# 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 study addresses unstable energy supply in rural China under the rural revitalization policy, noting distinct differences in energy-resource matching and load profiles between Chinese and Thai rural microgrids. A rooftop wind–PV–battery energy storage (BES) hybrid microgrid was designed for PuDu Village, Yunnan Province, using stratified random sampling for resource and load characterization and NSGA-II for optimal capacity configuration. A six-month pilot validated performance across technical, economic, environmental, and social dimensions.Key findings: the site offers complementary wind–solar resources (mean wind speed 3.8 m/s; solar irradiance 4.9 kWh/m²·day) with pronounced load peak–valley and seasonal variation. An optimized 5 kW wind + 10 kW PV + 20 kWh BES configuration balances cost, curtailment, and transmission utilization. The building-integrated design harmonizes with traditional rural architecture. The pilot achieved 86.7% system efficiency, 94.3% supply reliability, 44.7% energy-cost reduction, and 28.3 t $CO_2$/year abatement. Sensitivity analysis identified solar irradiance and wind speed as dominant performance drivers. The results confirm the techno-economic feasibility of rural building-integrated wind–PV–BES microgrids and offer a replicable model for rural energy transition in China and Thailand.

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

## Introduction

China's rural revitalization strategy demands improved energy infrastructure, yet villages like PuDu Village, Yunnan, face unstable supply constraining productivity and livelihoods. Differences in resource endowment and load profiles between Chinese and Thai rural areas preclude direct replication of Thai microgrid designs, requiring localized approaches. Rooftop wind–PV–BES hybrid microgrids offer a viable solution, and PuDu Village—with abundant wind–solar resources and traditional architecture near the China–Thailand border—provides an ideal case with cross-border relevance.Prior studies have validated rural PV-storage microgrids (Wu & Quan, 2021), applied NSGA-II cost optimization (Hao, 2023), and explored multi-source hybrid configurations (Tan et al., 2024), but gaps persist in Sino-Thai comparative design, building-integrated rooftop systems, and village-level empirical validation. This study addresses these gaps through four objectives: (1) quantify local wind–solar resources and load profiles benchmarked against Thailand; (2) optimize wind–PV–BES configuration with building integration; (3) validate performance via field experimentation across technical, economic, environmental, and social dimensions; and (4) analyze sensitivity of key performance drivers—delivering a replicable model for rural energy transformation in China and Thailand.

## Research Methodology

This engineering design-oriented study integrates field investigation, data analysis, and experimental validation. PuDu Village, Songming County, Yunnan Province—encompassing mountainous, hilly, and plain terrain—was selected as the study site. Stratified random sampling yielded 60 households (20 per topographic stratum) plus 4 public facilities. The village's load profile differs markedly from Thai rural areas, with pronounced farming-season and evening peaks (18:00–22:00) and distinct seasonal variation, informing localized BES design.

Data were collected through a pilot-tested 28-item questionnaire (60 households), semi-structured interviews (20 stakeholders), and continuous on-site measurements at 15-minute intervals using calibrated instruments (TES-132 solar irradiance meter, GM8901 anemometer, Fluke 435 power analyzer). Secondary data comprised 10-year meteorological records, government energy reports, and Thai rural energy statistics for cross-border benchmarking.

Quantitative analysis employed regression and resource characterization via SPSS/R/Python, NSGA-II multi-objective optimization (minimizing cost and curtailment; maximizing transmission utilization), and MATLAB/Simulink/HOMER simulation. Qualitative thematic analysis extracted resident attitudes and social acceptance factors. Both streams were integrated to co-optimize system configuration and building-integrated design.

A pilot system was constructed with three configurations (3 kW/8 kW/15 kWh, 5 kW/10 kW/20 kWh, and 7 kW/12 kW/25 kWh wind/PV/BES) using monocrystalline PV (≥22% efficiency) and $LiFePO_4$ storage. A controlled experiment compared 30 connected households (experimental) against 30 matched households (control) across technical, economic, environmental, and social dimensions over six months. Two energy management strategies—fixed-priority and dynamic adjustment—were tested to determine optimal control logic for local load characteristics.

## Result

### 1. Wind–Solar Resources and Load Profile

PuDu Village possesses abundant, seasonally complementary wind–solar resources (complementarity index = 0.76), with annual mean wind speed of 3.8 m/s and solar irradiance of 4.9 kWh/m²·day. Comparative load analysis reveals substantial differences from Thai rural areas (Table 1): PuDu Village's peak load (15.3 kW) is nearly double that of Thailand (+96.2%), while its load factor (56.2%) is 29.3% lower, with an extended daily peak period (18:00–22:00) and a pronounced farming-season annual peak. These disparities confirm the necessity of localized microgrid design.

**Table 1** 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 | - |

### 2. Configuration Optimization and Building Integration

NSGA-II multi-objective optimization identified 5 kW wind + 10 kW PV + 20 kWh BES as the Pareto-optimal configuration, achieving 5.3% curtailment, 89.2% transmission utilization, and a cost of 2,120 USD/kW. The building-integrated design accommodates the village's predominantly sloping roofs (78%) with slope-aligned PV at 30° tilt, roof-edge wind turbines, external BES enclosures, and color-matched panels preserving traditional architectural aesthetics.

### 3. Pilot Performance and Multi-Dimensional Benefits

Six-month continuous operation confirmed stable performance: 86.7% system efficiency, 94.3% supply reliability, and 93.9% renewable utilization—all within 3% of design targets. The dynamic energy management strategy outperformed fixed-priority control. Compared to baseline, the system reduced energy cost by 44.7% (to 0.21 USD/kWh), abated 28.3 t $CO_2$/year, saved 83.9% fossil fuel, and raised user satisfaction from 42.5% to 87.3%, with a payback period of 8.6 years.

### 4. Sensitivity Analysis

Solar irradiance is the most influential factor (sensitivity coefficient = 0.36), followed by wind speed (0.25–0.28), while load variation has the least impact (0.13–0.14), demonstrating strong system adaptability to demand fluctuations (Figure 1)

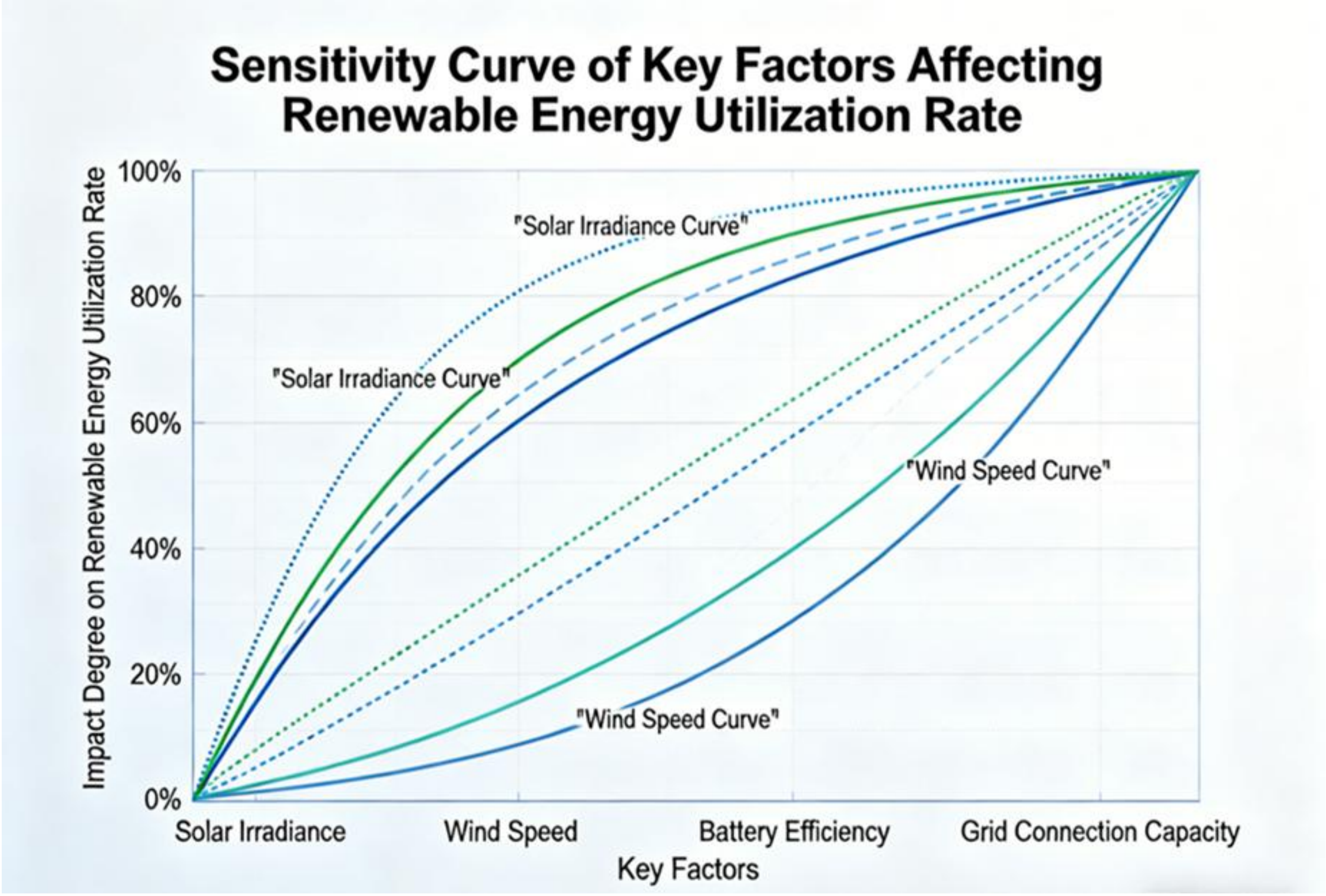

**Figure 1** Sensitivity Curve of Key Factors Affecting Renewable Energy Utilization Rate (Source: Author's own, 2025)

## Discussion and conclusions

PuDu Village possesses abundant, complementary wind–solar resources, yet its load profile—characterized by pronounced peak–valley disparity and seasonal variation—differs significantly from Thai rural areas in peak load, load factor, and peak duration, confirming that microgrid design requires localization rather than direct replication. NSGA-II optimization identified the 5 kW wind + 10 kW PV + 20 kWh BES configuration as the Pareto-optimal solution balancing cost, curtailment, and transmission utilization. The building-integrated design preserves traditional architectural aesthetics while resolving installation feasibility and structural safety constraints, offering a transferable model for other regions.The six-month pilot demonstrated stable operation with high system efficiency, reducing power outage duration by over 80%. The dynamic energy management strategy outperformed the fixed-priority approach, improving renewable utilization and reducing BES degradation. Multi-dimensional evaluation confirmed significant technical, economic, environmental, and social benefits—including lower energy costs, enhanced supply reliability, substantial $CO_2$ reduction, and local employment creation—supporting rural revitalization objectives.Sensitivity analysis identified solar irradiance and wind speed as dominant performance drivers while revealing strong system adaptability to load fluctuations, indicating suitability for rural areas with variable demand. Limitations include the single-village scope and exclusion of complementary sources such as biogas; future work should extend validation to diverse Sino-Thai rural contexts and explore multi-energy integration.Overall, this study confirms the techno-economic viability of building-integrated rural wind–PV–BES microgrids and delivers a replicable solution for rural energy transition in China and Thailand.

## Suggestion

Five directions are proposed for scaling rural wind–PV–BES microgrids and advancing future research. First, localized deployment across diverse Chinese and Thai rural contexts requires site-specific configuration, control strategies, and tailored design standards reflecting regional resource and load differences. Second, integrating additional renewables—biogas, small hydropower—into multi-energy complementary systems can enhance stability and utilization efficiency. Third, sustainable operation demands dedicated O&M teams, resident technical training, and remote monitoring with intelligent dispatch platforms. Fourth, governmental subsidies, tax incentives, and low-interest financing are essential to lower upfront investment barriers. Fifth, long-term performance tracking of pilot systems should address equipment degradation, BES capacity fade, and life-cycle optimization to strengthen economic viability.

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