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Article

Research on the behavioral mechanisms of rural distributed photovoltaic development: A view of prosumer perspective

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ABSTRACT

As global energy transitions accelerate, distributed photovoltaic (PV) systems are emerging as a key driver for rural energy transformation. However, their adoption faces challenges such as low household electricity demand, limited grid capacity, and complex stakeholder dynamics. This study employs game theory to develop a multi-agent dynamic model involving village organization, PV enterprise, grid company, and rural households, examining their behavioral mechanisms and strategic choices. Scenario simulations reveal that: (1) Collaboration between PV enterprise and village organization to promote the surplus electricity feed-in model is more effective in expanding distributed PV adoption. Low-demand households prefer full feed-in model, while high-demand households favor surplus electricity feed-in model. (2) Overpromoting surplus electricity feed-in model may lead to curtailment issues. Increasing self-consumption can reduce curtailment but may limit installed distributed PV capacity. (3) Rising incomes can encourage more rural households to invest in the surplus electricity feed-in model, but grid capacity constraints will lead to low investment efficiency in distributed PV systems. These findings recommend tailored policies, multi-stakeholder collaboration, and grid capacity-based self-consumption ratios to optimize rural distributed PV development.

KEYWORDS

Prosumer, distributed photovoltaic, behavioral mechanism, multi-agent game, rural energy transition.

1 Introduction

Amid the global energy transition and the pursuit of sustainable development goals, renewable energy development has become a central focus of energy policies in the word[1]. As the world's largest energy consumer, China has made significant progress in renewable energy. Particularly, distributed photovoltaic (PV) systems are playing a pivotal role in rural energy transformation. Distributed PV systems harness abundant solar resources to provide clean, sustainable electricity, bringing new development opportunities for rural sustainable energy systems[2]. With the distributed PV capacity increasing, rural households are evolving from traditional "energy consumers" to "prosumers", which are both producers and consumers of energy. The self-consumption model with surplus electricity fed into the grid presents new opportunities for rural revitalization but also introduces complex behavioral dynamics.

However, the promotion of rural distributed PV is facing several challenges. First, the relatively low electricity demand limits the efficiency of the practical promotion of distributed PV in rural areas[3]. Second, the limited capacity of rural grids poses a significant barrier to large-scale PV integration[4]. Additionally, factors such as insufficient awareness of PV systems among rural households, high investment costs, and uncertain returns reduce rural households' willingness to participate[5]. More significantly, as prosumers, rural households' decision-making depends not only on individual economic interests but also on the actions of multiple stakeholders including village organizations, PV enterprises, and grid operators, creating a complex network of interactions[6]. Therefore, a deeper understanding of prosumer behavior and the strategic choices within this multi-agent framework is essential for the sustainable development of rural distributed PV.

This paper employs game theory to construct a dynamic multi-agent model involving village organization, PV enterprise, grid company, and rural households. The model aims to explore the behavioral mechanisms and strategic choices of these stakeholders in the promotion of rural distributed PV. Sensitivity analysis is designed to study the impact of rural household income and grid capacity on the evolution of prosumer behavior and rural distributed PV development. The findings provide a theoretical foundation for promoting rural distributed PV and practical guidance for policy design and implementation.

2 Literature review

2.1 Research on stakeholder behavior in rural PV development

In the development of rural distributed photovoltaic (PV) systems, village organization, PV enterprise, grid company, and rural households are the core stakeholders, whose behavioral strategies interact to form a complex game relationship. Existing research shows that village organization can effectively enhance household participation through policy advocacy and demonstration effects, particularly in rural areas characterized by information asymmetry[7]. PV enterprises, as the primary investors, play a critical role in project promotion. By adopting optimal investment strategies such as leasing rooftop from farmers, PV enterprises can effectively mitigate project risks and enhance the economic returns[8]. However, PV enterprises' investment decisions are influenced not only by household participation but also by grid

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companies' strategies on grid connection. As the entities responsible for integrating distributed PV into the grid, Grid companies significantly impact the efficiency of PV integration[9]. Grid companies can improve distributed PV integration through targeted upgrades and connection policies, but their investment decisions are often constrained by limited grid capacity and high upgrade costs[10]. Rural households, influenced by factors such as awareness, electricity demand, and investment costs, strategically choose between "Surplus electricity feed-in model" and "Full feed-in model" to maximize personal benefits[11]. Households with higher policy awareness and greater educational attainment show a stronger willingness to adopt PV systems. From an infrastructure perspective, some studies suggest that rural households in regions with more developed economies and better power infrastructure are more likely to adopt distributed PV systems[12, 13]. Village committees' proactive engagement can substantially increase villagers' willingness to embrace solar PV technology, thus accelerating its rural deployment[14]. However, in less developed areas, community resistance that is driven by misconceptions about PV radiation or investment risks may impede the adoption of distributed PV[15].

2.2 Application of game theory in the energy sector

Game theory is an effective tool for modeling stakeholder behavior and evolutionary dynamics in energy systems, offering significant theoretical value for behavioral research. The studies on distributed energy systems have widely used game theory to analyze strategic interactions among governments, enterprises, and users and their impact on system development. For instance, Bonamini et al. (2019) employed game-theoretic approaches to analyze cost allocation mechanisms in rural energy cooperatives with distributed generation systems, proposing algorithms based on primal-dual optimal solutions[16]. Zhu et al. (2022) developed a tripartite evolutionary game model involving the government, banks, and PV investors to explore the role of government subsidies and bank loans in the diffusion of PV facilities[17]. Li et al. (2023) applied Nash bargaining theory to develop a multi-agent collaborative optimization model, analyzing benefit-sharing mechanisms in rural hybrid renewable energy systems[18]. Qi et al. (2025) constructed a Stackelberg-Nash game model between rural distributed energy systems and energy suppliers to study behavior strategies for rural systems participating in energy market transactions[19]. Wang and Chen (2025) used an asymmetric tripartite evolutionary game model to evaluate the efficiency of various guiding policies and business models, such as electricity spot trading and the financial leasing model[20].

In the context of rural distributed PV, evolutionary game models are commonly adopted to analyze stakeholder behavior. For example, Tang et al. (2021) used a two-party evolutionary game model between the government and rural households to determine optimal subsidy strategies for distributed PV under different economic conditions[21]. Su et al. (2023) developed a tripartite evolutionary game model involving enterprises, households, and rural PV cooperatives, finding that cooperatives are more effective in maximizing stakeholder benefits[22]. Shan and Yang (2019) examined PV poverty alleviation projects through a tripartite evolutionary game model involving impoverished households, PV enterprises, and the government, finding that active investment by PV enterprises can lead to optimal outcomes without government oversight[23]. Liu et al. (2025) established a multi-agent evolutionary game model, which involves the government, integrated energy service providers, village collectives, and households, to explore the promotion of distributed PV and electric heating integrated energy systems[24]. Yin et al. (2025) established a four parties evolutionary game model to reveal the cooperation mechanism among local government, photovoltaic enterprises, power grid enterprises, and farmers[25].

2.3 Literature review summary

The existing literature on rural distributed PV promotion has made significant progress, particularly in the application of game theory. However, several limitations remain: (1) Most studies focus on the behavior of households, PV enterprises, or the government, often overlooking the strategic choices of grid companies and their impact on other stakeholders. This omission leads to an incomplete understanding of multi-agent dynamics in rural PV development. (2) Evolutionary game analyses typically assume homogeneity among rural households, overlooking significant variations in income, electricity demand, and education within regions. (3) Many studies employ simplistic game-solving methods that are inadequate for capturing the complex multi-agent interactions. In rural PV development, the interplay of strategies among village organizations, PV enterprises, grid companies, and households forms a complex network, requiring more sophisticated analytical tools.

Compared to previous research, this study makes the following contributions: (1) It integrates the strategic choices of grid companies into the multi-agent framework, systematically analyzing how grid connection policies and upgrade decisions influence rural households, PV enterprises, and village organizations. It provides a more comprehensive understanding of multi-agent interactions in rural PV promotion to strengthen the scientific basis for policy design. (2) It constructs a dynamic game model that accounts for household heterogeneity, incorporating factors such as income levels, electricity demand, and educational attainment, to precisely capture the diverse behaviors of rural household and their impact on game's system development. It provides a new perspective to understand the complex behavioral mechanisms in rural PV promotion. (3) It employs a simulation-based approach to solve multi-agent game, addressing the oversimplification of existing methods. Through simulation, this study accurately models the complex interactions and dynamic evolution among multiple stakeholders, offering a more precise tool for analyzing multi-agent games in rural PV development.

3 Framework of the multi-agent dynamic game model

In line with the Implementation Opinions on Accelerating Rural Energy Transition to Support Rural Revitalization, this paper focuses on rural distributed photovoltaic (PV) projects that are regarded as the primary clean energy source.

3.1 Game participants

The multi-agent dynamic game model comprises two layers: a principal-agent game between a village organization (*VO*) and a PV enterprise (*PV*); and a dynamic sequential game between rural households (*RH*) and a grid company (*GC*). The village organization, PV enterprise, and grid company are modeled as single entities respectively. PV enterprise's roles include selling distributed PV equipment, providing maintenance services, and investing in PV projects. Rural households are treated as a collective group of N households.

3.2 Game strategies

3.2.1 Strategies of the first-layer game participants

In the principal-agent relationship, PV enterprise can entrust village organization to assist in promoting distributed photovoltaic projects. Through contractual constraints, PV enterprises can define rural PV promotion goals of rural distributed PV projects. If village organization assist in promoting distributed PV projects, they incur certain promotional costs but can provide households with more comprehensive investment information. If village organization refuses to assist, or PV enterprise don't entrust, PV enterprise must promote PV projects by themselves based on rural social media.

PV enterprise has two investment strategies: direct sales and roof leasing. In the direct sales model, PV enterprise sells PV equipment and provide maintenance services. Rural households buy PV equipment and bear the associated risks. In the roof leasing model, PV enterprise invests in PV projects, compensates rural households for rooftop use, and takes responsibility for project operation and maintenance. Revenue comes primarily from electricity sales.

3.2.2 Strategies of the second-layer game participants

Rural households have four investment strategies: (1) Neither invest in distributed PV nor lease their rooftops; (2) Don't invest in distributed PV but lease rooftops; (3) Choose the surplus electricity feed-in model; (4) Choose full feed-in model.

Under the first two strategies, households purchase electricity for daily needs such as heating and cooking, incurring corresponding electricity costs. If households choose the surplus electricity feed-in model, they use part of the PV-generated electricity for household appliances and sell the surplus to the grid, which means they become prosumers. If they choose the full feed-in model, all PV-generated electricity will be sold to the grid, and households purchase electricity for their needs. Once invested, PV projects operate until the end of their lifecycle.

Grid company has two project approval strategies. If grid company approves distributed PV project applications, rural households' investment strategies can be implemented. However, once grid capacity is exceeded, grid company may reject new applications. In such cases, grid company must decide whether to upgrade the grid. If the expected revenue from grid upgrades exceeds the costs, grid company will proceed with the upgrades.

Table 1 shows multi-agent game strategies.

Table 1 Multi-agent game strategies.

Game layer	Game participant	Main strategy	Sub-strategy
Principal-agent Game	PV enterprise	E0: Delegation strategy	E01: Self-promotion E02: Delegate promotion to village organization
		E1: Investment strategy	E11: rooftops and invest in PV projects E12: Direct sales of PV equipment
	Village organization	V0: Promotion strategy	V01: Refuse to assist PV enterprise in promotion V02: Agree to assist PV enterprise in promotion
Sequential Game	Rural households	R0: Investment strategy	R01: Neither invest in PV nor lease rooftops R02: Do not invest in PV but lease rooftops R03: Choose surplus electricity feed-in model R04: Choose full feed-in model
	Grid company	G0: Project approval strategy	G01: Reject project application G02: Approve project application
		G1: Grid upgrade strategy	G11: Refuse to upgrade the grid G12: Agree to upgrade the grid

3.3 Logic of the multi-agent game

Figure 1 illustrates the logical framework of the multi-agent game. In the principal-agent game, PV enterprise and village organization need to choose their respective strategies at first. If the PV enterprise submits a delegation contract, and the village organization accepts the delegation, the PV enterprise will pay them a promotional fee (C^{fee}). If the PV enterprise chooses the direct sales strategy, they earn revenue from equipment sales (R^{equ}) and maintenance services (R^{ope}). If PV enterprise opts for roof leasing, they earn revenue from electricity sales (R^{ele}) but bear the investment and maintenance costs of the PV projects (C^{pv}), as well as paying rooftop leasing fees to rural households (C^{rent}). If the PV enterprise chooses self- promotion, or the village organization refuses the delegation, the PV enterprise must promote the projects itself, incurring higher promotional costs ($C^{PV,pro}$).

After the village organization and PV enterprise determine their strategies, rural households decide on their investment strategies. If households anticipate negative returns from PV investments, they will reject the projects. If they choose not to invest, they may still lease their rooftops for additional income (C^{rent}). If they decide to invest, households incur additional costs (C^{add}) for inverters and other equipment under the surplus electricity feed-in model. Household investment decisions depend on the expected returns of different strategies, which are determined by available information and the perceived benefits. The extent of information accessibility ranging from 0 to 1 is influenced by village organization promotions, social media, and demonstration effects. Households will adopt an investment strategy only if its expected return exceeds a certain threshold.

Rural households who hope to invest in PV project must submit applications to the grid company for approval. Those rural households are ranked randomly to ensure the objectivity of the game. Upon receiving an application, the grid company evaluates it based on current grid capacity. If the application is approved, the rural household can proceed with the investment. If rejected, the grid company must then decide whether to upgrade the grid before making a final decision.

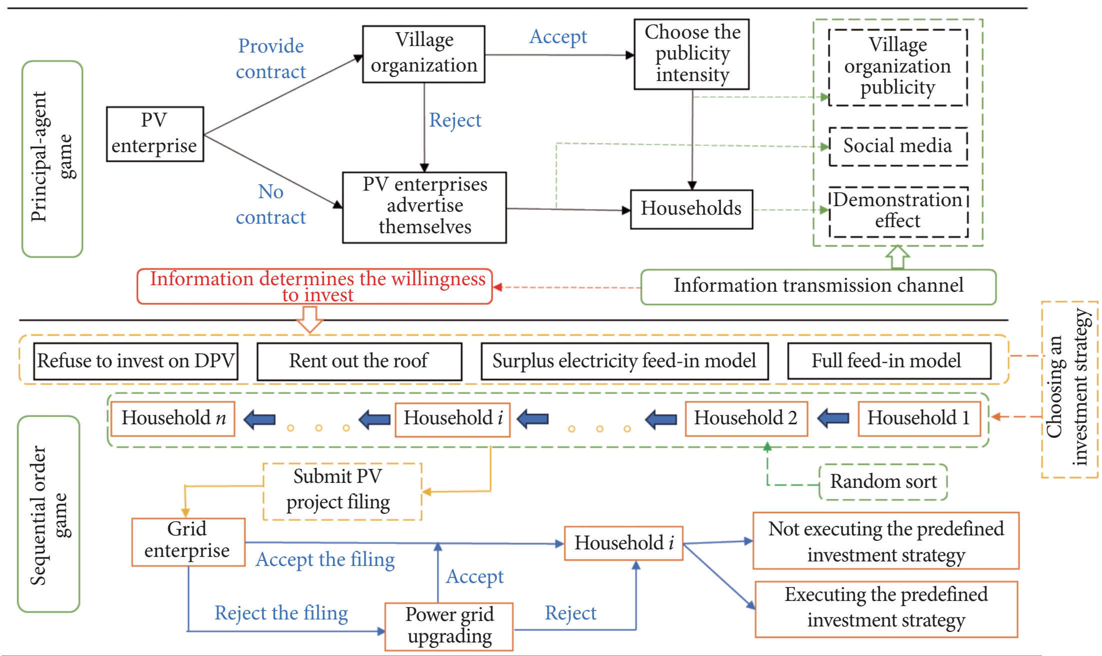


Fig. 1 Logical framework of the multi-agent game in round *t*.

After all participants determine their strategies, the total installed PV capacity is calculated, and the payoff of each participant in round *t* are assessed. In round *t*+1, the game repeats with the results of round *t* as the initial conditions, including the investment strategies, investment benefits, the status of rural PV development and the grid scale. Rural households in round *t*+1, will refer to the results in round *t* to form new expected revenue, and then choose the strategy that is more beneficial to themselves.

4 Construction of multi-agent game model

4.1 Definition of game participant revenue functions

To simplify the analysis, the PV enterprise is assumed to offer identical-scale distributed PV projects to all households. However, rural households differ in terms of electricity demand, education level, and income.

4.1.1 Definition of village organization revenue function

In the promotion of rural distributed PV systems, the revenue of the village organization includes the promotional fees (C^{fee}) paid by the PV enterprise, performance-based rewards ($V(Cap)$), and the costs of promotional activities ($C^{VO,pro}$). The revenue function Y^{VO} is defined as Equation (1):

$$Y^{VO} = C^{fee} + V(Cap) - C^{VO,pro} = C^{fee} + v \times (Cap - Cap*) - C^{VO,pro} \times I^{end} \tag{1}$$

where v represents the incentive coefficient. If the actual installed PV capacity (Cap) exceeds the expected capacity ($Cap*$), the village organization receives additional rewards; otherwise, it incurs penalties. I^{end} represents the endeavor level of the village organization in promotion, with a value range of [0, 1].

If the village organization refuses to assist the PV enterprise in promoting distributed PV projects, its revenue will be zero.

4.1.2 Definition of PV enterprise revenue function

If the PV enterprise only sells PV equipment, its revenue function is defined as Equation (2):

$$Y^{PV} = R^{equ} + R^{ope} - C^{PV,pro} - I^{pv} \times (C^{int} + V(Cap) - C^{PV,pro}) \tag{2}$$

where I^{pv} is an indicative variable. If the village organization chooses to help PV enterprise publicize distributed PV projects, $I^{pv} = 1$. Otherwise, $I^{pv} = 0$.

If the PV enterprise chooses to lease rooftops and invest in distributed PV projects, its revenue function is defined as Equation (3):

$$\begin{aligned} Y^{PV} = {} & R^{PV,ele} + R^{PV,gec} - C^{PV,pv} - C^{rent} \\ & - C^{PV,pro} - I^{pv} \times (C^{int} + V(Cap) - C^{PV,pro}) \end{aligned} \tag{3}$$

where $R^{PV,ele}$ represents revenue from electricity sales, $C^{PV,pv}$ denotes the investment costs of the distributed PV project.

4.1.3 Definition of rural household revenue function

If household i chooses not to invest in distributed PV or if the project cannot be implemented due to rejected grid applications, household's revenue $Y_i^{RH} = 0$.

If household i chooses not to invest in distributed PV but agrees to lease his rooftop, $Y_i^{RH} = C_i^{rent}$.

If household i installs a distributed PV system, Y_i^{RH} is defined as Equation (4):

$$Y_i^{RH} = R_i^{RH,ele} - C_i^{RH,pv} \tag{4}$$

where $R_i^{RH,ele}$ indicates the revenue from electricity generation, and $C_i^{F,pv}$ represents the investment costs borne by the household.

4.1.4 Definition of grid company revenue function

Assuming that by the time the (*i*+*1*)-th household applies for grid connection, the grid company can no longer approve the application, the grid company's revenue is defined as Equation (5):

$$Y^{GC} = \sum\nolimits_{k=1}^{i} R_k^{GC} \tag{5}$$

where R_k^{GC} represents the grid sales of electricity from the *k*-th household's PV system.

If the grid company chooses to upgrade the grid, it can approve more applications ($j > i$) while incurring grid upgrade costs (C^{GC}). The grid company revenue Y^{GC} is defined as in Equation (6):

$$Y^{GC} = \sum_{k=1}^{j} R_k^{GC} - C^{GC} \tag{6}$$

4.2 Revenue evaluation model for distributed PV projects

Based on Alrbai et al. (2025)[26], Equation (7) defines the lifecycle revenue of distributed photovoltaic (PV) projects.

$$Y^{pv} = \sum_{ti=1}^{T} (R_{ti}^{pv} - C_{ti}^{pv}) \times (1+r)^{-ti} \tag{7}$$

where R_{ti}^{pv} represents the revenue of the PV project. C_{ti}^{pv} represents the costs. T denotes the project lifecycle, and r represents the internal rate of return.

The project costs C^{pv} include fixed asset investment (C_{inv}) and operational costs (C_{ope}), expressed as Equation (8):

$$C^{pv} = C_{inv} + C_{ope} \tag{8}$$

The project revenue (R^{pv}) includes income from self-consumed electricity (R_{EC}) and income from grid-connected electricity R_{EG}, expressed as Equation (9):

$$R^{pv} = R_{EC} + R_{EG} \tag{9}$$

R_{EC} is calculated by the number of self-consumed electricity (E_{EC}) and the corresponding electricity price (P_{EC}), expressed as Equation (10):

$$R_{EC} = \int_{t1}^{t2} E_{EC} P_{EC} \tag{10}$$

R_{EG} is calculated as the product of grid-connected electricity (E_{EG}) and the local coal-fired power benchmark price (P_{EG}), expressed as Equation (11):

$$R_{EG} = E_{EG} P_{EG} \tag{11}$$

The total PV electricity generation (E_{TS}) is the sum of self-consumed electricity, grid-connected electricity, and curtailed electricity (E_{EA}), expressed as Equation (12):

$$E_{TS} = E_{EC} + E_{EG} + E_{EA} \tag{12}$$

4.3 Solution methodology of multi-agent game

To analyze game strategies in more complex environments, some scholars have integrated game models with simulation approaches. For example, Cao et al. (2025) developed a two-stage deterministic optimization model that incorporates capacity allocation in the planning phase of rural virtual power plants and Stackelberg games in the operational phase[27]. Luo et al. (2024) proposed a Stackelberg game-based optimization method for microgrid design[28]. Wu et al. (2024) combined the Stackelberg-Nash game model with a bi-level optimization model to explore the strategic behaviors of stakeholders in integrated energy systems[29]. Compared to traditional theoretical game analysis methods, simulation-based approaches are more intuitive and better suited to analyzing behavioral mechanisms in complex environments. Therefore, this study employs a simulation-based approach to determine the optimal strategies for each participant. As shown in Figure 2, the solution logic is as follows.

(1) Preparation phase: First, the income and education level characteristics of rural household group are defined, and the electricity demand and learning ability of each rural household are calculated. Then, the investment strategies of each stakeholder are established, and the expected revenue functions for households and the actual revenue functions for stakeholders are defined under different strategies. Finally, the number of game iterations is determined.

(2) Principal-agent game phase: In the principal-agent game, the PV enterprise first selects the delegation and investment

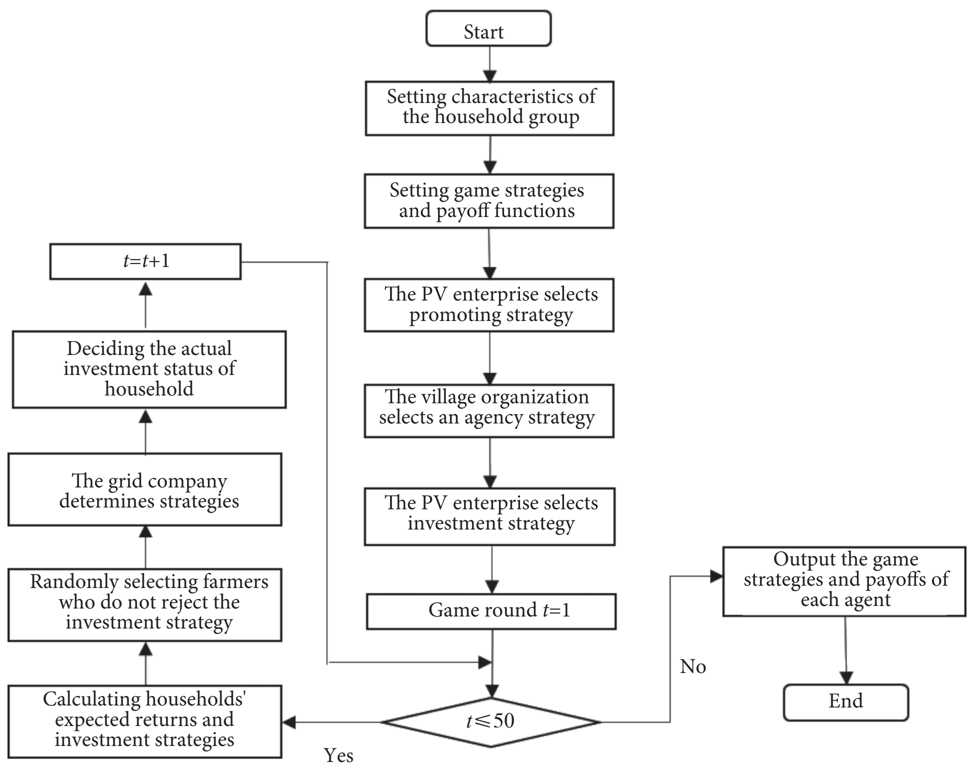


Fig. 2 Logic diagram of multi-agent game simulation.

strategies. The village organization then chooses game strategy. To simplify the simulation, only four strategy sets between the PV enterprise and the village organization are considered: (self-promotion, refuse delegation, sell equipment only), (self-promotion, refuse delegation, invest in PV), (delegate promotion, accept delegation, sell equipment only), and (delegate promotion, accept delegation, invest in PV).

(3) Sequential game phase: Based on the selected strategy set, the expected revenue of households is calculated, and households decide their strategies by maximizing expected revenue. The expected revenue of rural households is derived from online media, village organization promotions, and demonstration effects. If actual revenue of household i from investing in distributed PV is $R_i^{pv,b}$, the expected revenue is $R_i^{RH,b,e}$, where b represents the b-th distributed PV investment model. $\gamma_{i,j}$ is the expected revenue coefficient evaluated by household i from the j-th information source, which depends on the type of information transmission channel j, the effort level of village organization promotion (I^{end}), and the learning ability of rural household i (L_i). The expected revenue from different channels is defined as Equation (13):

$$\gamma_{i,j} = \min(xv_{j|j\neq 3} + ns_{t-1,k}/N \times xv_{j=3}, 1) \times (L_i + t/100) \tag{13}$$

where xv_j represents the proportion of information from the j-th channel. $ns_{t-1,k}/N \times xv_{j=3}$ is the proportion of information from demonstration effects. $ns_{t-1,k}$ indicates the number of rural households that choose the k-th investment strategy in the previous round. $t/100$ indicates that households can continuously acquire additional project information through the game.

If rural households intend to invest in distributed PV projects, they must apply to the grid company for approval. If the distributed PV capacity applied for by household i is within the grid's capacity, the application will be approved. The grid capacity constraint is written as Equation (14):

$$Limit\_Cap \geqslant \sum_{k=1}^{i} Cap_{t,k} \tag{14}$$

Otherwise, the application is rejected. The grid company then decides whether to upgrade the grid based on the principle of maximizing benefits and re-evaluates the application. The iteration count of the sequential game is set to 50. When the farmers' strategies no longer exhibit significant changes, a Nash equilibrium is achieved between the farmers and the grid company.

(4) Output of game strategies and related revenues: After 50 rounds of game, output the selected strategies, payoffs of all agents, rural PV installed capacity and operational performance. The Pareto-optimal strategy portfolio for PV enterprise and village organization can be determined by comparing multi-agent game results across different strategy sets.

5 Scenario design

5.1 Scenario design for rural energy transition from the prosumer perspective

In the baseline scenario, following the multi-agent game framework in Figure 1, neither village organization nor enterprises actively intervene in rural household decision-making. Each participant's strategy is determined based on their optimal Nash equilibrium. Building on this baseline, two scenarios are developed by modifying specific behavioral assumptions.

(1) Village organization guidance scenario

In this scenario, village organization influences rural households' expected revenues through policy advocacy and demonstration effects to promote the self-consumption of rural PV systems. Specific measures include: (a) prioritizing the promotion of the surplus electricity feed-in model in distributed PV projects; and (b) establishing demonstration projects to showcase operational benefits of distributed PV systems, thereby increasing households' willingness to adopt this model.

(2) Forced self-consumption scenario

In this scenario, the government encourages households to install distributed PV systems and prioritize self-consumption through policy guidance and incentives. Key measures include: (a) requiring households to consume at least 70% of PV-generated electricity, with grid company rejecting projects that fail to meet this threshold; (b) providing an additional subsidy of 0.1 CNY/W for households adopting the surplus electricity feed-in model.

5.2 Parameters related to rural energy transition

(1) Principal-agent parameters

Based on the distributed PV project in Zhangjiamiao Village, Shandong Province, the PV enterprise sets a target installation rate of 60%. For each successful installation, the PV enterprise pays the village organization a promotional fee of 100 CNY. If installations exceed the target, an additional reward of 50 CNY per household is granted. Conversely, if the target is unmet, a penalty of 50 CNY per household is deducted. The maximum promotional cost for the village organization is 60 CNY per household, while the PV enterprise's promotional cost is 500 CNY per household.

(2) Distributed PV project parameters

The parameters of the distributed PV project are designed by referring to the *China Rural Household PV Sustainable Development Report* published in 2023. It is assumed that the government aims to promote 5 kW distributed PV systems in rural areas. The initial investment cost for household distributed PV systems is 4 CNY/W, with an annual operation and maintenance cost of 0.04 CNY/W. For commercial distributed PV systems, the initial investment cost is 3.18 CNY/W, and the annual operation and maintenance cost is 0.048 CNY/W. The lifespan of distributed PV systems is 25 years, with a degradation rate of 2% in the first year and 0.7% annually thereafter. The average annual power generation hours for the rural distributed PV projects are assumed to be 1,450 hours. Under the surplus electricity feed-in model, rural households incur additional costs of approximately 0.15 CNY/W for inverters and energy storage systems. If the PV enterprise chooses the roof leasing strategy, the annual rooftop leasing fee is 15 CNY per square meter. Assuming the rooftops are sloped, each square meter can accommodate about 120 W of PV panels, and a 5-kW system requires approximately 42 square meters.

(3) Rural household electricity demand parameters

Regarding rural electricity consumption, it is assumed that Village A has 300 households. Based on data from the 7th National Population Census, the number of people per household has the following distribution: 25.39% for 1 person, 29.68% for 2 people, 20.99% for 3 people, 13.17% for 4 people, 6.17% for 5 people, 3.06% for 6 people, 0.93% for 7 people, 0.32% for 8 people, 0.13% for 9 people, and 0.15% for 10 people. Based on the distribution of rural household disposable income in 2024, income intervals are set as 4,000–8,000 CNY, 8,000–15,000 CNY, 15,000–23,000 CNY, 23,000–30,000 CNY, and 30,000–60,000 CNY. These intervals have the following probabilistic distribution, respectively, 10%, 20%, 50%, 15%, and 5%. Within each interval, the disposable income per capita is randomly defined. According to Wang et al. (2022)[30], rural per capita electricity consumption (PE) is positively correlated with rural per capita disposable income (PY), defined as in Equation (15):

$$PE = 0.0713 \times PY - 187 \tag{15}$$

(4) Information transmission parameters

Education has five levels: no formal education, below junior high school, high school, vocational high school, and university or above. For each education level, the learning ability (L_i) of the household head after receiving information is distributed as follows: 0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1. Education levels are positively correlated with household income levels[31]. Therefore, if the per capita disposable income of a rural household falls within the k-th interval, there is an 80% probability that the household head's education level belongs to the k-th category and a 20% probability of belonging to another category.

If the PV enterprise promotes the project independently, households can obtain 30% of the project policy information through media channels. In the baseline scenario, if the village organization does not actively promote the surplus electricity feed-in model, rural households can access information about each investment strategy $60\% \times I^{end}$. In the village organization-led scenario, households can obtain information about the roof leasing model, full feed-in model, and surplus electricity feed-in model with probabilities $40\% \times I^{end}$, $40\% \times I^{end}$, and $80\% \times I^{end}$, respectively.

Through demonstration effects, rural households can obtain up to 80% of the policy information related to investment models. In the baseline scenario, the demonstration effect of the k-th investment strategy is related to the number of households (ns_k) choosing that strategy, defined as $ns_k / N \times 80\%$. In the village organization guidance scenario, as long as some households choose the surplus electricity feed-in model, others can obtain 80% of the relevant policy information.

(5) Grid-related parameters

Referencing case studies from China's rural power grid renovation projects, such as those implemented in Yishui County of Shandong Province[a] and Ya'an City of Guangxi Province[b], it is assumed that the rural grid initially has a minimum capacity of 50 kW for distributed PV projects. If the newly added capacity is between 50 kW and 200 kW, the grid upgrade cost (C^{PG}) is 400,000 CNY. If it is between 200 kW and 500 kW, the upgrade cost is 2 million CNY. For capacities exceeding 500 kW, the upgrade cost is 6 million CNY. The typical lifespan of rural grids is 25 years.

Rural electricity prices generally follow a tiered pricing system. The electricity price in Shandong Province is taken as a reference. The electricity price is 0.5469 CNY/(kW·h) for monthly consumption of 0–210 kW·h, 0.5969 CNY/(kW·h) for 210–400 kW·h, and 0.8469 CNY/(kW·h) for consumption exceeding 400 kW·h. The feed-in tariff for distributed PV systems is based on the local coal-fired power benchmark price, set at 0.3949 CNY/(kW·h). In 2023, the average cost of coal-fired power generation was approximately 0.267 CNY/(kW·h) in Shandong Province.

Table 2 shows all parameters.

Table 2 Nomenclature.

Symbol	Description	Value	Symbol	Description	Value
PV	PV enterprise	—	Y^{VO}	Village organization revenue	—
VO	Village organization	—	Y^{PV}	PV enterprise revenue	—
RH	Rural households	—	Y^{GC}	Grid company revenue	—
GC	Grid company	—	R_{EC}	Income from self-consumed electricity	—
R_k^{GC}	The grid sales of electricity from the k-th household's PV system	—	R_{EG}	Income from grid-connected electricity	—
R^{equ}	Revenue from equipment sales	—	$R_i^{RH,b,e}$	The expected revenue from the b-th distributed PV investment model chosen by rural household	—
R^{ope}	Revenue from maintenance services	—	$V(Cap)$	Performance-based rewards	—
R^{ele}	Revenue from electricity sales	—	v	The incentive coefficient (CNY per household)	50
$R^{PV,ele}$	PV enterprise revenue from selling electricity	—	I^{pv}	An indicative variable	0.8
$R_i^{RH,ele}$	Rural household revenue from selling electricity	—	r	The internal rate of return	2%, 0.7%
C^{pv}	Costs of the PV projects (CNY/W)	4, 3.18	E_{EC}	The number of self-consumed electricity	—
C^{rent}	Rooftop leasing fees (CNY per household)	630	P_{EC}	The price of self-consumed electricity	—
$C^{PV,pro}$	Promotion costs of PV enterprise (CNY/W)	0.04	$C^{VO,pro}$	Promotion costs of village organization (CNY per household)	60
C^{add}	Additional costs for inverters and other equipment (CNY/W)	0.15	C^{fee}	Promotional fee (CNY per household)	100
$Cap*$	The expected capacity (kW)	900	$\gamma_{i,j}$	The expected revenue coefficient evaluated by household i from the j-th information source	—
I^{end}	The endeavor level of the village organization in promotion	40%, 60%, 80%	L_i	The learning ability of rural household i	—
$Limit\_Cap$	The grid capacity constraint (kW)	50, 200, 500	$ns_{t-1,k}$	The number of rural households that choose the k-th investment strategy in the previous round	—

[a] Source: https://sdxw.iqilu.com/share/YS0yMS0xNTc2MDE4MQ==.htm

[b] Source: https://www.yaan.gov.cn/xinwen/show/7ae24c2b-bdd3-40eb-94bb-bcc1a3107141.html

https://doi.org/10.26599/ECM.2025.9400022

6 Scenario analysis of rural energy transition from the perspective of prosumers

To simplify the scenario analysis, this section presents simulation results for four strategy sets under the multi-agent game framework. The four strategy sets are as follows: (1) strategy set 1: {“Self-promotion”, “Refuse Delegation”, “Sell Equipment Only”}; (2) strategy set 2: {“Self-promotion”, “Refuse Delegation”, “Invest in PV”}; (3) strategy set 3: {“Delegate Promotion”, “Accept Delegation”, “Sell Equipment Only”}; (4) strategy set 4: {“Delegate Promotion”, “Accept Delegation”, “Invest in PV”}.

6.1 Analysis of stakeholder behavioral strategies

6.1.1 Analysis of game results under the baseline scenario

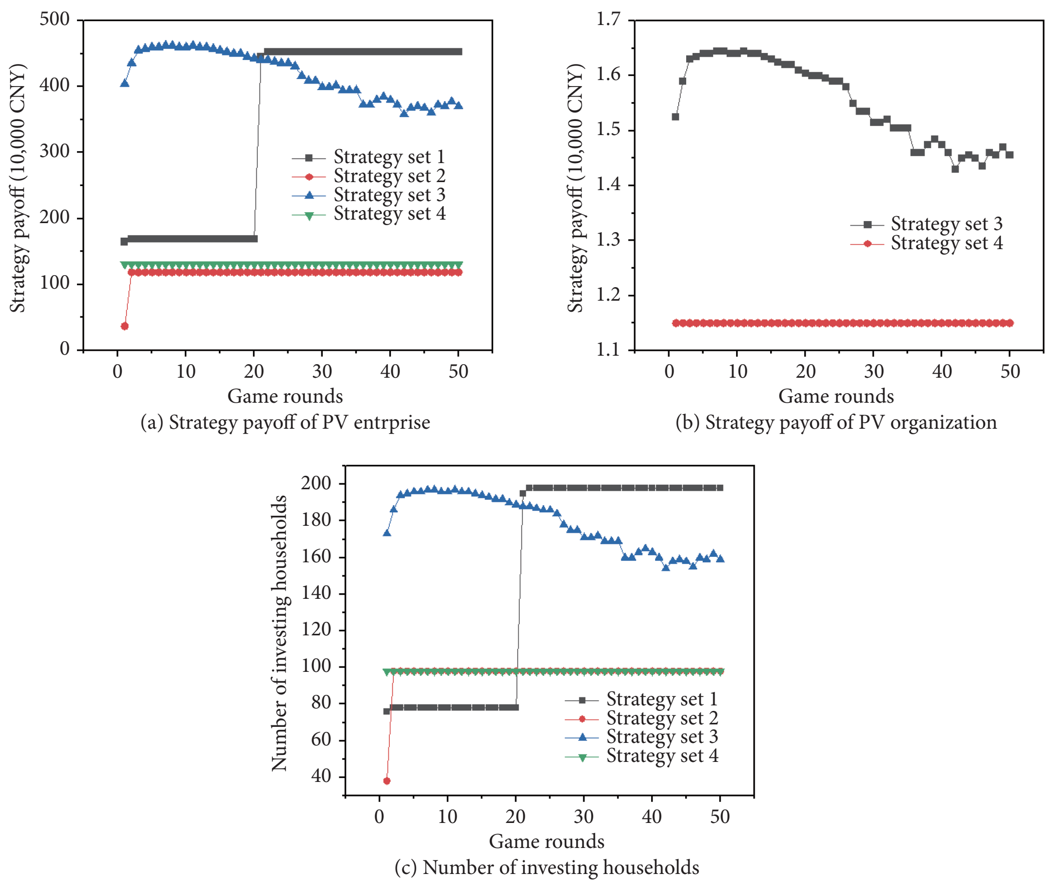
Figure 3(a) presents the investment returns of the PV enterprise under different strategy sets in the baseline scenario. Strategy sets 1 and 3 consistently yield higher returns than sets 2 and 4, indicating that the PV enterprise achieves greater profitability by focusing on equipment sales rather than a direct investment in PV projects. In the first 20 rounds of the game, returns from strategy set 1 are lower than those from strategy set 3. However, after 20 rounds, returns from strategy set 3 gradually decline. This suggests that delegating promotional activities to village organization enables the PV enterprise to achieve higher returns in the short term. As the demonstration effect strengthens over time, significant returns can also be realized through media-based promotion. Considering time cost, the PV enterprise should prioritize the “delegate promotion” strategy to capture a larger share of the rural energy market early on.

Figure 3(b) illustrates the returns for the village organization when they accept delegation from the PV enterprise under the baseline scenario. Returns from strategy set 3 are significantly higher than those from strategy set 4, indicating that the village organization derives greater benefits when the PV enterprise focuses on equipment sales rather than direct investment. Therefore, the optimal strategy for the village organization is to accept the delegation.

Figure 3(c) shows the total number of households investing in distributed PV under the baseline scenario. When the PV enterprise adopts a direct investment strategy, rural households can earn additional income by leasing their rooftops. Therefore, within the constraints of grid capacity, rural households prioritize rooftop leasing. In the long term, the number of households investing in PV under strategy sets 1 and 3 exceeds that in the other scenarios, suggesting that households are more inclined to invest directly in distributed PV rather than leasing rooftops. Comparing strategy sets 1 and 3, it is evident that village organization-led promotion encourages more households to adopt distributed PV in the short term.

6.1.2 Analysis of household investment strategies under the baseline scenario

Figure 4(a) depicts rural household investment strategies under strategy set 1 in the baseline scenario. When the PV enterprise promotes the project, rural households prioritize the “Surplus electricity feed-in model” strategy. This preference is driven by two reasons: (1) compared to the full feed-in model, the surplus

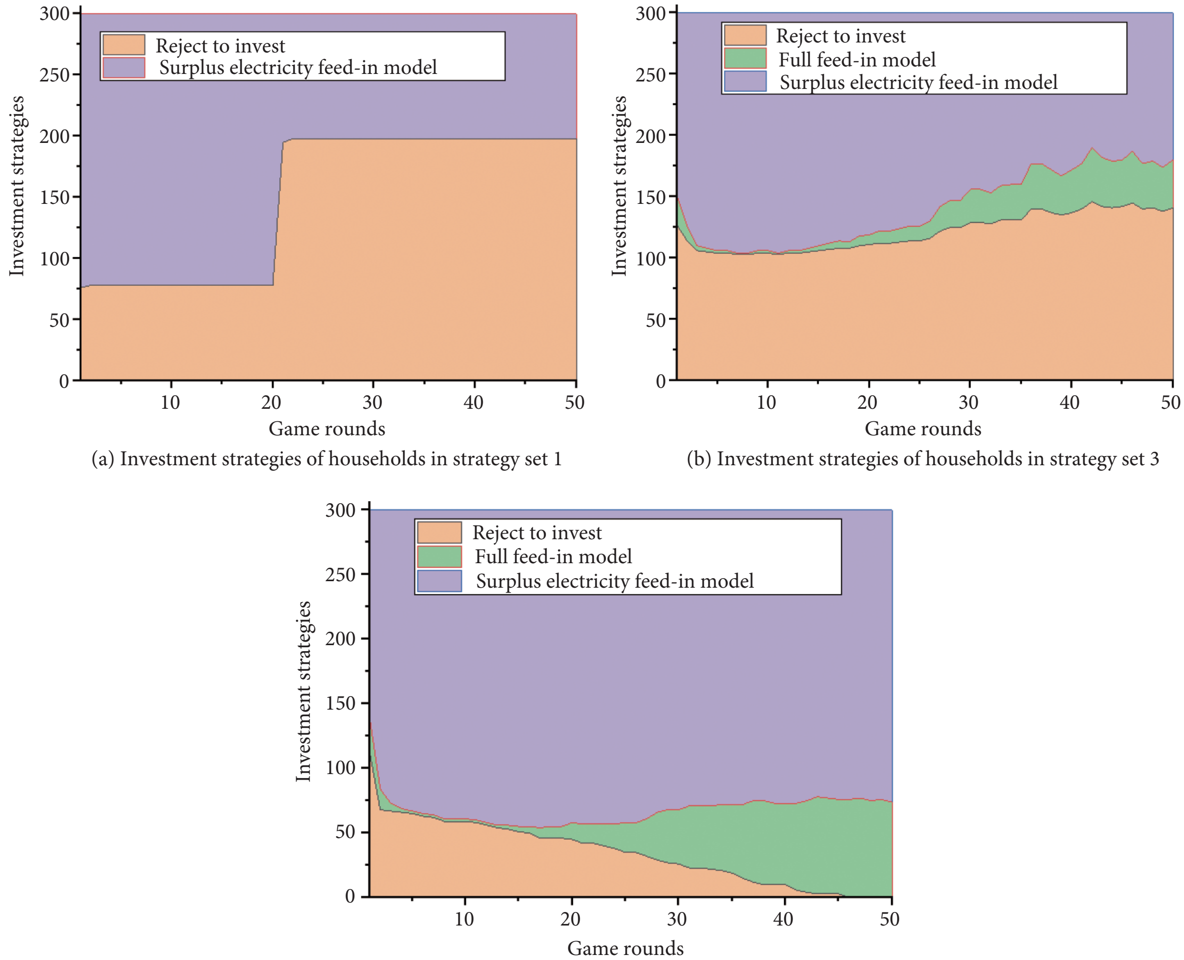


(a) Strategy payoff of PV entrprise

(b) Strategy payoff of PV organization

(c) Number of investing households

Fig. 3 Simulation results of the game under the baseline scenario.



(a) Investment strategies of households in strategy set 1
(b) Investment strategies of households in strategy set 3
(c) Expected investment strategies of households in strategy set 3

Fig. 4 Investment strategies of households in strategy set 1 and strategy set 3.

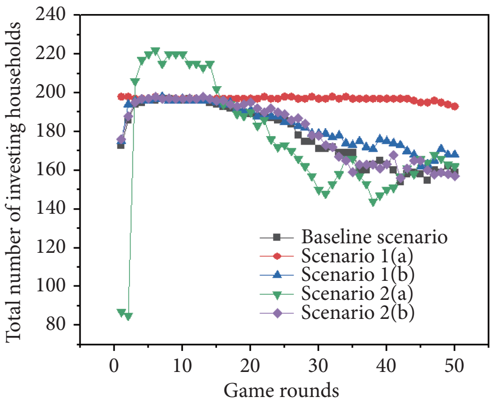
electricity feed-in model offers higher returns for most households; and (2) limited information access under the self-promotion strategy of PV enterprise prevents households from fully understanding the alternatives. As more households adopt the surplus electricity feed-in model, the growing demonstration effect further boosts its popularity.

As shown in Figure 4(b), when the PV enterprise delegates promotional responsibilities to the village organization, rural households can gain timely and comprehensive PV project information, resulting in higher expected returns. Consequently, under strategy set 3, a greater number of households invest in distributed PV in the short term. As the game progresses, rural households acquire more project information and form more accurate expectations of investment returns. After 20 game rounds, the number of households choosing the full feed-in model increases, while those opting for the surplus electricity feed-in model gradually declines. Further analysis reveals that rural households choosing the full feed-in model primarily have lower electricity demand, including both new investors with insufficient expected returns and those switching investment models. Additionally, under fixed grid capacity constraints, an increase in households choosing the full feed-in model reduces the number opting for the surplus electricity feed-in model. These findings suggest that the surplus electricity feed-in model enables greater installed PV capacity in rural areas.

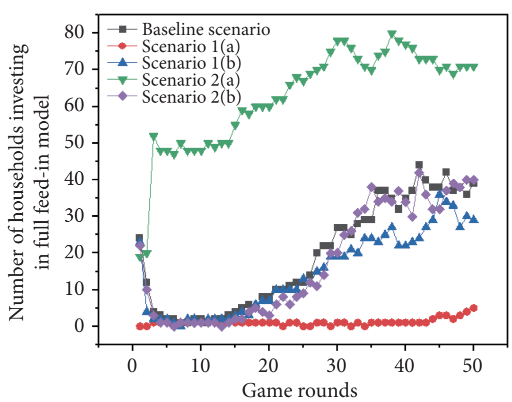
Figure 4(c) illustrates the expected investment strategies of rural households under strategy set 3 in the baseline scenario. In the early stages of the game, due to information asymmetry, some households have low expected returns and may be unwilling to invest in distributed PV. As expected returns increase, more households choose to invest. However, comparing Figures 4(b) and 4(c), it is evident that despite a large number of households willing to invest, some are unable to implement their investment strategies due to grid capacity constraints. This highlights that grid capacity is the decisive factor in determining the scale of distributed PV development in rural areas, which is similar with Teklebrhan et al. (2025)[32].

6.1.3 Analysis of household investment strategies under different scenarios

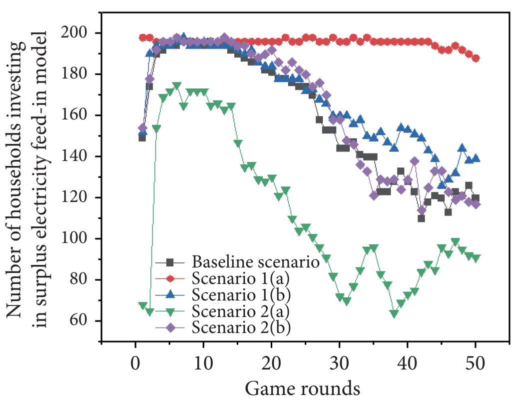
Figure 5 presents the total number of investing rural households, the number of rural households choosing the full feed-in model, and those opting for the surplus electricity feed-in model under different scenarios. Total number of investing rural households and those choosing the surplus electricity feed-in model in scenario 1(a) and 1(b) are higher in the long term compared to other scenarios, while the number choosing the full feed-in model is relatively lower. This indicates that targeted information dissemination can effectively promote the self-consumption of PV's electricity in rural areas. In scenario 2(a), the number of households choosing the full feed-in model is significantly higher, while those opting for the surplus electricity feed-in model is



(a) Total number of investing households under different secenarios



(b) Number of households investing in full feed-in model



(c) Number of households investing in surplus electricity feed-in model

Fig. 5 Farmers' investment strategies under different scenarios.

lower. This shift occurs because increasing the self-consumption ratio reduces the returns of the surplus electricity feed-in model, leading more households to choose the full feed-in model. In the short term, this may result in higher total installed capacity compared to other scenarios. In scenario 2(b), the total number of investing households, the number choosing the full feed-in model, and the number opting for the surplus electricity feed-in model are similar to the baseline scenario. This is because the current returns of the surplus electricity feed-in model are sufficiently high, making subsidy policies less effective in altering rural household preferences.

6.2 Analysis of rural distributed energy development pathways

Figure 6(a) illustrates the electricity fed into the grid under different scenarios based on strategy set 3. As the number of game rounds increases, the grid feed-in electricity in all scenarios shows a gradual upward trend. Among them, scenario 2(a) exhibits the fastest growth in grid feed-in electricity, while scenarios 1(a) and 1(b) record the lowest levels. In the long term, grid feed-in electricity is constrained by grid capacity, lowering the growth rate of scenario 2(a) after 33 rounds.

Figure 6(b) presents the self-consumed electricity under different scenarios based on strategy set 3. Since self-consumed electricity is directly related to the number of rural households adopting the surplus electricity feed-in model, scenario 2(a) has the lowest level of self-consumed electricity. Scenario 1(a) has the highest level of self-consumed electricity, followed by scenario 1(b). However, compared to the differences in the number of rural households adopting the surplus electricity feed-in model (as shown in Figure 5(b)), self-consumed electricity indicates insignificant differences across scenarios. An explanation for this observation is that self-consumed electricity is primarily determined by household electricity demand. If the increase in household electricity demand is limited, the growth in self-consumed electricity will also remain relatively modest.

Figure 6(c) shows the curtailed electricity under different scenarios based on strategy set 3. Is the self-consumption with surplus feed-in model always better? Figure 6(c) provides a negative answer. Compared to other scenarios, scenarios 1(a) and 1(b) have the highest levels of curtailed electricity. When approval requirements for self-consumption ratios are low, even rural households with low electricity demand may find it profitable to adopt the surplus electricity feed-in model, despite the risk of curtailing some PV electricity. This phenomenon exacerbates the inefficiency of rural energy investments, where increases in installed PV capacity are accompanied by higher curtailment rates. In the short term, limited access to project information may cause rural PV projects to experience overinvestment and consequently high curtailment. However, in the long term, if project information is not artificially restricted, the market's natural selection process can restore rural distributed PV development toward a more rational model, as demonstrated in the baseline scenario and scenario 2(a). Scenario 2(a) achieves lower curtailment rates in the long term, indicating that increasing the self-consumption ratio requirement can enhance the efficiency of

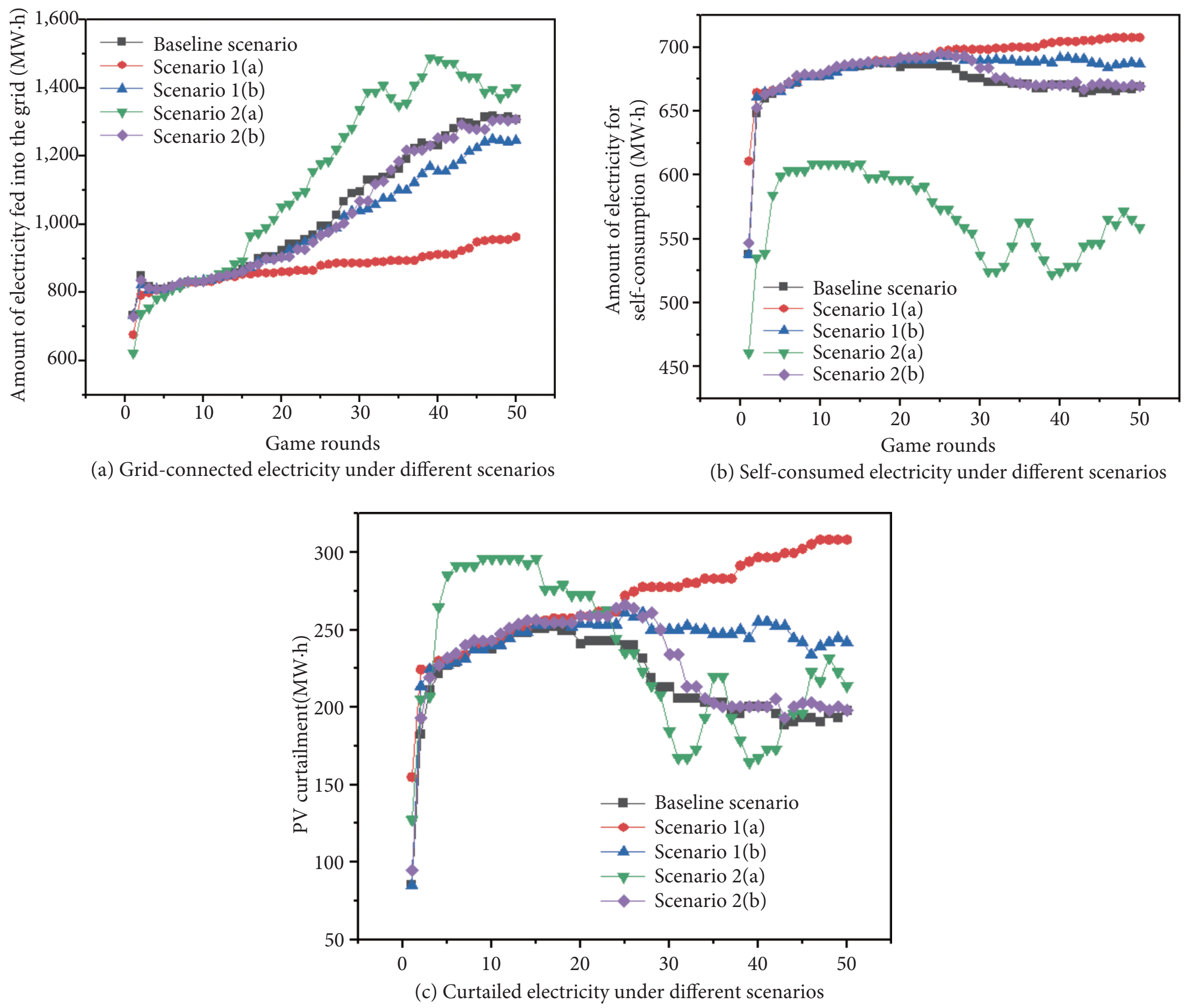


Fig. 6 Simulation results of multi-agent games under different scenarios.

rural energy investment and promote the orderly development of rural renewable energy.

6.3 Sensitivity analysis

This section examines the robustness of the game model and explores key factors influencing the final outcomes through sensitivity analyses based on household income characteristics and grid upgrade costs.

6.3.1 Sensitivity analysis based on household income characteristics

Rural household decisions to invest in distributed PV systems are influenced by various factors, with income being among the most significant[33]. Therefore, this study conducts a sensitivity analysis by varying the income distribution characteristics of rural households. To comprehensively reveal the impact of household income, it constructs five different income probability distributions including {15%, 25%, 42%, 14%, 4%}, {10%, 15%, 52%, 18%, 5%}, {8%, 14%, 55%, 18%, 5%}, {6%, 12%, 56%, 20%, 6%}, and {4%, 10%, 58%, 21%, 7%}. A higher probability in the high-income intervals indicates a greater proportion of high-income households in the rural area.

Figure 7 presents the total number of investing households, grid feed-in electricity, self-consumed electricity, and curtailed electricity under different income distributions in strategy set 3. As the proportion of high-income households increases, the number of rural households investing in distributed PV systems also increases significantly. The total number of investing households initially rises and then declines, with the differences between income distribution 5 and other distributions becoming more pronounced over game time. This suggests that increasing household income is a necessary condition for promoting rural distributed PV development. This conclusion is consistent with Mahn et al. (2024)[34].

Figures 7(b), 7(c), and 7(d) further demonstrate that while the surplus electricity feed-in model can facilitate the expansion of rural distributed PV capacity, it can also increase curtailment issues. Higher-income households, with greater electricity demand, benefit more from this model, leading to lower grid feed-in electricity and higher self-consumption. In contrast, when more low-income households adopt the surplus electricity feed-in model, their low electricity demand and strict self-consumption requirements will lead to higher curtailment rates, as shown in Figure 7(d). Additionally, because of demonstration effect, low-income households perceive higher expected returns from the surplus electricity feed-in model over a longer period compared to the full feed-in model. As a result, the curtailment rate under income distribution 5 continues rises over time. These findings

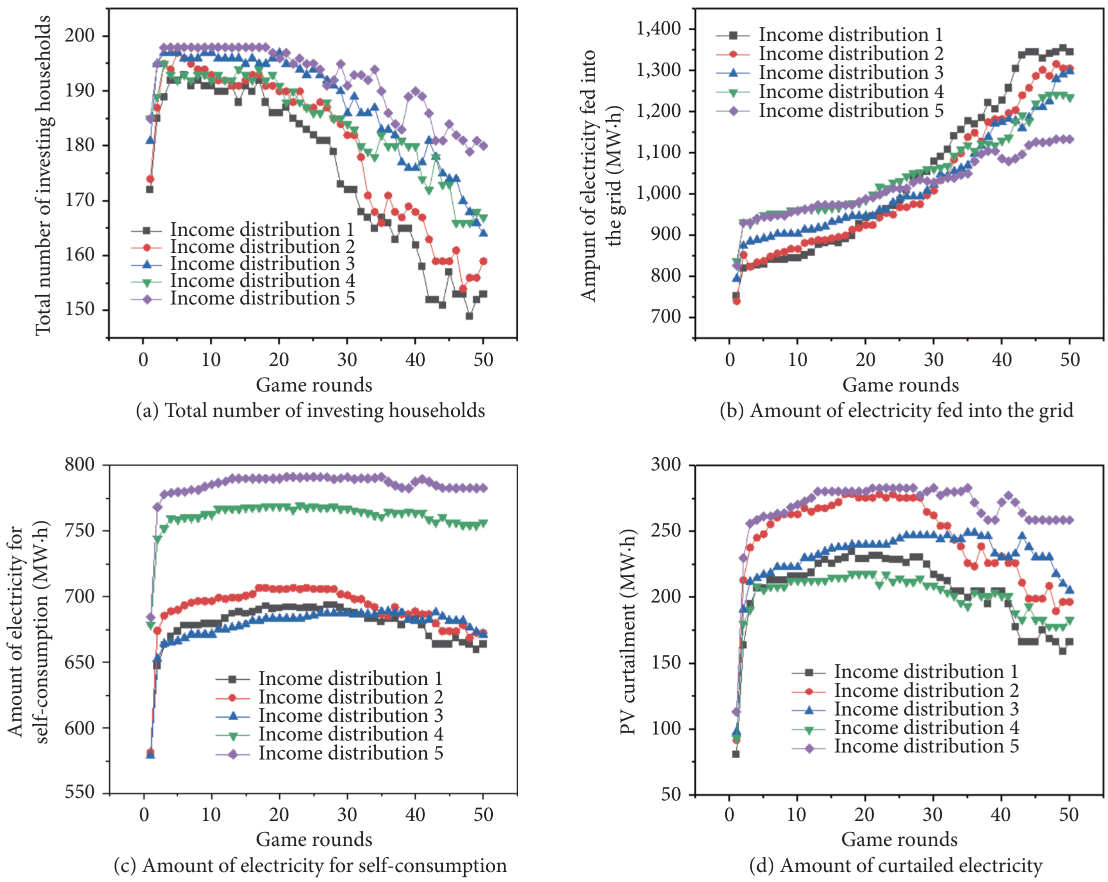


Fig. 7 Simulation results based on different income distribution characteristics.

suggest that in rural areas with more developed economies, stricter information disclosure and PV oversight are necessary to ensure efficient renewable energy development.

6.3.2 Sensitivity analysis based on grid upgrade costs

Grid capacity directly constrains the scale of rural distributed PV development. To further explore the impact of grid capacity, this study adjusts grid upgrade costs to 70%, 80%, 90%, 110%, and 120% of the baseline scenario. Higher grid upgrade costs correspond to stricter restrictions on the total PV capacity that the grid company can approve.

Figure 8 shows the total number of investing households, grid feed-in electricity, self-consumed electricity, and curtailed electricity under different grid upgrade costs based on strategy set 3. As shown in Figure 8(a), the total number of investing households under the "60% cost", "110% cost", and "120% cost" scenarios differs significantly from other scenarios, while the differences among other scenarios are relatively small. This indicates that the impact of grid technological advancements on rural distributed PV development is phased. Grid companies upgrade rural grids and approve more PV applications only when cumulative cost reductions surpass a certain threshold. These findings further confirm that grid capacity is the key factor determining the scale of rural distributed PV development in the long term.

As shown in Figures 8(b), 8(c), and 8(d), reducing grid upgrade costs does not necessarily improve the investment efficiency of rural distributed PV projects. Since the surplus electricity feed-in model is the predominant household strategy, changes in grid capacity significantly affect self-consumed electricity. For example, the self-consumed electricity in the "120% cost" scenario is notably lower than that in other scenarios. In the "60% cost" scenario, most approved applications are for the surplus electricity feed-in model, resulting in lower grid feed-in electricity and higher self-consumed electricity. Despite having the highest number of investing households, the "60% cost" scenario also experiences the highest curtailment rates due to limited electricity demand. Conversely, scenarios like "90% cost" have fewer investing households but achieve higher PV electricity utilization efficiency than the "60% cost" scenario. Therefore, governments should avoid indiscriminate grid upgrades and consider rural household electricity demand to ensure investment efficiency in rural distributed PV development.

7 Conclusions and policy recommendations

With the transformation of rural renewable energy, prosumer concept has emerged as a pivotal strategy for promoting distributed PV systems. This study employs game theory to construct a multi-agent dynamic game model involving village organization, PV enterprise, grid company, and rural households, focusing on the behavioral mechanisms among these stakeholders. Scenario simulations, including "Village Organization Guidance Scenario" and "Forced Self-Consumption Scenario", are designed to explore the formation mechanisms and evolutionary patterns of distributed PV investment strategies. The main conclusions are as follows:

(1) Collaboration is key: The optimal strategy for PV enterprise and village organization is to collaborate in promoting distributed PV projects. Compared to the roof leasing and full feed-in models,

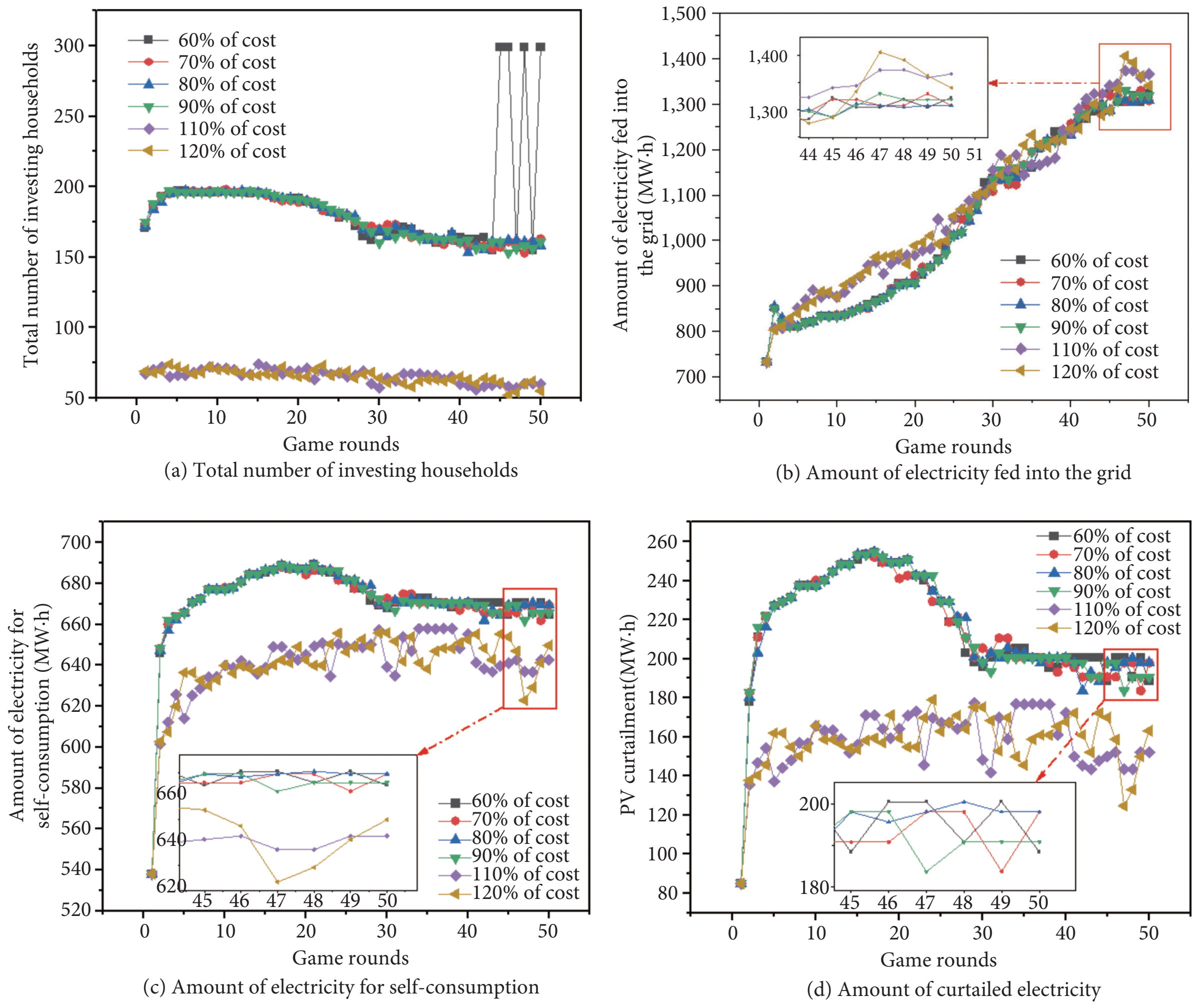


Fig. 8 Simulation results based on different grid upgrading costs.

the surplus electricity feed-in model is more effective in expanding rural distributed PV development. Rural households with low electricity demand prefer the full feed-in model, while those with high electricity demand prioritize the surplus electricity feed-in model.

(2) Balancing self-consumption and curtailment: Targeted promotion of the surplus electricity feed-in model can increase the total self-consumed electricity. However, inappropriate promotion of this model may cause significant curtailment. When grid companies review applications, raising the self-consumption requirement can reduce the scale of rural PV installations, and shift more households toward the full feed-in model. While this may limit installed capacity, it effectively lowers curtailment rates.

(3) Income and grid capacity constraints: A higher proportion of high-income households increases the total number investing in PV systems, but the final investment scale is limited by grid capacity. Within fixed grid capacity constraints, rising incomes can encourage more rural households to adopt the surplus electricity feed-in model, but this may also result in higher curtailment rates. Without corresponding growth in electricity demand, indiscriminate rural grid upgrades can lead to inefficient distributed PV investments.

From the perspective of prosumers, this study offers the following policy recommendations to promote high-quality development of rural renewable energy:

(1) Deepening village-enterprise cooperation and innovating promotion models. It is recommended that village organizations take the lead in establishing a "village-enterprise collaboration" mechanism with photovoltaic enterprises. PV project proposals and revenue-sharing schemes should be jointly formulated through case-by-case approval system. For promotion, localized profit estimation models should be developed based on regional policies, such as Beijing's rural PV subsidy standards, to showcase expected returns under different investment scenarios to farmers via digital platforms. What's more, the PV cooperative model should be promoted to establish a long-term win-win mechanism. It suggests that village organization should integrate rooftop resources for unified development and allocate a portion of the profits to village-level public services.

(2) Establish a dynamic self-consumption ratio mechanism based on grid absorption capacity. Grid companies should implement differentiated self-consumption requirements by region, referencing Guangdong Province's grid absorption capacity warning system. Areas under "red" warning must maintain a self-consumption ratio of at least 80% and are encouraged to deploy energy storage facilities; those under "green" warning may relax the requirement to 50%. Simultaneously, accelerate the full deployment of smart meters in rural areas and, leveraging the construction of new power systems, deploy a monitoring and control platform for distributed PVs to enhance

grid capacity for high-penetration PV integration.

(3) Implement differentiated development strategies based on regional classification. In eastern rural areas with high power load density, priority should be given to promoting the "self-consumption with surplus fed into the grid" model, with focused support for county-wide distributed PV pilot projects. In regions with limited grid integration capacity, the "full grid feed-in" or "rooftop leasing" models are encouraged, and should be planned concurrently with rural grid modernization initiatives. Emphasis must be placed on advancing integrated "PV+" applications, such as agrivoltaics on farmland and aquavoltaics in aquaculture zones, to achieve multidimensional and value-added land use. All projects shall be incorporated into rural revitalization infrastructure planning to avoid redundant investment.

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Author contribution statement

Wenbing Zhou: Writing – review & editing, Writing – original draft, Conceptualization, Supervision, Data curation, Methodology, Funding acquisition, Formal analysis. Songlin Tang: Supervision, Methodology, Formal analysis, Funding acquisition, Investigation, Supervision, Methodology.

Data availability

Not applicable.

Use of AI statement

None.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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