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# Exploration of Guangdong Rural Distributed Photovoltaic Construction Model from the Perspective of “Innovative Carbon-Neutral Rural Area”

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**ABSTRACT:** As China is a major carbon-emitting country, low-carbon development in rural areas will play a key role in achieving the national goal of carbon peaking and neutrality. With the advancement of the rural revitalization strategy, carbon emissions in rural areas have intensified; however, these areas also demonstrate significant advantages in spatial resources for ecosystem carbon sinks and new energy development. The two national strategies of “carbon neutrality” and “rural revitalization” are intrinsically linked. Therefore, a strategic coupling mechanism combining “carbon neutrality” and “innovative rural area” should be established. This mechanism aims to promote positive interaction between urban capital, talent, and technology and the rich ecological carbon sinks and vast spatial resources of the countryside, opening up new pathways for the flow of urban-rural capital and resources.

Based on this new perspective, and leveraging Guangdong Province’s abundant solar energy resources and vast stock of rural housing, this article explores the technical system, implementation path, and operation mode of rural distributed photovoltaics. The construction of this model is carried out at five levels. At the level of resource assessment and construction, it emphasizes the comprehensive investigation and evaluation of resources within a certain area (preferably at the county or town level) and establishes coordination between investment companies, multi-disciplinary teams, villagers, and governments. At the design and implementation level, it proposes combining distributed photovoltaics with the revitalization of rural landscapes in Guangdong Province to improve rural aesthetics, turning government costs into investments, and converting idle village resources into effective assets. At the commercial operation level, based on clarifying the functions and benefits of all parties, a win-win cooperation mechanism comprising “village joint-stock company-operating enterprise-government” is constructed, and three business models for the renovation of rural houses with solar panels have been designed to enhance their market promotion. At the level of operation and maintenance management (O&M), a rooftop solar energy smart management platform is built to manage the pre-development process, project approval, capital use, and O&M, promoting efficient management.

Furthermore, based on the construction of photovoltaic sun pavilions for rural houses, this paper further proposes a variety of models combining distributed photovoltaics with traditional rural construction and agriculture. It also puts forward ideas for the construction of a rural energy system featuring “source-grid-load-storage integration,” to promote the iterative upgrading of power generation technology and the combined utili-

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zation of resources in rural production and living spaces. Finally, this article proposes an extended reflection on the model of “Innovative Carbon-Neutral Rural Area”. It is a comprehensive concept that requires the comprehensive transformation and development of rural space, economy, and society in harmony with the environment, aiming to build a rural area developed with environmentally-friendly principles. Economically, it promotes the assetization of ecological resources and creates a new model of rural green industry and finance. Socially, it focuses on low-carbon production and lifestyle, establishing a new mechanism for smart and modern ecological governance.

**KEYWORDS:** rural revitalization; carbon neutrality; rural distributed photovoltaic construction model; Innovative Carbon-Neutral Rural Area

## Introduction

The increasing concentration of greenhouse gases, such as carbon dioxide, has intensified the greenhouse effect, leading to global warming and a higher frequency of extreme weather events. These changes exert irreversible and severe impacts on human production, living, and ecosystems [1]. In his important speech at the ninth meeting of the Central Financial and Economic Affairs Commission, General Secretary Xi Jinping pointed out that carbon peaking and carbon neutrality should be incorporated into the overall layout of ecological civilization, signifying a broad and profound systemic socio-economic transformation [2]. The trend of low-carbon consumption driven by ecological economics, which emphasizes returning to nature, is providing a vast market and impetus for the development of China’s rural ecological economy [3]. However, China has long exhibited a tendency to prioritize cities over rural areas (a phenomenon known as “urban bias”). Decision-makers have predominantly focused low-carbon economic development on cities, while rural areas are easily overlooked [4]. Standing at the new starting point of comprehensively promoting rural revitalization, we find it even more urgent to explore the transformation pathways for low-carbon development in rural areas, promote the development of rural ecological civilization, and help China achieve its carbon neutrality goal as soon as possible.

## 1 “Innovative Carbon-Neutral Rural Area”: Comprehensive advancement and high integration of the two major national strategies

### 1.1 The Challenges and potentials of low-carbon development in rural areas

China’s rural land area covers 5.53 million km<sup>2</sup>, including 1.23 million km<sup>2</sup> of arable land, with a rural population of about 577 million. Across such a vast area, the

total energy demand for rural living and production is large, widespread, and relatively dispersed [5]. In terms of rural life, in recent years, the per capita energy consumption in rural areas of China has been increasing, with a growth rate far exceeding that in urban areas, and carbon emissions have also shown an increasing growth trend. Regarding rural production, agricultural activities are not only a major source of greenhouse gas emissions, but also the sector most vulnerable to climate change [6]. As a major agricultural country, China’s total agricultural carbon emissions have consistently been higher than those of European and American countries. In addition, China’s agricultural production mainly relies on the application of chemical fertilizers and pesticides to achieve the goal of increasing yields [7]. The extensive use of pesticides, agricultural plastic films, and diesel fuel generates significant amounts of greenhouse gases—such as carbon dioxide, methane, and nitrous oxide—while also leading to a gradual decrease of soil organic matter. Evidently, the agricultural production sector holds significant potential for carbon emission reduction in the future.

Rural areas are not only an indispensable part of the nation’s energy consumption and greenhouse gas emissions, but also an important spatial carrier for ecosystem carbon sinks and new energy development. In terms of ecosystem carbon sinks, if the soil organic matter of the country’s 120 million hectares of farmland increases by 1‰, it can net absorb 3 billion tons of CO<sub>2</sub> from the atmosphere. Additionally, with a national forest area of 208 million hectares, the total carbon storage can reach 8.427 billion tons. If these vast carbon sink resources in rural areas can be effectively managed, they can be increased at a low cost, making a significant contribution to reducing greenhouse gas emissions. Regarding new energy development, biomass energy, solar energy, wind energy, and other

renewable energy sources are decentralized and relatively evenly distributed energy sources compared to traditional fossil energy. This characteristic gives rural areas a spatial resource advantage over cities. With the rapid development of new energy technologies such as photovoltaic and wind power generation, renewable energy is more economically viable than ever before [8], providing stronger support for the low-carbon transformation of rural areas.

### 1.2 The Significance and value of integrating the rural revitalization strategy with the carbon neutrality strategy

Green and low-carbon development is the endogenous driving force and inevitable requirement for high-quality rural revitalization, and the emission reduction potential inherent in rural areas can be effectively stimulated through rural revitalization.

Key documents, such as the *Strategic Plan for Rural Revitalization (2018-2022)* and the *No. 1 Central Document of 2021* (i.e., *Opinions of the CPC Central Committee and the State Council on Comprehensively Promoting Rural Revitalization and Accelerating the Modernization of Agriculture and Rural Areas*), have put forward specific requirements for the construction of modern rural energy systems, industrial upgrading, ecological protection and restoration, and the cultivation of low-carbon living concepts.

The concept of carbon neutrality presents both opportunities and challenges for rural development. Achieving carbon neutrality means a broad and profound transformation of the energy, socio-economic, and technological systems. In the energy system, the main approach is to promote the clean and efficient transformation of energy production and supply, while effectively integrating new energy sources with digital and intelligent technologies [9]. In the socio-economic system, the core lies in improving market mechanisms such as carbon trading and carbon emission taxes, and perfecting relevant carbon regulatory systems to open up new channels for the flow of capital and resources between urban and rural areas. In the technology system, the focus is on the innovative development of technologies such as nature-based negative emission technologies, sustainable agricultural development technologies, and carbon sequestration technologies.

Focusing on issues such as inefficient energy structure,

outdated energy facilities, underutilization of resources, severe pollution and low added value in agricultural production, and the lagging development of the rural financial system, a coupling mechanism of the rural revitalization strategy and the carbon neutrality strategy should be constructed (Figure 1). By organically integrating elements such as new energy, new institutions, and new technologies, this mechanism promotes a positive interaction of urban capital, talent, and technology with the abundant ecological carbon sink resources and vast spatial resources of rural areas. This approach opens up new pathways for the flow of urban-rural capital and resources, driving rural areas to transcend the traditional low-quality, high-pollution development model and transition towards resource efficiency, increased farmer income, and environmental friendliness.

### 2 Exploration of a new model for guangdong rural distributed photovoltaic construction from a new perspective

Based on the Kaya Identity Theory, improving energy efficiency in rural production and living, optimizing the energy structure, and reducing the carbon intensity of energy consumption are critical pathways for building a low-carbon countryside [10]. Among these, developing clean energy stands out as the core pathway. Rural areas possess abundant renewable energy resources, such as wind, solar, hydro, biomass, and geothermal energy. These resources should be effectively developed and utilized based on the resource endowments of rural “production-living-ecological” spaces. Under the “Innovative Carbon-Neutral Rural Area” perspective, rural areas in Guangdong should specifically tailor the construction of new energy systems to local conditions, promote the modernization and upgrading of industries, foster a new low-carbon economy, and facilitate the low-carbon transformation of rural production and lifestyles.

Exploring a new model for rural distributed photovoltaic construction based on Guangdong’s own resource endowment is one of the essential approaches to building a modern rural energy system in Guangdong. However, unlike those “photovoltaic poverty alleviation” projects that rely on government financial subsidies, in order to achieve widespread, large-scale construction and operation of distributed photovoltaics in rural areas, a comprehensive survey and assessment of resources within a certain area

(preferably at the county or town level) is required. This should be combined with relevant urban and rural development plans to conduct scientific spatial layout and integrated design. At the same time, enterprises with long-term operational capabilities should be introduced to invest in

construction in a manner that conforms to market rules, and relevant government financial funds should be used rationally. This will enable a multi-party, long-term win-win situation through a platform that links government, enterprises, villages, and professional teams.

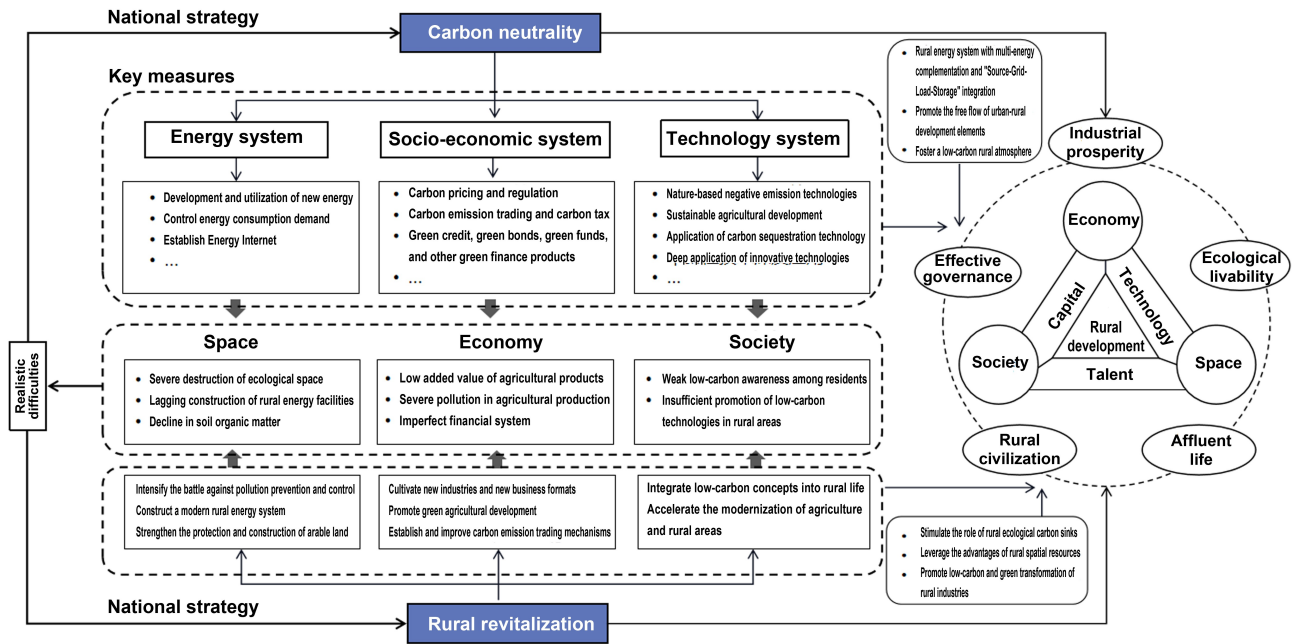


Figure 1 Strategic coupling mechanism of “Innovative Carbon-Neutral Rural Area”

In conjunction with the comprehensive improvement of rural housing appearance currently underway in Guangdong Province, the author and the research team utilized the vast number of existing rural housing rooftops to construct distributed PV systems. We explored the scientific technologies, implementation pathways, and operation models of “rural rooftop distributed photovoltaics” from multiple dimensions, achieving significant results. In addition, the author and research team took the development and construction of rooftop distributed photovoltaics as a starting point to further explore the development of rural composite distributed photovoltaics and the construction of rural new energy systems.

**2.1 The Practical significance of constructing composite photovoltaic systems for Guangdong**

**2.1.1 Land resources in Guangdong are scarce and lack the geographical conditions for large-scale single-function photovoltaic development**

From 2015 to 2020, both electricity consumption and generation in Guangdong Province continued to grow; howev-

er, the local power supply remained severely insufficient (Figure 2). With the development and construction of the Guangdong-Hong Kong-Macao Greater Bay Area, the power gap in Guangdong Province will further expand, while also providing support for the vigorous development of new energy sources. Guangdong Province is located in the East Asian monsoon region and has abundant light and heat resources, making it suitable for solar energy development. However, due to the scarcity of land resources, the province lacks the geographical conditions for developing large-scale single-function photovoltaic plants. Therefore, it is essential to utilize existing rooftop spaces of buildings—such as rural housing and public buildings—as well as production spaces involving agriculture, forestry, animal husbandry, and fishery to construct composite PV systems.

**2.1.2 The Vast stock of rural houses is an ideal carrier for distributed photovoltaics**

Guangdong Province possesses over 20 million rural houses. Calculated at a roof area of 80-100 m<sup>2</sup> per house, the total rural rooftop area exceeds 1.6 billion m<sup>2</sup>. Although

these rural houses are scattered across vast rural areas, they have similar heights and minimal mutual shading. Moreover, their property rights are clear, making them ideal carriers for the construction of distributed rooftop photovoltaic systems, from both technical and managerial-operational perspectives. Moreover, most of these houses were built after the 1990s and are unlikely to be reconstructed within the next 20 to 30 years (aligning with the lifecycle of photovoltaic systems). Furthermore, the era of large-scale new rural housing construction in Guangdong has passed. Therefore, exploring the construction of dis-

tributed photovoltaic systems on the stock of existing rural housing is a direct and effective pathway to restructure the rural new energy system in the context of the “Innovative Carbon-Neutral Rural Area.” It will also contribute significantly to energy saving and emission reduction in rural buildings. This initiative coincides with the National Energy Administration’s issuance of the *Notice on Submitting Pilot Schemes for Whole-County Promotion of Household and Distributed Rooftop Photovoltaic Development*, providing stronger policy support for the development of distributed photovoltaics in the rural new energy sector.

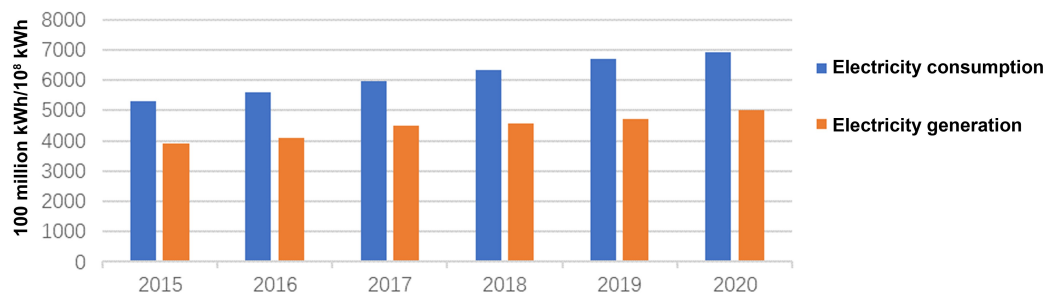


Figure 2 Statistical diagram of annual electricity consumption and power generation in Guangdong Province from 2015 to 2020

2.1.3 The ongoing renovation of rural housing appearance provides a good opportunity for the large-scale construction of rooftop photovoltaic systems

In 2020, Guangdong Province released the *Guiding Opinions of the People’s Government of Guangdong Province on Comprehensively Promoting Rural Housing Control and Rural Appearance Improvement*. The document identifies rural housing control and appearance improvement as inevitable requirements and crucial levers for implementing the provincial rural revitalization strategy and strengthening rural governance.

Consequently, the renovation and beautification of the exteriors of Guangdong’s distinctive “matchbox-style” rural houses have become the top priority for restoring and upgrading rural landscapes (Figure 3). In recent years, significant efforts and substantial public fiscal funds have been invested across the province to renovate and beautify the external walls and roofs of rural houses. Constructing distributed rooftop PV systems that integrate aesthetic design with power generation benefits is an effective pathway to prevent “dressing up” renovations from becoming superficial “vanity projects.” Crucially,

it transforms government “expense-based inputs” into “asset-based investments” and converts rural “idle resources” into “effective assets.”



Figure 3 Numerous “matchbox” style farmhouses are a key focus of rural landscape improvement

## 2.2 Integrated design and application of distributed photovoltaics combined with rural landscape improvement

2.2.1 Providing a “beautiful, practical, and safe hat” for rural houses

The roof is an important component of a building, and its form is an important carrier for inheriting traditional culture and regional characteristics. In terms of the aesthetic effect of rural landscape, visible sloping roofs are

more effective in beautifying the environment. Previously, when adding sloping roofs to rural houses in Guangdong, most projects used resin tiles to create “fake sloping roofs”. These were not only impractical but also problem-

atic due to limited funds and a lack of targeted design for rural housing. Consequently, most of these “hats” were aesthetically unpleasing and posed safety risks, such as being easily blown off by strong winds (Figure 4).



Figure 4 The lack of guidance in “flat-to-sloping” roof conversion practices does not yield satisfactory results in aesthetics and safety

In response, the joint research team combined the technical requirements of rooftop photovoltaics with the design needs of architectural appearance to develop the “Photovoltaic Sun Pavilion for Rural Housing Renovation” (Patent No.: ZL202030807781.1). This innovation effectively puts an “aesthetic, practical, and safe” hat on rural houses. Its characteristics are reflected in the following five aspects:

(1) Aesthetics. Compared to conventional photovoltaic greenhouses and metal sheet sheds built privately by farmers, photovoltaic sun pavilions are highly integrated with the overall appearance of farmhouses, resulting in higher aesthetic value. They also possess local rural characteristics, comply with farmhouse management requirements, and do not pose a risk of unauthorized construction.

(2) Practicality. Combining the functions of a photovoltaic greenhouse and a sun pavilion, it not only generates electricity but also provides farmers with more covered activity space on the roof. In addition, the sun pavilion provides heat insulation and ventilation for the interior, improves the comfort of the top floor space, and reduces energy consumption, which is in line with the practice of energy-saving renovation for existing buildings in Guangdong.

(3) Safety. Photovoltaic module technology is safe and mature. The entire process of the photovoltaic sun-

shine pavilion—from design and drafting to construction—is strictly supervised by relevant professionals. At the same time, it is necessary to provide villagers and maintenance workers with easy-to-understand knowledge, precautions, emergency measures, etc., so that villagers can consciously maintain and use the equipment safely.

(4) Replicability. Guangdong has a stock of rural houses, and photovoltaic sun pavilions have the potential to be promoted and applied on a large scale. From a cost control perspective, modular R&D enables the productization and mass production of sun pavilions, transforming them from single-project construction into market behavior.

(5) Carbon reduction and energy security. Photovoltaic sun pavilions provide clean energy for rural areas, effectively contributing to rural carbon emission reduction. If the pavilion is promoted on a centralized scale—taking 20,000 households as an example—it would be equivalent to constructing a PV power station with a capacity of 200 MW. Taking the western Guangdong region as an example, where the average effective annual irradiation hours are 1,100 hours/year, the power generation would reach as high as  $2.2 \times 10^8$  kWh. Since coal-fired power generation emits approximately 0.997 kg of CO<sub>2</sub> per kWh,  $2.2 \times 10^8$  kWh of electricity is equivalent to reducing CO<sub>2</sub> emissions by at least 200,000 tons annually. This volume is equivalent to the power generation of a thermal power plant occupying 10 hectares, yet the photovol-

taic sun pavilions utilize idle rural rooftops without occupying additional land resources.

### 2.2.2 Design practice of rural house renovation based on photovoltaic sun pavilions

One of the pilot sites for the photovoltaic sun pavilions was selected at the *Splendid 100-Li* Demonstration Section for Rural Revitalization in Fenjie Town, Gaozhou, Maoming City, possessing significant demonstration value. With the assistance of the government and the village, farmers in the demonstration section actively signed up to participate and were willing to provide the roofs of their farmhouses for the first batch of equipment installations.

Through visits and on-site measurements, the roof styles of farmhouses along the pilot county roads can generally be divided into two types: Type 1 is where the roof has only one stair well exit, maximizing the usable roof area; Type 2 is where a room is added next to the stairwell leading out onto the roof, with the non-accessible roof area occupying 30% to 50% of the roof area. After reserving a certain amount of open space on the roof for villagers to use for drying their laundry, the remaining space is used to create various types of sun pavilions, including double-slope, single-slope, and flat-mounted structures, depending on the available space (see Figure 5), ensuring that each household has an installed capacity of at least 10 kWp for photovoltaic modules.

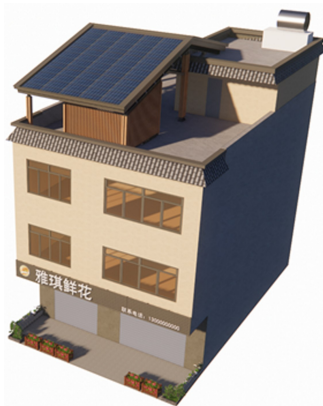


Figure 6 Overall design effect of photovoltaic sun pavilions and rural housing facade improvement

Structurally, the photovoltaic sun pavilion's support frame retains the space for movement beneath the pavilion while employing necessary structural columns for support (Figure 7). To transform the photovoltaic sun pavilion into a semi-

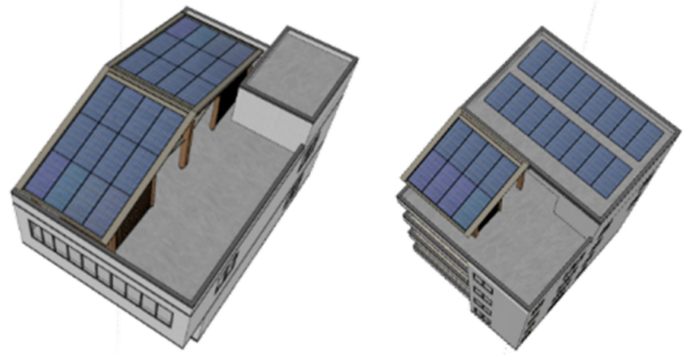


Figure 5 Construction combinations of photovoltaic sun pavilions for farmhouse renovation

In terms of appearance, the design of the photovoltaic sun pavilion is combined with the renovation design of rural houses (Figure 6). Combining local characteristics, the pilot rural housing renovation design uses a "Longan" color palette (based on the local fruit) as the main theme, with photovoltaic sun pavilions on the roof. It features uniform colors for the eaves and farmhouse tiles, uniform beige or off-white walls, a uniform gray-yellow base, and dark longan-colored metal panels. Concrete block walls and flower beds are built in the open space in front of the house, and movable flower boxes are placed to create a small garden. The unified design elements of the farmhouses, integrating the photovoltaic sunshade pavilions with the farmhouses, will significantly improve the appearance of the demonstration section.

indoor activity space, appropriate grille or railing elements are added to the design. These provide moderate visual screening, create semi-private spaces locally, and form a sense of architectural volume from the elevation view.



Figure 7 Overall construction effect of photovoltaic sun pavilions and rural housing facade improvement

In terms of materials, all frame materials are made of lightweight metals, with emphasis on anti-corrosion and anti-oxidation treatments. The photovoltaic panels use monocrystalline bifacial double-glass modules to achieve bifacial power generation, improve power generation efficiency, and increase the light transmittance of the space under the pavilion. In areas with lower energy efficiency, the design considers partially removing the backside power generation function and using colored glass or other textures instead. This approach enriches the surface texture and enlivens the atmosphere of the semi-indoor space (Figure 8).



Figure 8 Texture expression of the space under the photovoltaic sun pavilion

### 2.3 Establishing a co-construction and win-win development and operation model to transform rooftop space resources into long-term assets

#### 2.3.1 Multi-Party collaborative preliminary development and construction model

Based on the construction requirements and practical experience of photovoltaic sun pavilions in rural housing renovation projects, a model for the large-scale development of distributed photovoltaic rooftops in existing rural housing has been summarized, which involves mutual consultation and assistance between village governments and investment enterprises, joint coordination among multiple professional teams, and joint construction by villagers and village collectives (Figure 9). Its specific model is as follows:

(1) Confirm villagers' willingness to install: A project team composed of members from the village committee and the investment company will carry out the work, explain to village representatives the cooperation required for rooftop photovoltaic construction and the benefits to

villagers, encourage villagers to sign up for installation, and sign agreements with households who have a clear willingness to install and meet the standards, so as to form a spatial resource base map for the development of photovoltaic projects.

(2) Establish a rural housing screening mechanism: With safety as the primary criterion, rural houses must have clear property rights, stable building structure, sufficient roof load-bearing capacity, and no shading from surrounding obstacles or taller buildings. Houses that do not meet the requirements are excluded from construction.

(3) On-Site design by professional teams: First, the electrical design engineers will determine the basic structural framework of the power station and calculate the power generation efficiency based on factors such as the orientation of the house, space requirements, and building area. Subsequently, architectural or exterior design teams carry out facade improvement designs, integrating local requirements for rural appearance enhancement.

(4) Coordinate grid connection and upgrades: Understand the network structure and load rate of the medium-

and high-voltage distribution networks in the corresponding area; strengthen communication with local power supply bureaus. Prioritize compliance with existing power grid conditions to determine the scale and construction,

and clarify the access plan; determine the pre-installation batches based on villagers' application status, and clarify the grid connection point, grid upgrading plan, and ownership boundaries.

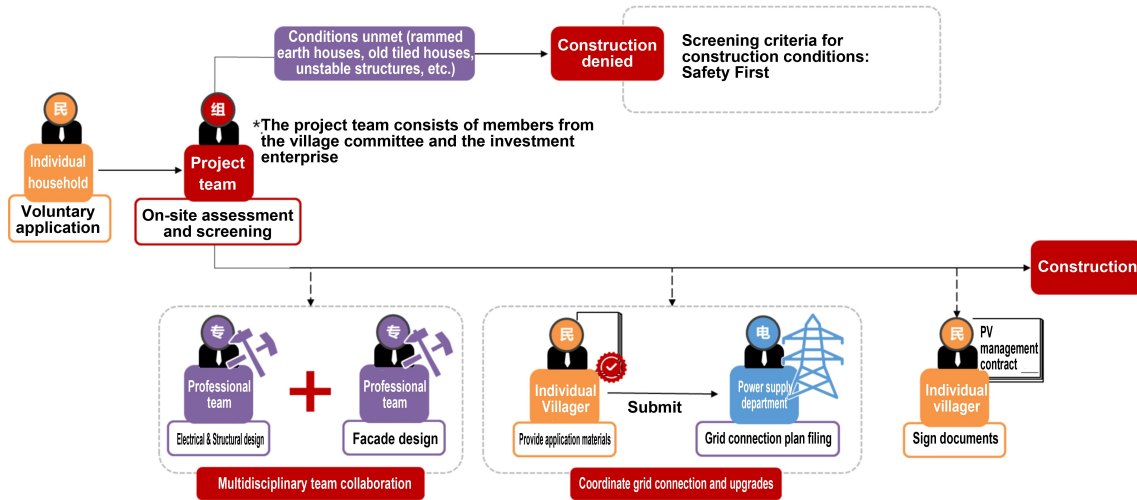


Figure 9 Multi-entity collaborative preliminary development and construction model

(5) Ensure legal validity and binding force of signed documents: Based on the needs of all parties and the installed capacity, the revenue is reasonably distributed. At the same time, the legal validity of the contract and the mutual supervision between the villagers and the project team serve as constraints to ensure the long-term operation and maintenance of the power station.

### 2.3.2 A Multi-party win-win commercial operation model

Currently, the market-oriented operation model for distributed photovoltaic systems in rural areas is not yet mature. The commercial models of existing domestic rural distributed photovoltaic implementation cases can be categorized into the "Poverty alleviation model," "Loan-based model," and "Leasing-based model" (Table 1). The development of the PV industry relies heavily on policy drivers. During the "Photovoltaic Poverty Alleviation" period, the state formulated generous subsidy policies for distributed photovoltaic projects. While this stimulated a growth in installed capacity, the projects became dependent on subsidies to sustain construction, placing immense pressure on public finance. For farmers, the payback period for investing in distributed photovoltaic power stations is long, which can easily lead to financial pressure and an unclear incentive mechanism. For enterprises, distributed photo-

voltaic power stations are low-profit products and require a certain scale to be profitable. However, the operational difficulty of organizing farmers for centralized construction is significant.

Distinct from traditional business models, this paper proposes to introduce enterprises with long-term operational capabilities, invest in construction on a large scale in a manner that conforms to market rules, make reasonable use of relevant government fiscal funds, build a platform for multi-party collaboration among government, enterprises, villages, and professional teams, and clarify the functions and benefits of each party. Because the rural houses involved are scattered and numerous, a cooperative mechanism for centralized management based on village collectives will be established. The county and township governments coordinate the establishment of village joint-stock companies to form a contractual relationship with project companies on behalf of the village collectives. The village joint-stock companies are responsible for integrating individual construction applications from villagers and submitting overall construction applications to the operating enterprises. At the same time, it is responsible for the maintenance and management of the photovoltaic power station, obtains operation and maintenance fees, and increases the income of the village collective. The compa-

ny is responsible for investing in the power generation portion and bearing the overall construction costs, while also receiving revenue from photovoltaic power generation. Villagers receive a corresponding rooftop rental fee each year and enjoy the right to use the pavilion and receive profit dividends according to their investment ratio. Local governments can match the scale of investment by enterprises in completing the renovation of rural houses with new energy resources, such as photovoltaic and wind power, to balance the revenue, and provide support in

terms of rewards and incentives, low-interest loans, and financing.

By combining the government’s requirements for aesthetic appeal, farmers’ needs for rooftop use, and businesses’ demands for power generation efficiency, the author and team ultimately developed 3 investment and benefit distribution models (Table 2): Scheme A (Pure power-Generating / Flat-Mounted), Scheme B (User-Friendly / Practical Pavilion), and Scheme C (Aesthetic / Demonstration Pavilion).

**Table 1 Business models of distributed photovoltaic implementation cases in rural China**

Model	Poverty alleviation model	Loan-based model	Leasing-based model
Construction form	Construction funds are comprised of government funds, social capital, and individual self-financing in certain proportions, and are mostly used for the unified construction of rooftops on public service buildings and new villages.	The company provides a full range of services for photovoltaic power plants, including product development, construction, grid connection procedures, and after-sales support. It also offers low-interest loans to individuals, forming financial products.	Individuals submit their photovoltaic power station construction requests to enterprises through a leasing agreement, while the enterprises are responsible for investing in the power station and managing its operation and maintenance throughout the entire process.
Grid connection method	The grid connection method will be determined based on the actual conditions of the power plant. The grid-connected portion will enjoy photovoltaic feed-in tariff subsidies.	Primarily, “Self-generation for self-consumption, surplus electricity fed to the grid,” achieves grid parity and enjoys local household photovoltaic subsidy policies.	Primarily, “Full feed-in to the grid” achieves grid parity; enterprises do not enjoy household photovoltaic subsidy policies.
Distribution of benefits	Rooftop owners receive rent. Revenue is distributed according to the investment proportion: allocated as government rural (poverty alleviation) construction funds, enterprise investment returns, and individual dividends.	Individuals save on daytime electricity costs. Income from electricity sales is used to repay the loan. The payback period is around 8 years.	Enterprises own the rights to electricity sales revenue and provide a fixed annual subsidy (spatial compensation) to individuals based on installed capacity. Distribution is also based on the proportion of the individual’s leasing fees.

**2.4 Building a full-process intelligent management platform to promote digital ecological governance**

The operation and maintenance (O&M) management of photovoltaic projects is gradually evolving towards an intelligent platform featuring centralized remote monitoring. By integrating high-tech applications such as “Internet+ ,” Big Data, and the Internet of Things (IoT), it is possible to technically resolve the issues associated with the traditional O&M model caused by the scattered nature of distributed photovoltaic projects—namely, their labor-intensive nature, low efficiency, high costs, and slow decision-making.

The author and the research team have constructed a Rooftop Distributed Photovoltaic Intelligent Management Platform (Figure 10) to conduct full-cycle and full-process

management—covering preliminary development, project approval, fund usage, and O&M—for the “Photovoltaic Sun Pavilions for Rural Housing Renovation”.

- In the early stages of development, a series of data is collected, including residents’ opinions, the suitability of rooftop photovoltaic construction for rural houses, and the current status of rural power grids. Through data consolidation, analysis, and entry, a basic database for distributed photovoltaic construction is established.

- In the project approval process, a corresponding business processing sub-platform is set up. Villagers can fill in relevant information via the online platform, which generates a service acceptance form. A professional team screens the applications through the backend to determine the feasible project pool, conducts on-site inspections, and




finally decides on approval.

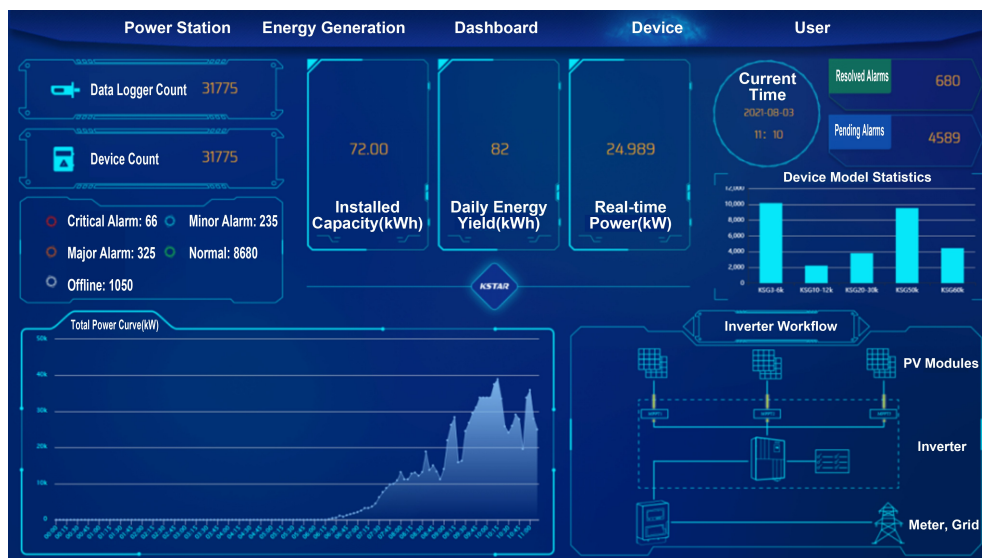
- Regarding the fund usage, the platform publicly discloses the funding sources and the allocation of economic benefits for different rooftop photovoltaic construction models, thereby improving the transparency of fund utilization.

- In terms of operation and maintenance, the platform will continuously collect data from rooftop photovol-

taic modules and detect environmental variables of the sun pavilions to assess the condition of the photovoltaic modules. At the same time, it will provide visual feedback on the power generation efficiency, electricity sales revenue, and environmental benefits such as carbon emission reduction, thereby promoting intelligent decision-making and efficient management of the entire rural rooftop photovoltaic process.

**Table 2** Three construction models for photovoltaic sun pavilions in farmhouse renovation projects

Specific models for rooftop photovoltaic investment and benefit distribution			
	Scheme A: Enterprise-Sole-Invested Rooftop Photovoltaic Project	Scheme B: "Enterprise + Household" Co-Invested Photovoltaic Sun Pavilion	Scheme C: "Enterprise + Government" Co-Invested Photovoltaic Sun Pavilion
Investment entities	Enterprise	Enterprises and farmers (invest in a certain proportion)	Enterprise and Government (invest in a certain proportion, or the Government allocates other higher-return new energy construction resources to the Enterprise)
Construction form	Flat-Mounted Style	Practical Pavilion Style (Prioritizing utility)	Aesthetic Demonstration Pavilion Style (Prioritizing aesthetic and demonstration benefits)
Farmer benefits	Rooftop rent	Rooftop rent and usage rights of the Sun Pavilion	Dividends (based on proportion) and usage rights of the photovoltaic sun pavilion
Government benefits	Fiscal and tax revenue	Fiscal and tax revenue; moderate improvement of local appearance	Fiscal and tax revenue; exemplary improvement of local appearance
Village collective benefits	Operation and maintenance revenue	Operation and maintenance revenue	Operation and maintenance revenue
Construction effect			



**Figure 10** Smart management platform for distributed rooftop photovoltaic systems

### 2.5 Utilizing distributed photovoltaic construction to promote the iterative upgrading of rural electrification and comprehensive resource utilization

The development of distributed photovoltaic projects is mainly limited by factors such as land use type, space ownership, grid connection, and local power absorption conditions. Therefore, it is essential to fully respect the resource conditions of different regions and make reasonable use of various available space resources.

In terms of diverse construction forms, in addition to rooftop photovoltaic systems for rural houses, photovoltaic systems can also be integrated into traditional rural construction, such as industrial and commercial rooftops, road systems, charging piles, public facilities (such as public toilets and garbage stations), and landscape features (Figure 11, 12). Furthermore, models combining photovoltaic generation with traditional agriculture are gaining increasing attention. They are widely applied in production spaces for agriculture, forestry, animal husbandry, and fishery, realizing models such as agrivoltaics, fishery-solar hybrid systems, forest-solar hybrid systems, and PV greenhouses. By integrating with technologies for breeding, irrigation, and agricultural machinery power, these systems drive the modernization of agriculture.



Figure 11 Photovoltaic landscape design of Liantanghu village wetland park in Maoming City

Regarding energy system construction, rural areas face problems such as low power grid carrying capacity, limited transmission capacity, and dispersed electricity load. Planning should comprehensively consider the grid architecture and local absorption levels, rationally layout the scale and connection of power stations, and coordinate rural energy system construction with new energy storage models. The author and the research team are currently conducting research on the “Source-Grid-Load-Storage Integration” and multi-energy complementary technology systems for rural new energy. We are exploring operation technologies for multi-level “PV-Storage-Charging In-

tegrated” energy systems (ranging from Regional to Community to Off-grid levels) and summarizing the standardization system and policy recommendations for rural distributed PV development. Increasing the proportion of green electricity use can reduce electricity costs and encourage the adoption of indoor and outdoor appliances and smart home systems. This increases investment in improving the living environment, thereby shaping low-carbon, livable spaces.



Figure 12 Photovoltaic building-integrated design of the Changshi Village Talent Station in Shaoguan City

### 3 Extended reflections on the “Innovative Carbon-Neutral Rural Area”

The large-scale construction of distributed PV will promote the transformation of the rural energy structure. From the perspective of the “Innovative Carbon-Neutral Rural Area,” the value of rural resources is being cognitively redefined. Its development opportunities lie not only in the development of new energy but also in a comprehensive exploration across spatial, economic, and social dimensions. In the context of the new era, “Carbon Neutrality” and “Innovative Rural Area” are not two independent concepts; rather, they can achieve a high level of coupling between two major strategies. This article further proposes a new model for rural development - “Innovative Carbon-Neutral Rural Area”. The key pathways to its realization lie in three dimensions: space, economy, and society.

#### 3.1 Spatial dimension: Constructing a rural regional complex for green development and shaping low-carbon rural “New production-living-ecological spaces”

“New Rural Construction,” led by rural planning and design, is the key to shaping low-carbon rural “Production-Living-Ecological Spaces.” Territorial Spatial Planning emphasizes the coordinated and efficient utilization of urban and rural resource elements against the backdrop of urban-rural integration. The strategic goal of “Carbon Neutrality” essentially poses higher requirements for rural low-carbon and even negative-carbon development. The delineation of “Three Control Lines,” as well as rural spa-

tial layout, industrial planning, energy structure systems, and ecological conservation and enhancement, should all emphasize the contribution rural areas can make in the process of “urban-rural carbon value exchange.” Meanwhile, more refined green and low-carbon design of rural spaces, buildings, and facilities is also key to achieving negative carbon contributions in rural areas. The realization of “Carbon Neutrality” must not be established at the cost of hindering economic development. The purpose of rural revitalization is to achieve “integrated development with urban-rural equivalence.” As future criteria for distinguishing urban and rural areas will lie more in the “differences in landscape conditions” [11], this indicates that the modes of contribution towards the “Carbon Neutrality” goal differ between cities and villages. Consequently, the “Innovative Carbon-Neutral Rural Area” inevitably poses new requirements for rural planning and design.

### 3.2 Economic dimension: Promoting the assetization of ecological resources and creating new models for rural green industries and green finance

In order to adapt to the low-carbon development of rural production and life and the adjustment, optimization and upgrading of the industrial system, the low-carbon adaptation and innovation of economic models is particularly important. On the one hand, it can combine existing technologies with traditional agricultural development; on the other hand, it can strengthen the branding of rural green industries. At the same time, from the overall perspective of low-carbon and sustainable development of the rural economy, we should establish and improve the rural green carbon finance system. The rural carbon finance system mainly includes investment and financing for rural low-carbon project development and rural carbon trading services [12]. Investment and financing for rural low-carbon project development can include providing financial services in areas such as green rural housing, clean energy, green agriculture, and green transportation. Rural carbon trading services can include forestry and grassland carbon sink trading, clean energy carbon trading, and low-carbon agricultural carbon trading. However, given that rural resource property rights are relatively scattered, and there is a lack of institutional mechanisms to sell carbon emission reductions to the market, an interest-linked carbon trading mechanism consisting of “Enterprise-Carbon Trading Institution-Rural Professional Cooperative Organization-Farmer” should be established to broaden the pathways for rural low-carbon development [13].

In this dimension, rural carbon sink trading and the “Carbon-neutral New Agriculture” are critical. Carbon sink trading offers the concept that “lucid waters and lush mountains are invaluable assets” with broader and more profound significance. Furthermore, by adjusting agricultural planting methods and leveraging capabilities and management levels in biotechnology, digital technology, and breeding technology, it is possible to reduce carbon emissions across the entire chain of agricultural production while simultaneously increasing the yield and output value of agricultural products. Achieving such “Carbon-Neutral New Agriculture” further reinforces the significance and value of rural areas in realizing the strategic goal of carbon neutrality.

### 3.3 Social dimension: Establishing a new mechanism for intelligent, law-based, and modernized ecological governance in rural areas, focusing on low-carbon production and lifestyles

Under the vision of the carbon neutrality goal, rural governance regarding ecological development—such as upgrading rural energy structures, structural emission reduction in agriculture, and environmental protection and pollution control—should integrate villagers’ livelihoods with existing technological levels. It is necessary to formulate scientific and rational management strategies tailored to local conditions [14]. Policies and regulations should be perfected by considering the actual needs of multiple stakeholders, including villagers, enterprises, and the government, thereby optimizing the system of co-construction and co-governance by rural multi-stakeholders. Rural carbon emission regulation and governance should further utilize digital and intelligent technologies to assist decision-making and implementation, thereby modernizing the rural governance system and governance capabilities.

At the same time, it is also necessary to build a new operating platform that links government, enterprises, villages, and professional teams to adapt to the marketization and sustainable development needs of rural areas. The construction system of the “Innovative Carbon-Neutral Rural Area” places higher demands on the overall quality of village officials and villagers. Rural construction requires “selecting talent locally,” “gathering talent from various quarters,” “nurturing talent through practice,” and “entrusting capable talent with heavy responsibilities,” so as to break the talent bottleneck in realizing rural revitalization [15]. A rural talent cultivation platform should be established to conduct training and lectures related to the “Innovative Carbon-Neutral Rural Area.” This involves cultivating leaders for

innovation and entrepreneurship in rural modern industries and providing multi-field thematic training for management cadres at all levels, villagers, professional technicians, and enterprise personnel. The goal is to foster a group of grassroots management talents, vocational technical service providers, and practitioners who possess new skills and are adapted to the “Innovative Carbon-Neutral Rural Area.” At the same time, it is equally important to focus on cultivating and enhancing the ecological awareness of cadres at all levels in villages and towns, as well as villagers, to raise their awareness of low-carbon development and foster a sustainable consumption concept in villages and towns.

### Conclusion

This article focuses on the carbon reduction potential of rural areas, taking distributed photovoltaic power as a key entry point, and takes the first step in the research and practice of the “Innovative Carbon-Neutral Rural Area”. The development of new energy sources will effectively transform existing rural space resources into high-quality and long-term ecological assets, continuously bringing benefits to villagers, providing clean energy for rural areas, and promoting rural electrification. Rural landscape management and renovation have facilitated the application of the building-integrated photovoltaic (BIPV) concept in existing rural housing, while the large-scale construction trend of distributed photovoltaics highlights the potential development value of rural space resources, triggering a series of research needs such as the development, construction, and commercial operation models of new energy in rural areas, as well as policy formulation strategies related to rural new energy development. The “Innovative Carbon-Neutral Rural Area” is a novel rural development concept that highly integrates the two major national strategies of Rural Revitalization and “Carbon Peaking and Carbon Neutrality.” Encompassing multiple fields such as energy, technology, and carbon finance, it demonstrates promising prospects for the future of rural areas. However, it still requires strengthened and continuous research and practice involving multiple dimensions—spatial, economic, and social—as well as the participation of multiple stakeholders.

### Sources of Figures and Tables

Figure 2: Created by the authors; data source: BJX Power Grid (Bei Ji Xing).

Figure 10: Adapted from the Smart Village Management Platform of Gaozhou City, Maoming.

All other figures and tables were drawn or photographed by the authors.

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