Design and Performance Evaluation of a Wind–Solar–Energy Storage Hybrid Microgrid Integrated with Rural Buildings A Case Study of PuDu Village, Yunnan

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Abstract

This research addresses the challenge of unstable energy supply in rural China by designing a rooftop wind–solar–energy storage (wind-PV-BES) hybrid microgrid integrated with rural buildings, using PuDu Village in Yunnan Province as a case study. The NSGA-II algorithm was employed to optimize system capacity, and a pilot system was operated continuously for six months. PuDu Village exhibits abundant, complementary wind-solar resources (annual average wind speed: 3.8 m/s; solar irradiance: 4.9 kWh/m²·day), and its load profile differs significantly from Thai rural areas in peak load and seasonal variation. The optimal configuration (5 kW wind + 10 kW PV + 20 kWh BES) achieved 86.7% system efficiency, 94.3% power supply reliability, a 44.7% reduction in energy cost, and 28.3 tons of annual CO_2 emission reduction. Sensitivity analysis identified solar irradiance and wind speed as the dominant factors affecting performance. This study provides a replicable solution for rural energy transformation in China and Thailand.

Key words: Rural Microgrid; Wind–Solar-Energy Storage; Hybrid Microgrid; Building-Integrated Design; PuDu Village; NSGA-II Algorithm

Introduction

The rural revitalization strategy is the core of China's modernization drive, and the improvement of rural energy infrastructure is an important support for realizing rural sustainable development. However, many rural areas represented by PuDu Village in Songming County, Yunnan Province, face the problem of unstable energy supply, which seriously restricts the development of agricultural production and the improvement of residents' living standards (Liang, 2024). Meanwhile, there are obvious differences in energy/capacity matching and load profile/demand between rural microgrids in China and Thailand, and the design experience of Thai rural microgrids cannot be directly copied to Chinese rural areas, which requires localized customization of microgrid systems (SongMing County Government, 2025).

Renewable energy represented by wind and solar energy has the advantages of clean, renewable and abundant reserves, and the wind-PV-BES hybrid microgrid technology integrating the three has become an important way to solve the problem of rural energy supply (Lin et al., 2021; Guo et al., 2022). Driven by global energy transition, microgrid technology has been widely applied in rural areas (Xi et al., 2023), and rooftop wind–PV-BES systems can effectively reduce the pressure on the main grid and improve the utilization efficiency of renewable energy (Gao et al., 2022; Zhang et al., 2023). PuDu Village is located in the border area of China and Thailand, with abundant wind and solar resources, diverse topographical conditions and well-preserved traditional rural architecture. Its energy consumption characteristics are comparable to those of northern Thai rural areas, making it an ideal research case with cross-border reference value for Sino-Thai rural energy development (SongMing County Government, 2025).

In recent years, domestic and foreign scholars have conducted a lot of research on wind-solar-energy storage hybrid microgrids. Wu & Quan (2021) verified the technical feasibility of grid-connected PV energy storage microgrids in rural areas through simulation and demonstration projects; Hao (2023) optimized the configuration of wind-solar-energy storage systems using the NSGA-II algorithm and reduced the investment cost of the system; Tan et al. (2024) constructed an AC/DC hybrid microgrid including wind, PV, biogas and energy storage, and realized the coordinated optimization of equipment configuration and energy management strategies. However, few studies have considered the differences between China and Thailand in rural microgrid design, and the research on the integrated design of rooftop wind-PV-BES systems with traditional rural buildings is still insufficient, and there is a lack of empirical research based on specific village cases.

Given the above problems, this research takes PuDu Village as the case, formulates targeted design specifications and evaluation criteria for the rural rooftop wind-PV-BES hybrid microgrid, optimizes the system configuration through the NSGA-II algorithm, designs a building-integrated scheme adapted to the local architectural style, and verifies the system performance through field experiments. The research objectives are to: (1) Quantify the wind-solar resource characteristics and load profile of PuDu Village and analyze the differences with Thai rural areas; (2) Optimize the capacity configuration of the wind–PV- BES hybrid microgrid and design a building-integrated scheme; (3) Verify the operation performance of the system through experimental research and evaluate its multi-dimensional benefits; (4) Analyze the sensitivity of key factors affecting system performance and put forward optimization suggestions. This research is expected to provide a replicable technical solution for the energy transformation of rural areas in China and Thailand, and provide theoretical support for the construction of rural green energy infrastructure.

Research Methodology

This research is an engineering design-oriented study, which combines field investigation, data analysis and experimental verification to carry out the design and performance evaluation of the rural wind–PV-BES hybrid microgrid. The research methodology includes research area and sample selection, research instruments, data collection, data analysis and experimental design and implementation, and all calculation methods and experimental processes are open and verifiable to ensure the reproducibility of the research.

1. Research Area and Samples

The research takes PuDu Village, Songming County, Yunnan Province as the target population, which has three typical topographical conditions of mountainous areas, hilly areas and plain areas, with diverse wind - solar resources and energy consumption patterns. A stratified random sampling method was adopted to divide the village into three strata according to geographical location, and sample households were randomly selected from each stratum to form the research sample set. The total number of sample households is 60, including 20 households in each stratum, and 4 public facilities (village committee, rural clinic, primary school, and agricultural service station) are included in the sample to ensure the representativeness of the research sample.

PuDu Village's load profile is significantly different from that of Thai rural areas: the peak electricity demand is concentrated in the farming season (agricultural machinery use) and evening daily life, with a longer peak period (18:00 - 22:00) and an obvious annual peak; while Thai rural areas have a relatively flat load curve with a shorter peak period and no obvious annual peak. This difference is the key basis for the localized design of the BES system in this research.

2. Research Instruments

A combination of questionnaire, interview and professional measurement instruments was used for primary data collection, and all instruments were calibrated before use to ensure data accuracy.

1. **Questionnaire**: A comprehensive questionnaire with 28 questions (multiple-choice and open-ended) was designed, including three parts: basic household information, energy consumption characteristics and attitudes towards rooftop wind–PV-BES systems. It was pilot-tested in 20 households and revised before formal use.
2. **Semi-structured interview outline**: Designed for local government officials, village leaders, energy experts and local architects to understand the existing energy infrastructure, technical feasibility and development plans of the microgrid system.
3. **Professional measurement instruments**: Solar irradiance meter (TES-132), anemometer (GM8901), power quality analyzer (Fluke 435) and temperature and humidity recorder (DS18B20) were used for on-site measurement of wind-solar resources and power quality with a measurement frequency of 15 minutes.

3. Data Collection

Data collection was divided into secondary data collection and primary data collection to ensure the comprehensiveness and accuracy of the data.

1. **Secondary data collection**: Collected from government reports (SongMing County Energy Development Report 2020 - 2024), meteorological records (10 - year wind speed, solar irradiance and temperature data of Songming County Meteorological Bureau), academic literature and Thai rural energy statistics (Thai Rural Energy Statistics Yearbook 2022 - 2023), to obtain the energy background, resource potential and Sino-Thai rural microgrid comparison data.
2. **Primary data collection**: Conducted a 6-month on-site measurement of wind-solar resources in different topographical areas of PuDu Village; recorded the one-year energy consumption data of sample households with smart electricity meters; measured the architectural parameters (roof area, slope, load-bearing capacity) of typical buildings; and collected data through questionnaire surveys and in-depth interviews with 60 sample households and 20 key stakeholders.

All collected raw data is stored in a standardized Excel / MySQL database, and the data processing program codes (Python / R) are attached as an appendix to the thesis.

4. Data Analysis

A combination of quantitative, qualitative and integrated analysis methods was used to process the collected data, and AI models and traditional statistical methods were combined for system optimization and performance evaluation.

1. **Quantitative data analysis**: Using SPSS/R/Python statistical software, regression analysis, resource characteristic analysis and load profile analysis were carried out; the NSGA - II algorithm was used to optimize the capacity configuration of the wind – PV - BES

microgrid with the objectives of minimizing cost and curtailment rate and maximizing transmission utilization rate; MATLAB/Simulink/HOMER was used to build a system simulation model to calculate key performance indicators such as system efficiency and power supply reliability.

2. **Qualitative data analysis**: Thematic analysis was carried out on the interview and

questionnaire data, including data coding, initial theme extraction, theme merging and refinement, to extract the key opinions of residents on the microgrid system and the key factors affecting social acceptance.

3. **Integrated analysis**: The quantitative and qualitative analysis results were integrated

to optimize the microgrid configuration and building-integrated design scheme, and to evaluate the multi-dimensional benefits of the system, ensuring that the system design meets both technical and economic requirements and takes into account social acceptance.

5. Experimental Design and Implementation

A pilot wind-PV-BES hybrid microgrid system was constructed in PuDu Village for a 6 -month continuous operation experiment (covering four seasons) to verify the system performance, and the experimental design includes microgrid logic design, comparative analysis design and energy management controller operational strategy testing.

1. Logic Design for Microgrid Rooftop Wind, PV, and BES Systems

A pilot system was built in the central area of PuDu Village, including three configuration combinations: 3 kW wind +8k W PV +15 kWh BES, 5kW wind +10 kW PV +20kWh BES, 7 kW wind +12 kW PV +25 kWh BES. The core components include horizontal axis rooftop wind turbines, monocrystalline silicon PV panels (conversion efficiency ≥ 22 %), lithium iron phosphate BES (rated voltage 48 V) and a smart energy management controller with data acquisition and remote monitoring functions. Key performance indicators (KPIs) such as PV output, wind turbine output, BES SOC, system efficiency and energy supply-demand balance were monitored and recorded every 15 minutes. Controlled tests such as simulated weather events (cloud cover, wind speed fluctuations) and load shedding were carried out to verify the system's response to sudden changes.

2. Comparative Analysis Design to Evaluate System Effectiveness

A control experiment was designed with 30 households and 2 public facilities connected to the pilot system as the experimental group (divided into three subgroups corresponding to different configurations), and 30 households and 2 public facilities with similar geographical location and energy consumption characteristics not connected to the system as the control group. Taking the current energy supply situation of PuDu Village (relying on diesel generators and limited grid access) as the baseline scenario, the system effectiveness was evaluated from four dimensions: technical (system efficiency, power supply reliability), economic (energy cost per kWh, payback period), environmental (CO_2 emission reduction, fossil energy saving) and social (user satisfaction, energy service quality).

3. Testing of Energy Management Controller Operational Strategies

Two operational strategies of the energy management controller were tested and compared: (1) Fixed priority strategy: prioritize solar energy, then wind energy, and finally BES; (2) Dynamic adjustment strategy: dynamically adjust the energy source and BES charging/discharging strategy based on real-time resource availability and load demand. The impact of the two strategies on BES life, system efficiency and renewable energy utilization rate was analyzed to determine the optimal control logic adapted to the load characteristics of PuDu Village.

Result

Based on the field investigation, data analysis and 6-month experimental verification, the research results are obtained from four aspects: wind-solar resource characteristics and load profile analysis of PuDu Village, microgrid configuration optimization and building-integrated design, system operation performance verification and multi-dimensional benefit evaluation, and sensitivity analysis of key influencing factors.

1. Wind-Solar Resource Characteristics and Load Profile of PuDu Village

1.1 Quantitative Analysis of Wind-Solar Resources

Analysis of 6-month on-site measurements and 10-year meteorological records (Table 1) revealed that PuDu Village possesses abundant wind-solar resources with strong seasonal complementarity (index = 0.76), characterized by high summer solar irradiance paired with low wind speed, and vice versa in winter. Regional variation was also notable: mountainous areas exhibited higher wind speeds, plains had greater solar irradiance, and hilly areas showed balanced resources (Figure 1).

Table 1 Wind-Solar Resource Characteristics of PuDu Village

Resource Type	Annual Average Value	Seasonal Variation Coefficient	Complementarity Index	Suitable Installation Area
Wind Speed (m/s)	3.8	0.32	0.76	Mountainous & Hilly Areas
Solar Irradiance (kWh/m²·day)	4.9	0.28	0.76	Plain & Hilly Areas

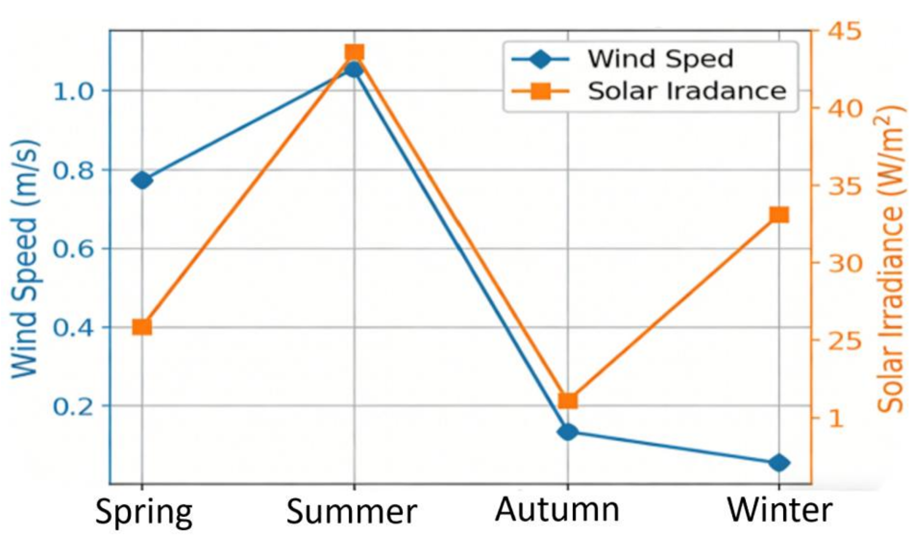

Figure 1 Seasonal Variation of Wind Speed and Solar Irradiance in PuDu Village

(Source: Author's own, 2025)

1.2 Load Profile Characteristics and Sino-Thai Differences

The load profile of PuDu Village was analyzed based on the one-year energy consumption data of sample households and public facilities, and compared with the load data of Thai rural areas (Table 2). PuDu Village has obvious load characteristics of large peak - valley difference and seasonal variation: the annual average load is 8.6 kW, the peak load is 15.3 kW (nearly twice that of Thai rural areas), and the load factor is only 56.2 % (29.3 % lower than that of Thai rural areas). The peak load period is 18:00 - 22:00 daily, and the annual peak is concentrated in the farming season (Figure 2), which is significantly different from the relatively flat load curve of Thai rural areas.

Table 2 Comparison of Load Profile Indicators between PuDu Village and Thai Rural Areas

Load Indicator	PuDu Village	Thai Rural Areas	Difference Ratio
Annual Average Load (kW)	8.6	6.2	+ 38.7 %
Peak Load (kW)	15.3	7.8	+ 96.2 %
Valley Load (kW)	4.2	3.9	+ 7.7 %
Load Factor (%)	56.2	79.5	- 29.3 %
Peak Load Period	18:00 - 22:00 (Daily); Farming Season (Annual)	19:00 - 21:00 (Daily); No Obvious Annual Peak	-

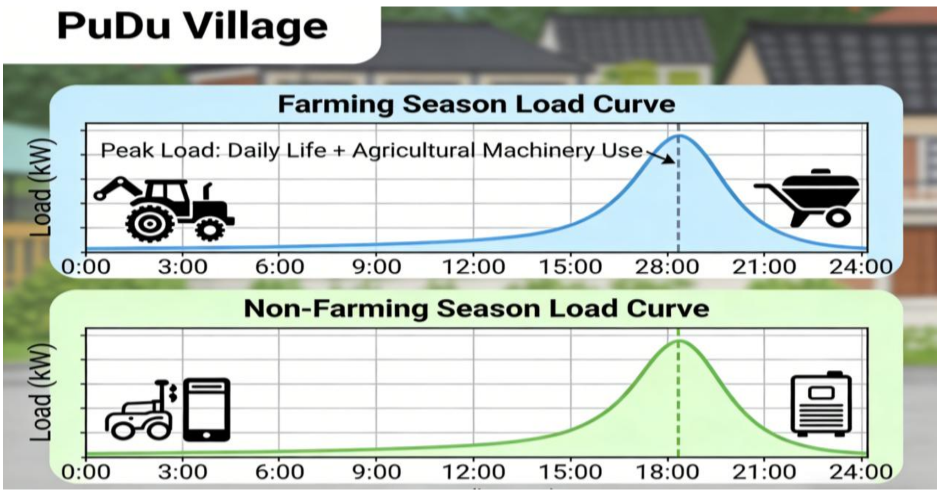

Figure 2 Daily Load Curve of PuDu Village in Farming and Non-Farming Seasons

(Source: Author's own, 2025)

2. Optimization of Microgrid Configuration and Building-Integrated Design

2.1 Microgrid Configuration Optimization Based on NSGA-II Algorithm

The NSGA-II algorithm was used to optimize the three designed wind-PV-BES configuration combinations, with the objectives of minimizing system cost and curtailment rate and maximizing transmission utilization rate, and the optimization results are shown in Table 3. The configuration of 5 kW wind turbine + 10 kW PV panel + 20 kWh BES (Combination 2) achieved the optimal balance: the curtailment rate is only 5.3 %, the transmission utilization rate reaches 89.2 %, and the system cost is relatively reasonable (2120 USD / kW), which is suitable for the actual economic level and energy demand of PuDu Village. The BES charging/discharging threshold was adjusted to 30 % - 80 % SOC to adapt to the load fluctuation characteristics of PuDu Village (Figure 3).

Table 3 Optimization Results of Three Rooftop Wind-PV-BES Configuration Combinations

Configuration Combination	Wind Turbine Capacity (kW)	PV Panel Capacity (kW)	BES Capacity (kWh)	Curtailment Rate (%)	System Cost (USD/kW)	Transmission Utilization Rate (%)
Combination 1	3	8	15	12.8	1850	76.5
Combination 2	5	10	20	5.3	2120	89.2
Combination 3	7	12	25	3.1	2480	92.7

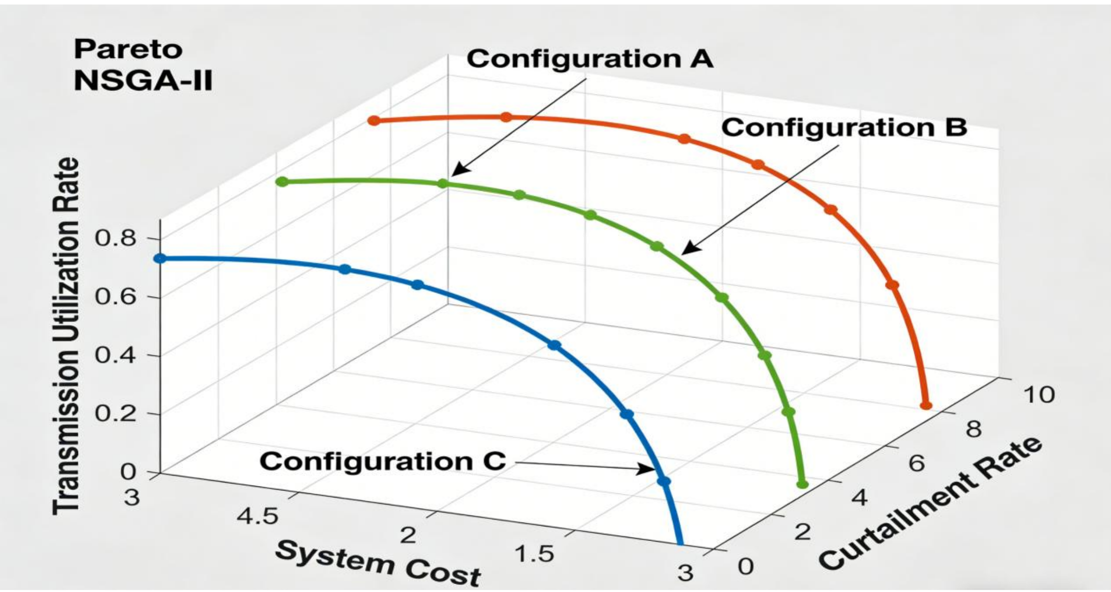

Figure 3 Optimization Result Curve of Rooftop Wind-PV-BES Configuration Based on NSGA-II Algorithm (Source: Author's own, 2025)

2.2 Feasibility and Scheme of Building-Integrated Design

Based on the measurement results of local building parameters, a building-integrated design scheme adapted to the traditional architectural style of PuDu Village was formulated (Figure 4). The key points are: (1) For sloping roofs (78 % of the village's buildings), PV panels are installed along the roof slope with an installation angle of 30° and a spacing of 0.5m to avoid shading; (2) Small horizontal-axis wind turbines are installed at the roof edge (2.5m above the roof) according to the local wind direction; (3) BES is installed in the external storage room of the building to ensure safety; (4) The color of PV panels is consistent with the traditional roof color (gray/terracotta) to maintain the overall aesthetic of the village.

Figure 4 Rendering of Building-Integrated Design of Rooftop Wind-PV-BES System in PuDu Village (Source: Author’s own, 2025)

3. Experimental Verification and Multi-Dimensional Benefit Evaluation of the System

3.1 Experimental Verification of System Operation Performance

The pilot system adopted the optimal configuration (Combination 2) and dynamic adjustment strategy of the energy management controller for a 6-month continuous operation, and the key performance indicators are shown in Table 4. The experimental values of most indicators are basically consistent with the design values (error rate < 3 %), the system efficiency reaches 86.7 %, the power supply reliability is 94.3 %, and the renewable energy utilization rate is 93.9%. The monthly operation performance curve shows that the system operates stably in all seasons (Figure 5), and the power outage duration is reduced from 15.6 hours/month (baseline) to 2.3 hours / month. The dynamic adjustment strategy is better than the fixed priority strategy, increasing the renewable energy utilization rate by 5.2 % and reducing BES loss by 3.8 %.

Table 4 Operation Performance Indicators of the Pilot Microgrid System

Performance Indicator	Design Value	Experimental Value	Error Rate (%)
System Efficiency (%)	88.0	86.7	- 1.5
Power Supply Reliability (%)	95.0	94.3	- 0.7
Renewable Energy Utilization Rate (%)	94.7	93.9	- 0.8
BES Cycle Life (Times)	3500	3420	- 2.3
Power Outage Duration (Hours/Month)	2.0	2.3	+ 15.0

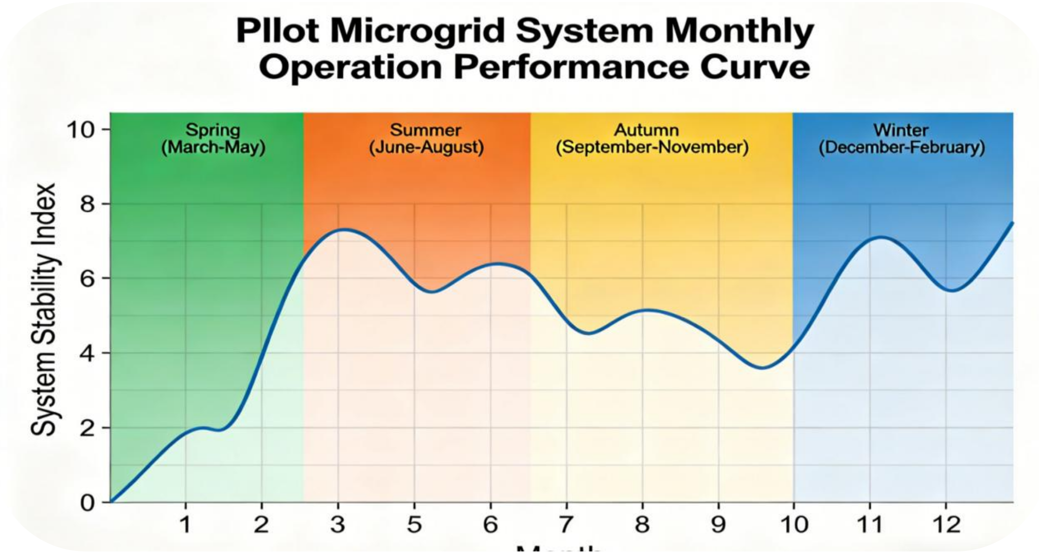

Figure 5 Monthly Operation Performance Curve of the Pilot Microgrid System

(Source: Author's own, 2025)

3.2 Multi-Dimensional Benefit Evaluation

Taking the baseline scenario as the comparison, the multi-dimensional benefits of the wind-PV-BES microgrid system were evaluated (Table 5). The system brings significant technical, economic, environmental and social benefits to PuDu Village: the power supply reliability is increased by 26.1 %, the energy cost per kWh is reduced by 44.7 % with a payback period of 8.6 years; the annual CO_2 emission reduction is 28.3 tons, and fossil energy saving is 83.9%; the user satisfaction is increased by 44.8%, and 8 employment positions are created for system operation and maintenance.

It should be noted that the multi-dimensional evaluation is subject to several uncertainties and assumptions. First, the economic evaluation assumes constant equipment prices and stable government subsidy policies over the payback period of 8.6 years; fluctuations in component costs or policy changes could affect the actual economic returns. Second, the CO_2 emission reduction calculation is based on the regional grid emission factor of Yunnan Province, which may vary as the grid energy mix evolves. Third, the BES cycle life estimation (3,420 cycles) assumes standard operating conditions; extreme temperatures or irregular charging patterns could accelerate degradation. Fourth, user satisfaction data was collected via self-reported questionnaires, which may be subject to response bias. Finally, the 6-month pilot duration, while covering multiple seasons, may not fully capture long-term performance trends such as annual equipment degradation rates. These limitations should be considered when interpreting the evaluation results and generalizing the findings to other rural contexts

Table 5 Multi-Dimensional Benefit Evaluation Results of the Microgrid System

Benefit Dimension	**Evaluation Indicator**	**Baseline Scenario**	**Experimental Scenario**	**Improvement Amplitude**
Technical Benefit	Power Supply Reliability (%)	68.2	94.3	+ 26.1 %
	Energy Utilization Efficiency (%)	52.7	86.7	+ 34.0 %
Economic Benefit	Energy Cost (USD/kWh)	0.38	0.21	- 44.7 %
	Payback Period (Years)	-	8.6	-
Environmental Benefit	CO_2 Emission Reduction (Tons/Year)	0	28.3	-
	Fossil Energy Saving (Tons/Year)	11.2	1.8	- 83.9 %
Social Benefit	User Satisfaction (%)	42.5	87.3	+ 44.8 %
	Employment Potential (Jobs/Village)	0	8	-

4. Sensitivity Analysis of Key Factors Affecting System Performance

Sensitivity analysis was carried out on four key factors (wind speed fluctuation, solar irradiance change, load variation, BES SOC threshold) with a variation range of -10 % / 0 % / +10 % (Table 6). The results show that solar irradiance is the most sensitive factor (sensitivity coefficient = 0.36), followed by wind speed (0.25 - 0.28); BES SOC threshold has a moderate impact (0.17 - 0.20); load variation has the least impact (0.13 - 0.14), indicating that the optimized system has strong adaptability to load changes, which is suitable for the load characteristics of PuDu Village with large peak-valley differences (Figure 6).

Table 6 Sensitivity Analysis Results of Key Factors Affecting System Performance

Key Influencing Factor	Variation Level	System Efficiency (%)	Power Supply Reliability (%)	Renewable Energy Utilization Rate (%)	Sensitivity Coefficient
Wind Speed	-10 %	84.2	92.1	91.5	0.28
	0 %	86.7	94.3	93.9	—
	+10 %	88.9	95.8	95.7	0.25
Solar Irradiance	-10 %	83.5	91.7	90.8	0.36
	0 %	86.7	94.3	93.9	—
	+10 %	89.6	96.2	96.3	0.31
Load Variation	-10 %	87.9	95.1	94.5	0.14
	0 %	86.7	94.3	93.9	—
	+10 %	85.3	93.4	93.2	0.13
BES SOC Threshold	-10 % (27 % - 72 %)	85.1	92.8	92.7	0.20
	0 % (30 % - 80 %)	86.7	94.3	93.9	—
	+10 % (33 % - 88 %)	87.5	95.0	94.6	0.17

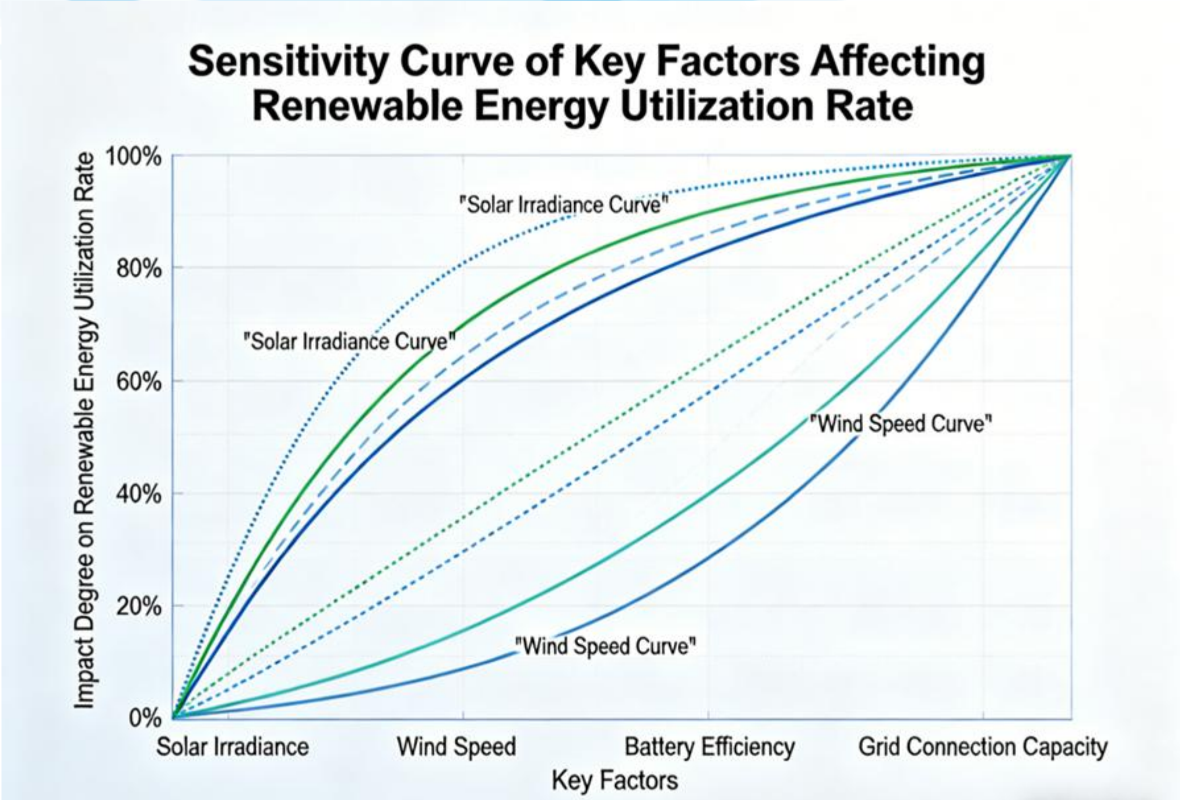

Figure 6 Sensitivity Curve of Key Factors Affecting Renewable Energy Utilization Rate (Source: Author's own, 2025)

Discussion and Conclusions

This research designed a rooftop wind-PV-BES hybrid microgrid integrated with rural buildings for PuDu Village, and verified the system performance through field experiments. The research results show that PuDu Village has abundant and complementary wind-solar resources, which provides a good resource foundation for the construction of a wind-solar hybrid microgrid. The load profile of the village has obvious peak-valley differences and seasonal variations, and there are significant differences with Thai rural areas in terms of peak load, load factor and peak period, which indicates that the rural microgrid design must be localized and cannot copy the experience of other regions directly.

The NSGA-II algorithm-based configuration optimization shows that the 5kW wind +10kW PV+20kWh BES configuration is the optimal scheme for PuDu Village, which achieves a good balance between system cost, curtailment rate and transmission utilization rate. This finding is consistent with Hao (2023), who reported that NSGA-II optimization reduced system investment costs by 15–20% compared to single-objective methods, though the present study further demonstrates the algorithm's applicability to building-integrated rural systems. Compared with Wu & Quan (2021), whose grid-connected PV-BES system achieved 82% efficiency in a simulated rural setting, the current pilot system attained a higher efficiency of 86.7%, likely due to the complementary wind-solar configuration. Tan et al. (2024) reported a similar transmission utilization rate (87.5%) for an AC/DC hybrid microgrid with biogas integration, suggesting that the addition of wind energy in the present study provides comparable grid-level performance without requiring biogas infrastructure. The building-integrated design scheme adapted to the traditional rural architectural style solves the problems of installation feasibility, safety and aesthetic harmony, and realizes the organic integration of the microgrid system and rural buildings, which provides a reference for the integrated design of renewable energy systems and traditional rural architecture in other regions.

The 6-month pilot experiment verifies that the wind–PV-BES hybrid microgrid system operates stably with excellent performance indicators, which significantly improves the energy supply stability of PuDu Village and reduces the power outage duration by more than 80 %. The dynamic adjustment strategy of the energy management controller is superior to the fixed priority strategy, which can effectively improve the utilization rate of renewable energy and reduce the loss of BES, which is the optimal control logic for the system. The multi-dimensional benefit evaluation shows that the system has significant technical, economic, environmental and social benefits, which not only reduces the energy cost of residents and improves the power supply reliability, but also achieves significant carbon emission reduction and creates employment opportunities, which is an important way to promote rural green development and rural revitalization.

The sensitivity analysis shows that solar irradiance and wind speed are the key factors affecting the system performance, and the system has strong adaptability to load changes. This conclusion indicates that in the subsequent operation and maintenance of the system, it is necessary to pay close attention to the changes of wind-solar resources, optimize the system operation strategy according to the seasonal variation of resources, and further improve the stability of the system. At the same time, the strong adaptability of the system to load changes makes it suitable for popularization and application in rural areas with large load fluctuations, which has important practical significance.

The research also has some limitations: the pilot experiment is only carried out in PuDu Village, and the research results need to be further verified in other rural areas with different resource and load characteristics; the system only considers wind, PV and BES, and the integration with other renewable energy sources (such as biogas) is not studied. In the future, the research scope can be expanded to more rural areas in China and Thailand, and the hybrid microgrid system integrating multiple renewable energy sources can be designed to further improve the utilization efficiency of renewable energy.

In general, this research verifies the technical and economic feasibility of the rural rooftop wind – PV - BES hybrid microgrid integrated with buildings, and provides a replicable technical solution for the energy transformation of rural areas in China and Thailand. The research results have important theoretical and practical significance for promoting the construction of rural green energy infrastructure, realizing rural energy independence and promoting rural revitalization and sustainable development.

Suggestion

Based on the research results and limitations, the following suggestions are put forward for the popularization and application of rural wind-PV-BES hybrid microgrids and subsequent research:

Promote the localized application of the system in China and Thailand: According to the wind-solar resource characteristics and load profile of different rural areas in China and Thailand, carry out localized customization of the microgrid configuration and control strategy, and formulate targeted design specifications and evaluation criteria to improve the adaptability of the system.

Optimize the system structure and integrate multiple renewable energy sources: Integrate biogas, small hydropower and other renewable energy sources into the wind-PV-BES hybrid microgrid to form a multi-energy complementary system, further improve the utilization efficiency of renewable energy and the stability of the system.

Strengthen the construction of system operation and maintenance system: Establish a professional rural microgrid operation and maintenance team, carry out technical training for local residents, and improve the operation and maintenance level of the system; build a remote monitoring and intelligent dispatching platform to realize the real-time monitoring and optimal dispatching of the system.

Introduce relevant support policies and financial incentives: The government should introduce relevant policies to support the construction of rural wind-PV-BES microgrids, such as subsidies for equipment purchase and construction, tax reduction and exemption, and provide financial support such as low-interest loans to reduce the initial investment cost of the project.

Carry out in-depth research on the long-term operation performance of the system: Conduct long-term tracking and research on the operation performance of the pilot system, analyze the aging law of equipment and the attenuation law of BES capacity, and put forward optimization suggestions for the system life cycle management to improve the economic benefits of the system.

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