# The Application of the Multi-Energy Complementary Distributed Power Generation Systems in Global Rural Areas in the Smart Grid

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**Abstract.** The study focuses on the application of multi-energy complementary distributed power generation systems in rural smart grids, aiming to address the issues of unstable energy supply and low utilization rates of renewable energy in rural areas. By integrating various forms of energy, such as solar, wind, and biomass, combined with energy storage technology and intelligent control strategies, a multi-energy complementary smart grid model suitable for rural areas in countries at different levels of economic development has been proposed. Research shows that this system can significantly enhance power supply stability, optimize energy efficiency, and bring environmental and economic benefits. However, issues such as weak rural grid infrastructure and high energy storage costs still need to be addressed. To this end, it is recommended to strengthen grid upgrades, promote smart monitoring technologies, and support technology implementation through policy measures. The research findings provide theoretical support and practical pathways for global rural electrification and energy transition.

## INTRODUCTION

Globally, the electrification gap in rural areas remains one of the major challenges for rural development. Despite the increase in electricity coverage in recent years, many remote rural areas still face the problem of unstable power supply or even no electricity. At the same time, these areas are rich in renewable resources such as solar energy, wind energy, and biomass energy. But they are limited by technical limitations and systemic integration capabilities, which leads to a problem that the utilization rate is low, resulting in waste of energy. The current research focuses more on the optimization of a single energy system and less on the application of multi-energy complementary systems in smart grids.

In this context, it is of great significance to study the application of multi-energy complementary distributed energy systems in rural smart grids. On the one hand, it can improve the power supply stability in rural areas and reduce the dependence on external power grids. On the other hand, it can effectively integrate local renewable resources through multi-energy complementarity and improve energy utilization efficiency. In addition, the rational application of renewable energy is also conducive to the effective integration of local renewable resources in rural areas with strategic significance for global environmental issues, thereby achieving the control of environmental pollution and resource complementarity in rural areas [1].

This study begins at the key technical level, examining physical layer, technical layer, and information layer technologies to explore the technical feasibility of multi-energy complementary systems, thereby offering theoretical support and technical pathways for global rural electrification.

## TECHNOLOGY FRAMEWORK OF MULTI-ENERGY COMPLEMENTARY DISTRIBUTED POWER GENERATION

This article constructs a key technology system for distributed intelligent power grids from three levels: the physical layer, the technology layer and the information layer, which can be seen in figure 1. The physical layer technology serves as the foundation for the operation of the entire system, ensuring efficient and stable operation during the production and storage of electrical energy. The technology layer highlights AI-based load forecasting technology, which utilizes deep learning algorithms to achieve precise predictions and dynamic optimizations of electricity demand, thereby enhancing the efficiency of energy dispatch and the flexibility of the system. The information layer, through digitalization and intelligent approaches, provides the system with efficient data collection, analysis, and decision-making capabilities, ensuring the automated operation of the system.

### Physical Layer: Flexible Matching of Infrastructure

#### *Integration of Multi-Energy Power Generation Equipment*

First of all, in the integration of multiple energy generation equipment in rural areas, it is necessary to select suitable primary renewable energy devices, such as photovoltaic panels and wind turbines, based on the characteristics of resources like solar, wind, and biomass energy in rural areas. Considering the diversity of energy types in rural regions and future expansion needs, a modular design concept is introduced to better accommodate load variations and the volatility of renewable energy [2]. Additionally, by employing standardized and mass-produced modules, the manufacturing costs of the systems can be reduced [3]. Furthermore, by dynamically adjusting the ratio of solar and wind energy through weather forecasting technology, seamless energy supply can be achieved under varying climatic conditions. The use of biomass to produce biogas complements solar and wind energy, mitigating shortages caused by the instability of solar and wind energy. By integrating various energy resources, efficient complementary energy utilization can be realized [4].

#### *Hybrid Energy Storage Systems*

Currently, the commonly used energy storage methods include: electrochemical energy storage, pumped hydro storage, flywheel storage, and electric double layer capacitors storage. Among them, while electrochemical energy storage has high energy density, it has a limited lifespan and certain safety hazards; the construction of pumped hydro storage is heavily restricted by geographical factors, making it unsuitable for widespread promotion; the latter two methods have long lifespans and high power density but low energy density. Therefore, a single energy storage system often struggles to simultaneously meet the demands for high power and high energy density. This paper will explore the composition of various energy storage systems into a hybrid storage system to satisfy the needs of rural micro-grids [5].

In light of the significant fluctuations in rural electricity demand and the strong intermittency of distributed power sources, a differentiated energy storage combination is required. For instance, lithium batteries boast a response speed that is five times faster than that of lead-acid batteries. With its ability to respond quickly within 2 seconds and their high energy density of 150-200 Wh/kg, they can effectively smooth out minute-level power fluctuations. However, due to the substantial damage that high-frequency loads can inflict on lithium batteries, its overall lifespan is directly affected. On the other hand, the rapid charge and discharge capabilities of electric double layer capacitors can make up for the insufficient transient response of lithium battery packs while also extending the lifespan of those packs. Consequently, a system composed of both can optimize system response characteristics while ensuring the longevity of lithium batteries, thereby reducing costs [6].

### Technology Layer: Intelligent Optimization and Cooperative Control

For the technical perspective, this article primarily discusses load forecasting based on artificial intelligence models.

The electricity consumption in rural areas has significant spatiotemporal fluctuations. AI-based load forecasting models can analyze characteristics of rural electricity usage, such as seasonal peaks during busy farming periods and nighttime lighting demands, allowing for dynamic adjustments in energy allocation strategies. Among the AI methods, deep learning techniques, utilizing multi-layer nonlinear mappings, can progressively extract hidden abstract features from large-scale data, thereby effectively enhancing predictive performance [7]. For instance, employing Long Short-Term Memory (LSTM) networks, which integrate historical electricity consumption data, meteorological conditions, and agricultural activity calendars, can predict the load curve for the next 24 hours with an accuracy of over 90% [8]. Additionally, using Convolutional Neural Networks (CNNs) to analyze equipment vibration, temperature, and current waveform data facilitates early fault warning [9].

## Information Layer: Data Perception and Decision Support

At the information layer, the data integration and intelligent analysis of the whole chain drive the effective operation of the system and user participation.

The information layer first integrates real-time data from sensors such as light intensity, wind speed, and energy storage state in the physical layer and control instructions in the technical layer to build a comprehensive data warehouse covering power generation, energy storage, load and trading, providing accurate input for dynamic decision-making. Based on machine learning and clustering algorithms, the platform deeply analyze the characteristics of users' electricity consumption behavior, identifies different load patterns, and formulates differentiated energy management strategies accordingly. In order to improve user engagement, the platform adopts a low-threshold interactive design, develops a visual interface that supports multi-language and voice control, and reduces the complexity of operation through intuitive graphical identification and real-time feedback mechanism, ensuring that users of different cultural levels can easily grasp energy usage. At the same time, lightweight data encryption and hierarchical management of permissions ensure the security of information transmission and storage, forming a closed-loop architecture of "data collection-intelligent analysis-user empowerment-privacy protection" to realize the transparent and democratic operation of the energy system. For example, Xiangtan Power Supply Company of State Grid Corporation of China deploys the distribution network operation monitoring function in the production control area, disposes the distribution network operation status control function in the management information area, and sets up the corresponding safety access area for the production control area. The integrated operational monitoring and control optimization has comprehensively enhanced the perception capability for distributed energy and has achieved refined grid management for it [10].

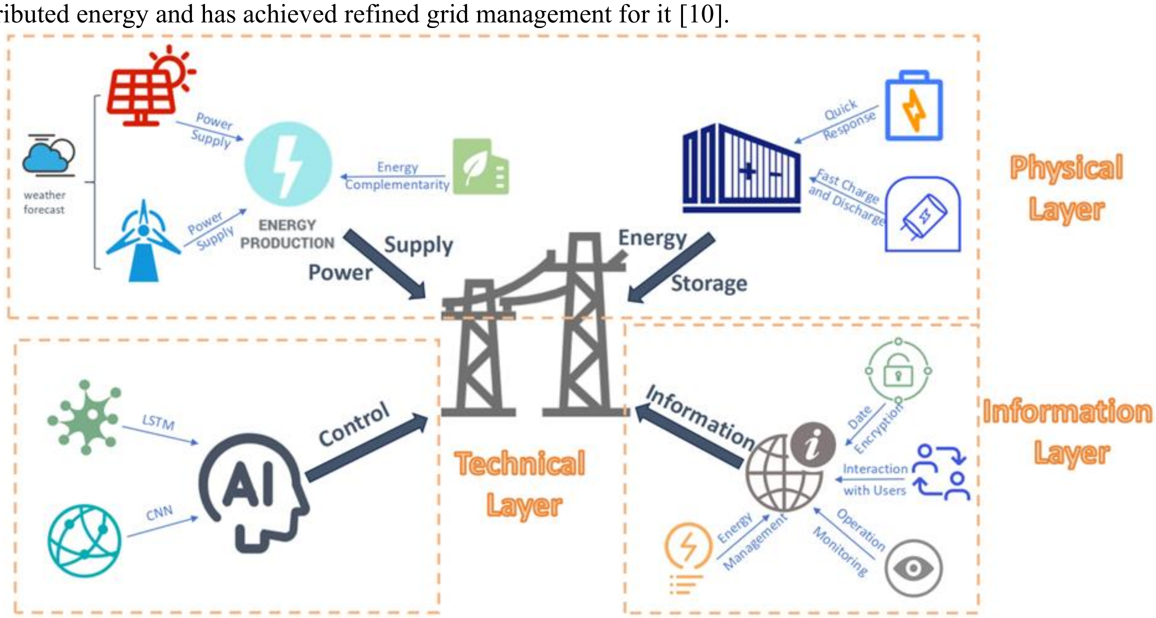


**FIGURE 1.**The theoretical and technical framework of the multi-energy complementary distributed power generation system

# BREAKTHROUGH INNOVATIONS AND APPLICATION CASES

## Breakthroughs and Innovations in Key Technologies

Distributed generation systems with complementary abilities in rural areas not only improve the rural micro-grid but also provide strong assurance for the reliable operation of the main grid. Through the flexible grid connection strategy in smart grid interaction technology, the focus is on the efficient collaboration and stable interconnection between rural micro-grids and the main grid, achieving a dynamic balance of bi-directional energy flow.

The core consists of intelligent control and power electronics technology. Among them, the adaptive control algorithm perceives the state of the main grid in real-time and dynamically adjusts the output of the micro-grid. It maintains power quality when connected to the grid, and seamlessly switches to autonomous mode when off-grid, relying on local energy storage and distributed power sources to ensure power supply for critical loads. The bidirectional interaction mechanism supports the micro-grid in flexibly switching between 'buying electricity - selling electricity' modes, based on electricity price signals or energy supply-demand status. For example, when renewable energy is abundant, it feeds back electricity to the main grid, enhancing economic returns; when generation is insufficient, it intelligently calls upon the main grid for supplementation, increasing power supply reliability. This strategy strengthens the autonomous resilience of rural microgrids while achieving deep compatibility with the main grid, providing an adaptable framework for high proportions of distributed energy integration.

## Case Analysis

*South Asian Agricultural Region: Agricultural and Photovoltaic Complementation + Biogas Power Generation*

The pilot project in the South Asian agricultural intensive zone integrates photovoltaic power generation with agricultural production, establishing a "complementary agriculture and solar energy biogas recycling" system. Photovoltaic panels are installed above the farmland, with a height designed to meet both the light requirements of crops and the maintenance needs of the equipment. It provides clean electricity while reducing land occupation. At the same time, agricultural waste such as rice husks, sugarcane residues, and livestock manure is used for anaerobic fermentation to produce biogas, with the fermentation residues returned to the fields as organic fertilizer, forming a closed loop of "planting - power generation - fertilizer." This system has increased the annual self-sufficiency rate of electricity for farmers to 80%, reduced the use of chemical fertilizers by 30%, achieved coordinated growth in energy, agriculture, and ecological benefits, while ensuring food production.

*African Off-grid villages: Hybrid Renewable Energy Systems*

Remote villages in sub-Saharan Africa, faced with the issue of lacking grid coverage, are piloting a hybrid energy model that primarily relies on photovoltaic, with diesel as backup and energy storage for peak shaving. The photovoltaic system leverages the abundant solar resources in the region to meet the daytime electricity needs of households and small processing workshops. The lithium battery storage system captures excess electrical energy for use during the night, thereby reducing dependence on diesel generators. Diesel generators serve merely as backup power during extreme weather conditions such as sustained rain or unexpected high loads, which significantly lowers fuel consumption and carbon emissions. This model achieves rapid deployment through modular design, resulting in an approximately 50% reduction in average household electricity costs and a 70% decrease in diesel usage, thus greatly enhancing energy accessibility and environmental sustainability.

Central and west Africa has long faced issues with weak power infrastructure, and in this context, Cameroon's rural hybrid energy projects offer a solution. Most local villages are not connected to the national grid, relying on diesel generators, which are both costly and heavily polluting. The new system provides round-the-clock power supply through a combination of wind and solar energy, energy storage buffers, and diesel backup. It utilizes MOPSO (Multi-Objective Particle Swarm Optimization) to determine the optimal configuration, primarily relying on wind and photovoltaic power, with lithium battery systems providing 67% of nighttime energy supply, significantly reducing the use of diesel generators. After optimization, fuel consumption is reduced by 89%. The project employs containerized modules for quick deployment, decreasing average household energy expenditure, increasing the renewable energy self-sufficiency rate, and providing communities with a reliable and energy-secure system[11].

As shown in Table 1, the Sahara pilot project focuses on low-cost and rapid deployment, with affordability and accessibility suited for off-grid villages. In contrast, the Cameroon research case employs a multi-energy complementary approach and MOPSO algorithm optimization, resulting in more reliable grid operation, which is suitable for community-level energy planning.

**TABLE 1.** Hybrid Energy Systems in Off-Grid Africa

| Dimension | Sahara Pilot Project | Cameroon Research Case |
|---|---|---|
| Core Technology | Modular and rapid deployment | MOPSO algorithm optimization configuration |
| Energy diversity | Single photovoltaic dominance | The complement of wind, solar, and energy storage |
| Applicable scenarios | Off-grid remote villages | Community-level energy system planning |
| Core Objective | Low cost, accessibility | Reliability, energy security |

Through the aforementioned innovative technologies and practical application cases, it can be seen that multi-energy complementary distributed generation systems have significant advantages in enhancing the stability of energy supply, economic benefits, and environmental friendliness in rural areas.

## CURRENT ISSUES AND RESPONSE STRATEGIES

Although the rural multi-energy complementary distributed generation system is theoretically feasible, it still has many problems in practice.

Firstly, the large-scale integration of distributed power sources is constrained by infrastructure issues, including aging lines, insufficient substation capacity, and the lack of monitoring systems. These challenges lead to unstable power supply and risks of excessive equipment load. It is necessary to improve system stability by replacing aging lines, optimizing grid structure, expanding substation capacity, enhancing absorption capability, and deploying intelligent monitoring. It is recommended to adopt ‘modular retrofit digital twin’ technology: utilizing prefabricated modular substations to shorten construction time in remote areas, and deploying intelligent distribution terminals in town centers to achieve self-healing in case of faults; creating a line health monitoring system that utilizes fiber optic sensing to track equipment status in real-time, thereby improving operation and maintenance response speed by 40%. This lays the material foundation for transforming rural energy systems into more efficient and flexible formats [12].

In addition, one of the core challenges that the widespread application of renewable energy will face lies in the inefficiency and high cost of energy storage technology, particularly in rural areas where grid infrastructure is weak. Energy storage systems are crucial for stabilizing fluctuations in intermittent energy sources such as wind and solar power [13]. For instance, while the installed capacity of new energy in Jilin Province is growing rapidly, there has been a significant rate of wind and solar energy abandonment [14]. To address this challenge, it is necessary to develop localized solutions: Edge computing can reduce communication latency and bandwidth pressure through distributed data processing, enhancing the real-time responsiveness of energy storage scheduling; artificial intelligence further optimizes energy management by accurately predicting load demand and dynamically adjusting energy storage charge and discharge strategies. Moreover, by employing anomaly detection algorithms, AI can timely identify equipment failures, mitigating system downtime risks. The collaboration between edge computing and artificial intelligence not only lowers the deployment costs of energy storage systems but also enhances the adaptability of rural micro-grids to the high penetration of renewable energy, providing technical support for stable energy supply in off-grid or weak-grid areas.

Moreover, existing research often neglects the adaptive transformation of operation and maintenance systems. It is recommended to establish a 'online-edge-end' collaborative operation and maintenance architecture: the online builds a digital twin platform that integrates multiple sources of information such as meteorological data, equipment records, and operational logs; the edge side deploys energy routers with local decision-making capabilities that can maintain autonomous operation for 72 hours even in the event of network disconnection; at the terminal level, a simple operation and maintenance app is developed for farmers, providing basic functions such as power generation inquiry and fault reporting. At the same time, a dual-track system of 'professional teams and villager co-management' should be established, enabling villagers to master basic maintenance skills such as inverter restart and module cleaning through skill training.

## CONCLUSION

This study explores the application of multi-energy complementary distributed generation technology in smart grids in rural areas, addressing issues such as insufficient electrification and low energy utilization efficiency. By integrating renewable energy sources such as solar, wind, and biomass energy into rural smart grids, along with the incorporation of energy storage technology and intelligent control systems, the aim is to improve the stability of rural power supply, reduce dependence on external grids, dynamically adjust the energy supply ratio to optimize resource utilization efficiency, and decrease energy waste. This system enhances the energy structure in rural areas and brings environmental and economic benefits. For instance, reducing the use of fossil fuels can lower carbon emissions, while farmers can gain economic benefits through savings on electricity bills and increased added value of agricultural products. Additionally, smart grid technologies like flexible grid connectivity and bi-directional interaction can enhance the autonomy of micro-grids, promoting a higher proportion of renewable energy integration.

However, challenges still exist in reality, such as weak infrastructure of rural power grids and high energy storage costs. It is recommended to strengthen grid renovation, promote smart monitoring systems, and reduce costs through policy support and technological innovation. Case studies demonstrate the feasibility of projects such as ‘Agricultural Photovoltaic and Biogas’ in South Asia and hybrid energy projects in off-grid villages in Africa.

In conclusion, multi-functional complementary distributed generation systems provide an effective pathway for the energy transition in rural areas. In the future, it is necessary to further promote technological advancements and the implementation of plicies to contribute to the achievement of global sustainable development goals.

## REFERENCES


1. T. Wang, Q. Wang, and C. Zhang, "Research on the Optimal Operation of a Novel Renewable Multi-Energy Complementary System in Rural Areas," Sustainability **13**(4), 2196 (2021).
2. Y. Zhou, J. Wang, H. Xu et al., "Improving Full-chain process synergy of multi-energy complementary distributed energy system in cascade storage and initiative management Strategies," Energy Conversion and Management **322**, 119120 (2024).
3. Y. Tian, J. Chang, Y. Wang et al., "The capacity planning method for a Hydro-wind-PV-battery complementary system considering the characteristics of multi-energy integration into power Grid," Journal of Cleaner Production **446**, 141292 (2024).
4. X. Li, "Research on the Two-stage Robust Capacity Configuration of Biomass Gas-Solar-Wind Integrated Energy System," Shandong University (2022).
5. K. Shi, "Research on the Quick Response of Active Power in Photovoltaic Power Plant Based on Hybrid Energy Storage," Shenyang University of Technology (2020).
6. Editorial Team of Power Plant Auxiliary Machines, "Introduction to Lithium Battery Energy Storage," Power Plant Auxiliary Machines **43**(3), 10 (2022).
7. F. Han, X. Wang, J. Qiao et al., "A Review of Load Forecasting Research in New Power Systems Based on Artificial Intelligence Technology," Proceedings of the CSEE **43**(22), 8569-8592 (2023).
8. S. Luo, M. Ma, L. Jiang et al., "Medium and Long-term Load Forecasting Method Considering Multi-time Scale Data," Proceedings of the CSEE **40**(S1), 11-19 (2020).

9. J. Su, "Construction and Application of Distributed Energy Management Platform in New Power Systems," Popular Electric Power **40**(2), 30-32 (2025).
10. W. F. M. Rafi, R. D. N. S. Jacques, and J. M. R. J. et al., "Exploring the Technical Feasibility of Hybrid Renewable Energy Systems Connected to the Grid in Combating Respiratory Diseases: A Case Study of a Community in Douala," Solar Compass **8**, 100062 (2023).
11. IEEE PES Working Group on Rural Electrification, "Maximizing Injection of Rural Distributed Generation," 2015 IEEE Power & Energy Society General Meeting, 1-5 (2015).
12. M. H. Sifat, S. M. Choudhury, S. K. Das et al., "Towards Digital Twin Grids: A Review of Technologies and Framework," Energy and Artificial Intelligence **11**, 100213 (2023).
13. Y. Li, Y. Yang, X. Wang et al., "Research on Collaborative Development Paths of New Energy and Agricultural Electrification in Jilin Province," Agriculture and Technology **42**(3), 137-140 (2022).
14. International Energy Research Consortium, "Smart Grid and Renewable Energy Systems: Prospects and Challenges of Grid Integration," Energy Strategy Reviews **51**, 101299 (2024).