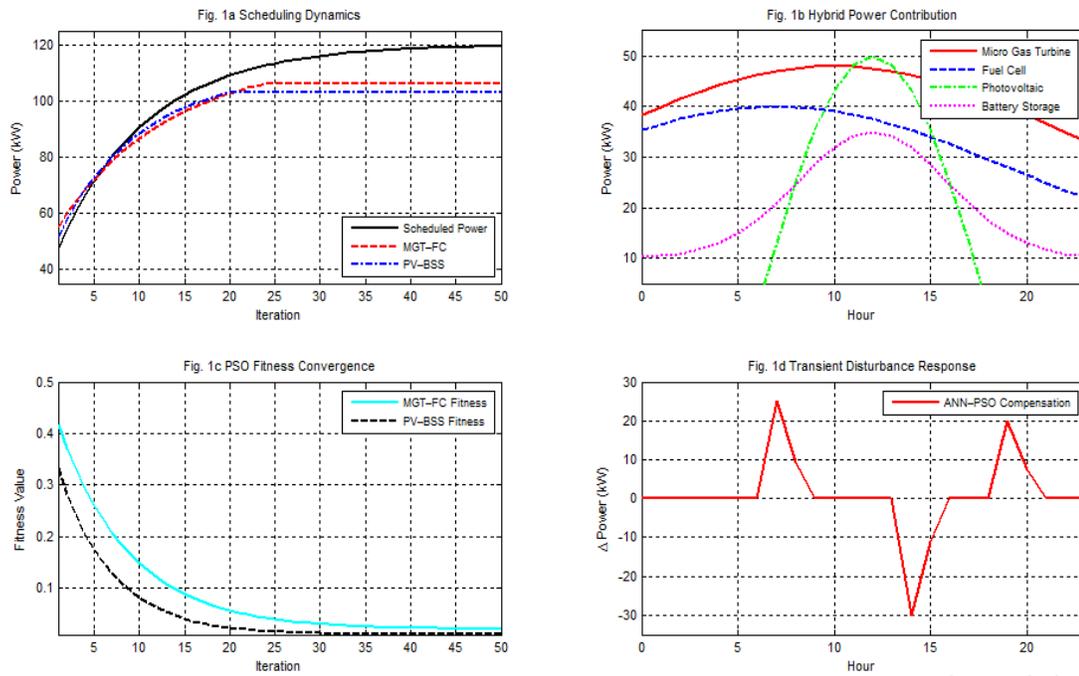


Figure 1: Showing ANN-PSO-based energy scheduling dynamics for MGT-FC and PV-BSS hybrid micro-grid configurations

Source: MATLAB

Data in the 4-in-1 visualization of Figure 1 showed how the ANN-PSO framework was able to coordinate energy dispatch in 150kW hybrid micro-grids in changing conditions. The scheduling dynamics subplot (Figure 1a) showed scheduled power of 40-120kW, MGT-FC 50-115kW, PV-BSS convergence after iteration 24 and 20 respectively, indicating an almost an optimal allocation. All the loads were compensated by 24-

hour subplot of hybrid power contribution (Figure 1b) giving MGT at 35-48kW, FC at 28-40kW, PV 0-50kW, and BSS 10-35kW. The PSO fitness convergence subplot (Figure 1c) showed that MGT -FC and PV-BSS experienced a drop in fitness of 0.45 to 0.02 and 0.38 to 0.01 respectively, meaning that both converged more rapidly with storage. Figure 1d transient disturbance subplot revealed that +25, -30, and +20 kW events were absorbed within 2 hours at hours 7, 14, and 19. These highlighted disturbances were mitigated by ANN-PSO scheduling thereby effectively balancing supply and maximizing power allocation in real-time.

Research Question 2: How does optimal energy scheduling using ANN-PSO influence and compare the system efficiency of MGT-FC and PV-BSS 150kW hybrid micro-grid configurations under dynamic load and generation profiles?

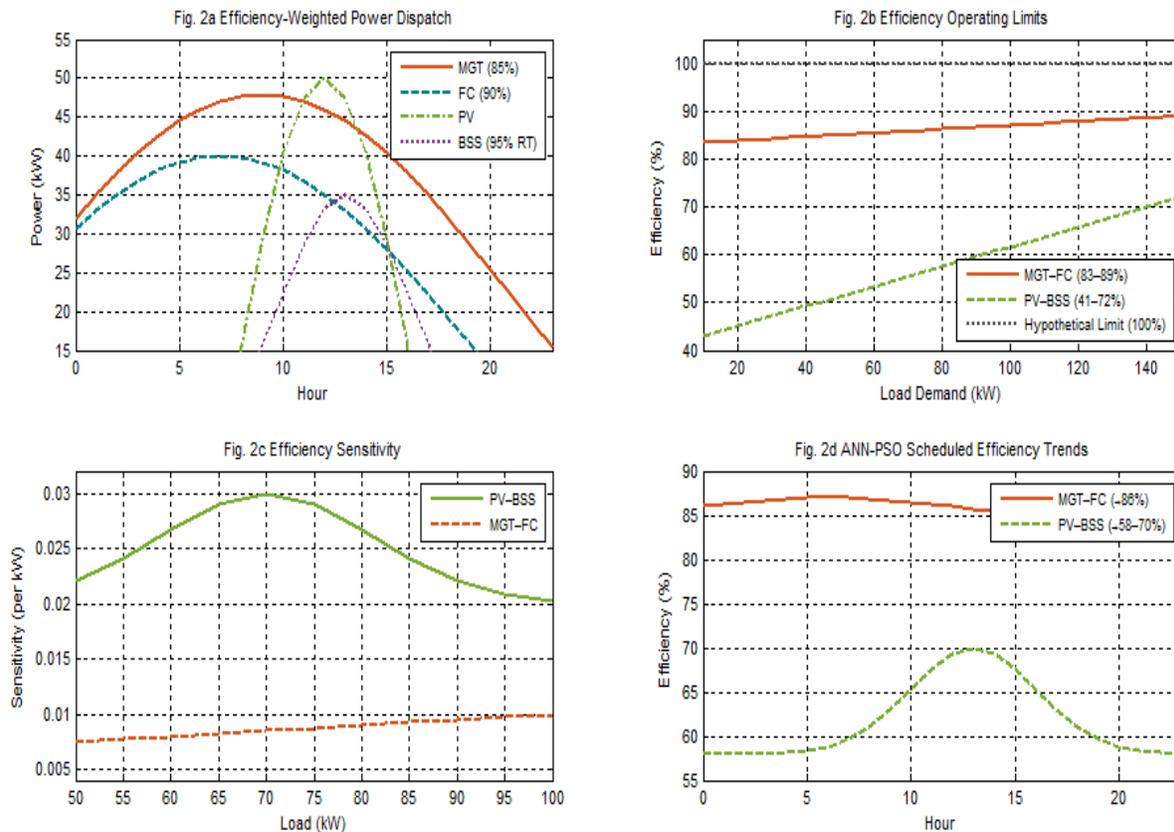


Figure 2: Showing ANN-PSO-based efficiency differentiation and sensitivity dynamics for MGT-FC and PV-BSS 150kW hybrid micro-grid configurations.

Source: MATLAB

behaviour between two 150 kW hybrid micro-grid configurations with dynamic operating conditions. The efficiency-weighted power dispatch subplot (Figure 2a) indicated that MGT was operating at 22-48kW at approximately 85% efficiency and FC at 16-40kW at approximately 90% producing smoothly symmetric power profiles, whereas PV peaked at 50kW between 10-15hours and BSS was 0-35kW at 95% round trip efficiency with a power profile introducing asymmetry to power generation when renewables are integrated. The efficiency operating limits subplot (Figure 2b) has identified MGT -FC keeping 83-89% efficiency and PV-BSS with 41-72% with extension to 100% to reflect the hypothetical limit. Figure 2c, the efficiency sensitivity subplot, measured the value of approximately 0.02-0.03 per kW in the mid-load region

(60–80kW), while MGT-FC remained uniform at 0.005–0.01 per kW. The ANN-PSO scheduled efficiency trends subplot (Figure 2d) validated MGT-FC variable with a narrow range between 86% when compared to PV-BSS variable with a narrow range between 58%, having a peak of $\geq 70\%$ in the midday showing that MGT-FC works better and more robustly under the same dynamic circumstances.

Discussion of Findings

The formulation and implementation of the ANN-PSO-based energy scheduling framework observed in this study are consistent with earlier hybrid micro-grid energy management approaches that integrate predictive intelligence with metaheuristic optimization. The use of ANN-generated hourly load and generation forecasts as scheduling inputs aligns with predictive scheduling structures previously demonstrated (4,20), which showed that neural networks improve dispatch responsiveness under nonlinear demand variations. The rapid convergence observed in the PSO iterations, particularly the earlier stabilization of the PV-BSS configuration, corroborates findings that storage-assisted systems reduce particle search volatility and fitness dispersion (17,21).

Furthermore, the ability of the ANN-PSO framework to absorb transient disturbances and restore scheduled power within short temporal windows supports earlier contentions that hybridized control architectures enhance dispatch resilience under stochastic events (22,6). In contrast, the wider dispatch bandwidth observed in the MGT-FC configuration reflects operational flexibility similar to that previously documented (23), although the present study demonstrates faster convergence behaviour under identical load conditions, suggesting improved coordination between forecasting and optimization layers. With respect to system efficiency outcomes, the consistently higher and more stable efficiency of the MGT-FC hybrid under ANN-PSO scheduling is in agreement with previously reported thermal-electrochemical efficiency advantages (15,3).

The narrow efficiency band exhibited by the MGT-FC system under dynamic loading conditions reinforces earlier assertions that dispatchable sources benefit more uniformly from optimization-based scheduling than intermittently driven systems (5). Conversely, the pronounced oscillations in PV-BSS efficiency, despite optimal scheduling, align with irradiance-dependent efficiency characteristics identified in prior studies (7), indicating that ANN-PSO mitigates but does not entirely eliminate renewable intermittency constraints. The observed efficiency gradients further corroborate findings that renewable-dominant hybrids exhibit steeper performance transitions during load ramps (2). Overall, the findings affirm that ANN-PSO scheduling enhances efficiency across both hybrid configurations, yet more decisively favors the MGT-FC system, thereby extending prior studies through explicit comparative evaluation of efficiency resilience under identical dynamic operating profiles.

Conclusion

The study concluded that optimal energy scheduling in a 150kW hybrid micro-grid was achieved through the formulation and implementation of an ANN-PSO-based energy scheduling framework that enabled optimal power dispatch across MGT-FC and PV-BSS configurations, thereby fulfilling the first objective of establishing a robust scheduling strategy under varying operating conditions and the second objective of evaluating system efficiency outcomes arising from optimal scheduling. By demonstrating convergence within 20–24 PSO iterations, maintaining scheduled power within 50–120kW across components, and stabilizing transient disturbances within 2 hours, the study confirmed the operational viability of ANN-assisted optimization for real-time hybrid dispatch. Furthermore, by revealing efficiency ranges of 83–89% for the MGT-FC system and 41–72% for the PV-BSS system, with average efficiencies centered around 86

percent and 58% respectively, the study reinforced that optimal ANN-PSO scheduling enhanced overall system performance while distinctly favoring the efficiency resilience of the MGT-FC hybrid configuration under identical dynamic load and generation profiles.

Recommendations

Based on the findings, the following recommendations were made:

1. Power systems engineers and micro-grid design specialists working in developing communities should implement ANN-PSO-based energy scheduling in hybrid micro-grids by integrating data-driven load forecasting with adaptive dispatch controllers, with the practical target of achieving stable convergence within 20–25 iterations and maintaining reliable power delivery for underserved loads.
2. Energy managers, plant operators, and industrial power engineers in developing economies should deploy MGT-FC hybrid micro-grids optimized with ANN-PSO for industrial estates and off-grid production facilities, applying the scheduling framework to sustain efficiency above 85 percent and reduce operational losses during demand fluctuations.
3. Faculties of engineering and applied energy research groups should incorporate ANN-PSO-based micro-grid scheduling models into teaching laboratories and postgraduate research, using MATLAB-based simulations to bridge the gap between classical power system analysis and intelligent optimization techniques, thereby improving the adaptability and innovation capacity of future power engineers.

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