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The role of rural cooperatives in the development of rural household photovoltaics: An evolutionary game study

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ABSTRACT

Promoting photovoltaics (PV) in rural households is a crucial step towards green development and rural revitalization. The current practice negatively affects the profit margins of rural households, creating a challenge in balancing efficiency and equity. This paper utilizes evolutionary game theory to construct a bipartite evolutionary game model involving enterprise and rural households, and a tripartite model involving enterprise, rural households, and rural PV cooperatives. We then investigate the strategic behavior and choices of stakeholders and examine the evolutionary trajectory of the system under different parameters based on numerical simulations. Results show that the rural PV cooperatives can increase the strategic choices of enterprises by reducing their market entry costs. The rural PV cooperatives also increase the expected profits of enterprises, rural households, and total social welfare. Our findings suggest that rural PV cooperatives may encourage the adoption of rural household PV and provide insights to balance efficiency and equity.

1. Introduction

The rapid increase in total energy consumption from rural regions in China has led to various pollution issues caused by the burning of coal, diesel, and biomass, making the shift to a more sustainable energy structure and efficient consumption patterns a necessity. Household-distributed photovoltaic (PV), a new mode of electricity generation and consumption, can potentially alleviate the dependence on traditional energy sources and improve the rural environment by reducing pollution. Household PV can also promote rural modernization, accelerate the planning and construction of a new energy system, and enhance rural revitalization. Thus, household PVs have been increasingly supported by various policy incentives. At the end of 2022, the newly installed capacity of distributed photovoltaics (DPVs) power generation in China reached approximately 51.11 GW, accounting for roughly 58.48% of the total newly installed capacity in the world. The newly installed capacity of household PVs was approximately 25.25 GW, comprising approximately 49.39% of the newly installed capacity of DPVs (NEA, 2023). Consequently, household PVs have become an essential component of renewable energy power generation.

As the household PV subsidy policy gradually phases out (Zhang et al., 2021), other market instruments are needed to further promote household PV adaptation (Yu et al., 2022). Existing studies focused on non-fiscal policy incentives such as green certificate trading and P2P (peer-to-peer) energy-sharing mechanisms (Bae et al., 2021; Li and Ma, 2020), the role of organizational structure has often been overlooked. There are two primary organizational structures, a vertical collaboration model established through signed contracts between enterprises and rural households, and a horizontal cooperation model formed through written or verbal agreements between rural households and cooperatives. In the horizontal collaboration model, rural households are allowed to join cooperatives and have stronger decision-making power in the transaction. Compared to conventional market transactions, vertical and horizontal collaboration models effectively leverage households' social network, which can successfully overcome decentralized production, reduce transaction costs, and increase transaction efficiency (Maertens and Velde, 2017). The horizontal cooperation model has tighter network relationships. Incentive policies typically focus on the effects on individuals, whereas organizational structures mostly focus on how to ensure incentive alignment among all stakeholders. Therefore, an effective organizational structure is crucial in coordinating the actions of various stakeholders to maximize social benefits. The current

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vertical collaboration model depends on autonomous negotiations between rural households and enterprises to establish contractual relationships for rooftop leases or self-built PV systems (Chen and Gao, 2023). Asymmetric information has led to concerns among rural households regarding the quality of PV products, brand reputation, and the subsequent operation and maintenance costs (Qureshi et al., 2017; Garlet et al., 2019; Li et al., 2021; Wang et al., 2023). Firms also face high promotion costs in the early stage of construction, and limited investment motivation due to the geographic dispersion of rural households. These factors have created significant challenges for establishing efficient and sustainable models for promoting household PV adoption (Wu et al., 2022).

To address these challenges, the government proposed county-wide pilot projects (Lyu et al., 2023). However, several problems remain. First, local governments may prioritize political performance over the needs of rural households, resulting in policy biases towards preferable firms. When choosing the investors and constructors, local governments tend to give priority to the state-owned enterprises, resulting in a crowding-out effect on private photovoltaic enterprises and fairness concerns. Secondly, due to the lack of knowledge on the local market, state-owned enterprises still need to implement the project through local developers, and the extended operation chain reduces project profits, resulting in lower returns for rural households and reducing incentive to participate. The underlying cause for the diminished returns can be attributed to the presence of imperfect market competition (Kinnucan and Forker, 1987; Assefa et al., 2017). The implementation of the county-wide PV pilot policy tends to foster an oligopoly market structure characterized by a distorted pricing mechanism, leading to aberrant price transmission through the upstream and downstream segments of the industrial chain. Rural households, a downstream segment in the household PV industry chain, experience the influence of information asymmetry and unclear regulatory responsibilities. Consequently, the interests of rural households are compromised due to the absence of sufficient bargaining power when faced with the government, state-owned enterprises, and private enterprises. To ensure the long-term and effective promotion of household PV in rural areas, new organizational structures need to be explored. One possible approach involves intermediate organizations, such as rural cooperatives, to enhance efficiency and address fairness concerns. Rural cooperatives represent a voluntary organizational framework wherein rural households actively participate and collectively manage their productions and operations to enhance the performance and efficiency. Through the integration of resources from rural households, reduction of transaction costs between enterprises and rural households, and augmentation of bargaining power, rural cooperatives establish an effective linkage between rural households and the market.

This paper proposes the use of rural PV cooperatives with rooftop equity to lead and integrate the promotion of household PV. We first analyze the strategic interactions and benefits of rural households, PV enterprises, and rural PV cooperatives. We construct a bipartite evolutionary game model including enterprises and rural households, and a tripartite evolutionary game model with the addition of rural PV cooperatives. We then compare and analyze the behavioral strategies and benefit changes of enterprises and rural households before and after the participation of rural PV cooperatives, and simulate the evolutionarily stable strategies using numerical simulations. Finally, we propose an innovative organizational structure suitable for the proper operation of household PV projects, using parameter analysis to provide effective conditions for compatible incentives for tripartite decision-making.

Our results indicate that rural PV cooperatives may reduce the market entry cost for private enterprises, decrease the transaction cost between rural households and enterprises, and improve the bargaining power of rural households. Rural PV cooperatives have the potential to enhance the expected profits of enterprises, rural households, and the overall social benefits. Our results suggest that the equilibrium strategy is for enterprises to choose "investment, construction, and operation", rural households to choose "self-investment in construction", and rural PV cooperatives to choose "participation". The impact of cost controls, tariff changes, solar resources, and asset returns on investment intentions of stakeholders differs significantly. Our findings have important implications for policymakers seeking to implement differentiated policy incentives.

This paper presents two main contributions. Theoretically, we incorporate the behavioral characteristics of stakeholders in promoting household PV projects based on an evolutionary game, and propose targeted management measures and incentive strategies. Based on the existing studies, the applicability of the evolutionary game is discussed in comparison with the traditional Nash equilibrium. Practically, this paper fills the gap regarding the design of rural household PV organizational structure. While previous studies have focused on incentive perspectives to create positive PV development environments for enterprises and households (Liu et al., 2021a, 2021b; Luan and Lin, 2022), they overlook potential conflicting interests among stakeholders, which could hinder individual motivation. Our proposed organizational structure resolves compatibility problems among individual incentives to maximize overall benefits. There are also studies on the role of government in the household PV development process with both positive and negative findings (Shan and Yang, 2019; Xu et al., 2019; Han et al., 2020). However, these studies overlook the government's preference for state-owned enterprises that generate crowding-out effects on private enterprises, resulting in a negative impact on the overall household PV market environment. This paper systematically addresses the inequity problems caused by government participation in household PV projects and proposes a horizontal cooperative organizational structure that includes rural cooperatives. This new structure is compared with the existing vertical collaboration model and widens the perspective on the design of organizational structures for household PV projects.

The remainder of the paper proceeds as follows. Section 2 summarizes the relevant literature. Section 3 presents the model assumptions, framework, and theoretical analysis of the bipartite evolutionary game model for the enterprises and rural households. Section 4 builds the tripartite evolutionary game model for the enterprises, rural households, and rural PV cooperatives. Section 5 conducts numerical simulations and sensitivity analysis. Section 6 discusses the potential applicability of the model. The last section concludes the paper.

2. Literature review

2.1. Household PV polices

Household DPV projects first emerged in Europe, the United States, and other developed countries around late 1990s. There are three key stages in the development of domestic DPV in China, which started out slowly. In 2009, China carried out the photoelectric and building integration and Golden Sun demonstration projects (CGOV, 2009), these projects provide financial support for DPV power generation systems and accelerated the growth of the DPV market. To further increase grid connection efficiency, the State Grid Corporation of China (or the State) proposed preferential policies such as supporting DPV grid connection and full acquisition of excess power in October 2012 (SGCC, 2012). The first household DPV system was fully operational at the end of 2012, and the DPV power supply of Qingdao Jialinggou District was formally connected to the grid via "self-generation, surplus electricity feed-in" policy.

During 2013 to 2014, the State further issued several incentive policies that focus on financing, subsidies, large-scale constructions (NEA, 2014a; NDRC, 2013; NEA, 2014b). However, the growth of PV installations in rural households fell short of market expectations due to a long investment cycle. In the subsequent phase starting from 2016, the cost of PV power generation is gradually reduced as the PV industry technology continues to progress. Consequently, the incentives for large ground power plants and preferential tariffs decreased significantly, while national policies supporting household PV resulted in rapid growth.

To further enhance the household PV development, the State has analyzed the development bottleneck of the household PV market. The decentralization of rural homes has been cited as a major obstacle. The government then issued the notice of Announcing the Pilot Program of Distributed Rooftop PV Development in Whole Counties (Cities and Districts) on June 20, 2020, to address potential conflicts between centralization and decentralization (NEA, 2021). At the same time, the State still provides financial support for household PV projects. In 2021, the National Development and Reform Commission has explicitly stated that it will no longer offer subsidies for new centralized PV power plants, industrial and commercial DPV projects, etc., but still provides compensation at a rate of 0.03 RMB/kWh for new household PV projects (CGOV, 2021).

2.2. The studies related to household PV

Household photovoltaics are emerging as viable alternatives to traditional energy sources with the rapid development of renewable energy. Government subsidies create incentives for household PV expansion by effectively reducing installation costs for households and enterprises through improving installation efficiency (Chen and Chen, 2021; Dong et al., 2017; Hagerman et al., 2016). However, government subsidies may generate problems such as over-capacity and financial pressure (Li et al., 2018). Xiong and Yang (2016) investigated the driving impact of subsidies on PV development based on product life cycle theory and argued that subsidies play a vital role in driving PV development during the early stages, but their influence gradually diminishes as PV development matures. Braito et al. (2017) suggested that a high level of subsidies is not critical in driving the Italian PV industry in the long term. According to Tang et al. (2021), the impact of government subsidies on household PV installation is contingent upon the regional economic development status where government subsidies demonstrate an effective incentive for encouraging household PV installation in regions with high levels of economic development. However, in regions with lower levels of economic development, government subsidies lose their incentivizing effect and increase fiscal deficit risks. Consequently, the household PV market moves towards adopting market-oriented incentives when subsidies gradually phased out.

At a micro level, Chen and Wang (2022) employed a simulation approach to assess the effects of PV subsidy withdrawal based on a bipartite game model. They found that enterprises tend to choose a passive strategy, while households' disposition towards participation has gradually changed from being active to passive. Bae et al. (2021) examined the inclination of Korean residents to engage in the green certificate program and found that residents prefer solar energy as a green certificate option. Residents' participations in the green certificate market also foster the cost-efficient development of renewable energy. Castellini et al. (2021) constructed a real option model to investigate the impact of peer-to-peer (P2P) trading on the value of joint PV investments. Results suggest that P2P trading potentially encourage consumer involvement in energy markets, while the energy trading among consumers is determined by the individual supply and demand curves.

In addition to the implementation of incentive policies, administrative interventions have also impacted the installation of household PV. Numerous studies have investigated the impacts of the government's involvement in the household PV market. Shan and Yang (2019) constructed a tripartite evolutionary game model among poor households, enterprises, and the government, and concluded that an optimal behavioral strategy needs participation of poor households, active support from enterprises, and non-regulation by the government. In contrast, Xu et al. (2019) argued that the government's supervisory role is crucial to achieving a win-win situation, as its supervision, rewards, and punishments can effectively encourage enterprises and households to invest and install PV, and also effectively promote the operation and maintenance of household PV, ultimately benefiting all stakeholders. However, existing studies focused on the participation decisions of firms and rural households, while neglected how they may participate. Our study investigates the potential strategic choices of firms and rural households, considering specific forms of participation firms and rural households may adopt.

Past research also analyzes the behavioral intentions of stakeholders to understand participation incentives and motivations. Price incentives continue to be an important factor that drives households PV installation decisions (Kim et al., 2014; Pyrgou et al., 2016; Dong and Shimada, 2017). Non-price factors such as network effects can significantly impact households' decisions to participate in household PV (Graham, 2015; Graziano and Gillingham, 2015). The preference of non-installed households for household PV is influenced by the social context and may incur a psychological cost.

Household PV has become a link to achieve poverty alleviation and rural economic development in certain rural areas with prevailing energy poverty (Li et al., 2023). Since the introduction of the Notice on the Work Program for Implementing the PV Poverty Alleviation Project in 2014, many researchers have conducted studies on the economic, social, and environmental effects of PV poverty alleviation. PV poverty alleviation lowers the barrier to accessing clean energy in poor areas and transform household energy consumption patterns to mitigate rural pollution (Djanibekov and Gaur, 2018). PV poverty alleviation projects potentially augment per capita disposable income in counties and contribute to the accumulation of financial capital, including per capita household income. These positive outcomes arise from the direct benefits derived from electricity generation and the indirect labor benefits generated by the provision of anti-poverty public service jobs (Zhang et al., 2020; Han et al., 2020; Liu et al., 2021a, 2021b). Empirical evidence further indicates that PV poverty alleviation efforts can foster heightened awareness and advocacy of energy and environmental concerns, foster the adoption of low-carbon and energy-saving behaviors, and ultimately foster a sense of social responsibility among residents (Huang et al., 2020; Huang et al., 2022).

Macro-level household PV studies primarily investigate market incentives, non-market incentive policies, and the assessment of PV's impact on poverty alleviation. Micro-level research focuses on analyzing stakeholder behavior strategies and identifying price and non-price factors that influence individual behaviors. Various incentive policies have high requirements for realistic economic conditions, although such incentive policies are the key measures to promote PV installation. An optimal design of organizational structures shall encourage household PV installation at a low cost. Existing studies have mainly focused on the government's role, leading to inconsistent conclusions regarding the benefits of government regulation. Therefore, exploring the potential of rural cooperatives, which assume a similar role to the government while avoiding regulatory disadvantages, may yield more favorable outcomes for household PV installation.

2.3. Evolutionary game theory

Game theory is an effective method for studying the strategic behavior of stakeholders in complex decision-making situations. Traditional game theory assumes that the stakeholders are perfectly rational, which makes it difficult to analyze complicated game scenarios. Humans possess bounded rationality, which limits their ability to optimize decisions when facing complex problems (Gintis, 2014). As such, individuals often rely on intuitive behavior or imitate successful strategies, similar to biological behavior patterns and evolutionary processes. Evolutionary game theory (Smith and Price, 1973) analyzes complex game problems in human society (Abbass et al., 2015; Li et al., 2017; Chica et al., 2017; Wang et al., 2019) and extends the research objects from simple individuals to the whole population, emphasizing the bounded rationality of stakeholders and the bounded information of the game environment (Simon, 1955; Wang et al., 2021a). The evolutionary game theory advocates stakeholders repeat the game by learning and adjusting to achieve a dynamic stable situation (Nowak and Sigmund, 2004; Adami et al., 2016).

The core of evolutionary game analysis is not the prediction of the optimal strategy results for a one-time choice, but is more focused on the strategy adjustment process, trend and stability of bounded rationality groups in the long-term choice process. This approach has several characteristics, including repeated games and dynamic adjustment, which avoid the assumption of perfect rationality in repeated games, leading to a more accurate judgment when explaining economic and social reality. For the behavioral strategy choices of DPV stakeholders, existing literature has constructed a bipartite game involving households and enterprises or a tripartite game including households, enterprises, and government, covering topics including the sustainability of PV poverty alleviation (Shan and Yang, 2019), how DPV can be promoted (Chen et al., 2022), the impact of PV subsidy withdrawal (Chen and Wang, 2022), and the role of government subsidies and bank loans on PV development (Zhu et al., 2022). However, most of these studies have only examined the effects of incentive measures and have not considered the design of an organizational structure based on the principle of incentive compatibility. To address this gap, we use an evolutionary approach to investigate an organizational structure suitable for promoting household PV.

3. Evolutionary game model for household PV development based on "enterprises + rural households" mode

3.1. Evolutionary game model and assumptions

In this section, we illustrate a new organizational structure of household PV projects based on evolutionary game theory, assuming bounded rationality of stakeholders who can adjust their strategies and eventually reach a dynamic stable state in a repeated game. In repeated games, replicator dynamic equations are usually constructed to simulate the process of comparison, learning, and imitation of stakeholders. The basic form can be expressed as Eq. (1),

$$\frac{dx}{dt} = x\left(u_y - \overline{u}\right) \tag{1}$$

where x represents the proportion of the players chosen for a specific strategy, u_y represents the expected payoffs of the players who adopt the strategy, $\overline{u}$ represents the average payoffs of the players, and $\frac{dx}{dt}$ represents the change rate over time in the proportion of the players who choose the strategy. When $\frac{dx}{dt}$ reaches a stable state, the equilibrium points will be reached (Smith and Price, 1973; Taylor and Jonker, 1978).

We first assume that the household PV market has only two economic agents, private enterprises and rural households, both are of bounded rationality with the ability to learn, imitate, and innovate. Different from profit-oriented of private enterprises, state-owned enterprises participate in PV projects to fulfill national tasks and giving more consideration to the rapid acquisition of high-quality assets. Therefore, the strategic choices of state-owned enterprises are not influenced by rural households and private enterprises, but may impact their strategic choices. Thus, we treat the behavior of state-owned enterprises as exogenous factors and considers only the strategic choices of private enterprises and rural households.

The private enterprise integrates investment, construction, and operation (ICO) are the mainstream and most profitable business mode under the households and enterprises voluntary negotiation process, and the gross profit can exceed 1 yuan/W (Teng et al., 2022). However, this is limited to the long investment return cycle of the project, ICO require the enterprise to have sufficient financing ability, which is usually dominated by the large private enterprises. For small and medium-sized enterprises, they often choose the construction and operation (C&O), where the state-owned enterprises are responsible for the pre-investment of the project, and the small and medium-sized enterprises are responsible for the implementation of the project, i.e., the construction and operation link, which does not require a large capital expenditure and the payoffs are faster. Therefore, the C&O mode has gradually become the mainstream mode for state-owned enterprises to participate in PV projects with private enterprises in the context of county-wide promotion, though private enterprises have relatively low profits of about 0.2 Yuan/W (Teng et al., 2022).

Rural households choose to participate in household PV projects to obtain economic benefits, mainly in the form of self-investment and construction (SIC) and rooftop leases (RL) (Chen and Gao, 2023). Under the SIC mode, rural households have clear property rights, pay for the construction and operation costs, and obtain revenues by using the "self-generation, surplus electricity feed-in" mode. Under the RL mode, enterprises are required to pay rent for rural households and use the "full electricity feed-in" mode to generate revenues. "Self-generation, surplus electricity feed-in" represents a business mode wherein electricity generated by the PV system is consumed by residents, with any surplus electricity sold back to the grid for financial gains. The "full electricity feed-in" means selling all generated electricity to the grid. As government subsidies gradually phase out and the feed-in tariff approaches the benchmark tariff for coal-fired power, surplus electricity feed-in has become a more economically viable approach. However, this option does entail additional workload related to meter reading during the operational process. In cases where rural households opt to lease rooftops, challenges arise due to information asymmetry surrounding unclear rights and responsibilities associated with rooftop ownership. Thus, selecting full electricity feed-in mode can help mitigate unnecessary complications. There are two possible strategy choices for both enterprises and rural households in the context of county-wide promotion, i.e., enterprises choose {ICO, C&O} and rural households choose {SIC, RL}. We use x and y to denote the proportion of enterprises and rural households choosing the strategy of ICO and SIC with $x, y \in [0,1]$.

To proceed, we assume that the household PV construction cost is denoted as C_1, the operation cost is C_2, the transaction cost is C_3, the investment cost is C_4, the market entry cost is C_5. The above costs are divided into every year. The electricity price in the area of rural households is P_1, the price of the feed-in tariff is P_2, the annual electricity generation capacity of household PV is denoted as E, the annual electricity consumption of rural households is E_1, the surplus electricity is $(E\text{-}E_1)$. The rooftop rent is R_1, and the potential value-added assets gains is R_2 when the enterprises choose the ICO strategy. Transaction cost coefficient is λ, feed-in tariff revenue share coefficient is ρ, cost and income control coefficient are θ and h, respectively.

We next consider the costs and revenues under the SIC and RL strategies. When the SIC strategy is chosen, the construction cost (C_1) and operation cost (C_2) are paid by the rural households, who usually use the "self-generation, surplus electricity feed-in" mode to obtain electricity savings $(P_1 \times E_1)$ and feed-in tariffs revenues $(P_2 \times (E\text{-}E_1))$. When the RL strategy is chosen, the construction cost (C_1) and operation cost (C_2) are paid by the enterprises, which use the "full electricity feed-in" mode to obtain the feed-in tariff revenues $(P_2 \times E)$, and the rural households only get the rooftop rent (R_1). The rooftop lease mode requires rural households and enterprises to negotiate at a higher transaction cost $(\lambda C_3, \lambda > 1)$ due to unclear property rights compared to SIC mode, which is also incorporated in our model.

Under the ICO and C&O strategies, due to the local government prefers state-owned enterprises, resulting in a crowding-out effect on private PV enterprises. Although enterprises can earn additional potential value-added assets gains (R_2) when choosing the ICO strategy, they need to pay extra and expensive market entry cost (C_5) and investment cost (C_4). In cases where rural households choose to lease their rooftops, enterprises can earn the full feed-in tariff revenues $(P_2 \times E)$, but also pay additional rooftop rent (R_1). Thus, we impose the following assumption.

Assumption 1. *The extra costs incurred by the enterprises in choosing the ICO strategy are more than the additional revenues earned, i.e.,* $C_4 + C_5 > R_2$, $C_4 + C_5 + R_1 > (1-\rho)P_2 \times E + R_2$, *when rural households choose the SIC or RL strategy,*

The cooperation between state-owned enterprises and local private enterprises under the C&O mode leads to a long operational chain from investment to implementation of household PV, and profit margins are further reduced. Compared to enterprises choosing the ICO strategy, rural households have lower returns under the C&O strategy, expressed as $\theta > 1$, or $0 < h < 1$.

3.2. Construction of the bipartite evolutionary game model

3.2.1. Expected profits of the enterprises

Table 1 shows the payoff matrix of the game between enterprises and rural households. When the enterprises adopt the ICO strategy and the rural households choose the SIC strategy, the enterprises will get the construction and operation expenses paid by the rural households $(C_1 + C_2)$, and the potential value-added assets gains (R_2), and pay the transaction cost (C_3), investment cost (C_4) and market entry cost (C_5). When rural households choose the RL strategy, the enterprises will receive the feed-in tariff revenues $(P_2 \times E)$ through the "full electricity feed-in" mode, and the potential value-added assets gains (R_2), but pay the rooftop rent (R_1), construction cost (C_1), operation cost (C_2), transaction cost $(\lambda C_3, \lambda > 1)$, investment cost (C_4), and market entry cost (C_5).

When the enterprises adopt the C&O strategy and the rural households choose the SIC strategy, the enterprises only get the construction and operation expenses $(C_1 + C_2)$ paid by the rural households, and pay the transaction cost (C_3). When rural households choose the RL strategy, enterprises will share the feed-in tariff revenues $(\rho(P_2 \times E), \rho\in(0,1))$ with state-owned enterprises, and pay the construction cost (C_1), operation cost (C_2), and transaction cost $(\lambda C_3, \lambda > 1)$.

3.2.2. Expected profits of the rural households

When rural households choose the SIC strategy and enterprises adopt the ICO strategy, rural households will obtain electricity savings $(P_1 \times E_1)$ and feed-in tariff revenues $(P_2 \times (E-E_1))$ through the "self-generation, surplus electricity feed-in" mode, and pay construction and operation costs $(C_1 + C_2)$. When the enterprises choose the C&O strategy, the construction and operation costs $(\theta(C_1 + C_2), \theta > 1)$ paid by the rural households are relatively higher.

When rural households choose the RL strategy, they receive only the rooftop rent (R_1) without paying any cost. However, the rent $(hR_1, h\in(0, 1))$ received by rural households is relatively lower when the enterprises choose the C&O strategy. The specific expected profits are shown in Table 2.

3.3. Bipartite evolutionary stable analysis

3.3.1. Replicator dynamic equations for PV enterprises and rural households

When enterprises play the game, each enterprise may confront both the rural households choosing the SIC strategy and the rural households choosing the RL strategy. The former probability is y and the latter probability is $1 - y$. Thus, the expected payoff of the enterprises when choosing the ICO strategy (UA_1) is:

Table 1
The payoff matrix of bipartite evolutionary game.

		Rural households	
		SIC *(y)*	RL *(1-y)*
PV enterprises	ICO *(x)*	(φ_1, τ_1)	(φ_2, τ_2)
	C&O *(1-x)*	(φ_3, τ_3)	(φ_4, τ_4)

Table 2
Specific expected profits of enterprises and rural households.

Expected profits	PV enterprises	Rural households
(φ_1, τ_1)	$C_1 + C_2 + R_2\text{-}(C_3 + C_4 + C_5)$	$P_1 \times E_1 + P_2 \times (E\text{-}E_1)\text{-}(C_1 + C_2)$
(φ_2, τ_2)	$P_2 \times E + R_2\text{-}R_1\text{-}(C_1 + C_2 + \lambda C_3 + C_4 + C_5)$	R_1
(φ_3, τ_3)	$C_1 + C_2\text{-}C_3$	$P_1 \times E_1 + P_2 \times (E\text{-}E_1)\text{-}\theta(C_1 + C_2)$
(φ_4, τ_4)	$\rho(P_2 \times E)\text{-}(C_1 + C_2 + \lambda C_3)$	hR_1

$$UA_1 = y\varphi_1 + (1-y)\varphi_2 = (2y-1)(C_1+C_2) + R_2 - [y(1-\lambda)+\lambda]C_3 - C_4 - C_5 + (1-y)P_2 \times E - (1-y)R_1 \tag{2}$$

The expected payoff for the enterprises in choosing the C&O strategy (UA_2) is:

$$UA_2 = y\varphi_3 + (1-y)\varphi_4 = (2y-1)(C_1+C_2) - [y(1-\lambda)+\lambda]C_3 + \rho(1-y)P_2 \times E \tag{3}$$

The profits of the enterprise depend on the strategy choices of the rural households and also on their own strategy choices. Thus, the average expected payoff of the enterprises $(\overline{UA})$ is:

$$\overline{UA} = xUA_1 + (1-x)UA_2 \tag{4}$$

Thus, unless UA_1 and UA_2 are equal, there are significant differences in the firms' returns. The enterprise with lower profits will notice the differences and start simulating other types of enterprises. The proportion x and $1\text{-}x$ of the initial strategy choices varies over time, and its dynamic rate of variation can be expressed by the replicator dynamic equation. Taking the proportion of the ICO strategy as an example, the replicator dynamic equation of the enterprises can be expressed as:

$$F(x) = \frac{dx}{dt} = x\,(UA_1 - \overline{UA}) = x(1-x)[R_2 - C_4 - C_5 + (1-y)(1-\rho)P_2 \times E - (1-y)R_1] \tag{5}$$

Similarly, the replicator dynamic equation for rural households choosing to the SIC strategy can be expressed as follows:

$$F\left(y\right) = \frac{dy}{dt} = y\left(UB_1 - \overline{UB}\right) = y\left(1-y\right)\left\{P_1 \times E_1 + P_2 \times \left(E - E_1\right) - \left[\left(1-\theta\right)x + \theta\right](C_1 + C_2) - \left[\left(1-h\right)x + h\right]R_1\right\} \tag{6}$$

The calculation process is detailed in Appendix B.

3.3.2. Equilibrium solution and asymptotic stability analysis

When $F(x) = \frac{dx}{dt} = 0$, $F(y) = \frac{dy}{dt} = 0$, the equilibrium points of the evolutionary game between enterprises and rural households are obtained as $D_1\ (0,0)$, $D_2\ (1,0)$, $D_3\ (0, 1)$, $D_4\ (1,1)$, $D_5\ (x^*, y^*)$, where, (See Eq. (7)),

$$\begin{cases} x^* = \dfrac{P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2) - hR_1}{(1-h)R_1 + (1-\theta)(C_1 + C_2)} \\ y^* = \dfrac{R_1 - (1-\rho)P_2 \times \mathrm{E} - R_2 + (C_4 + C_5)}{R_1 - (1-\rho)P_2 \times \mathrm{E}} \end{cases} \tag{7}$$

According to assumption 1, when the condition $R_1 - (1-\rho)P_2 \times \mathrm{E} > 0$ is satisfied, we can conclude that $y^* > 1$, if not, $y^* < 0$. $D_5\ (x^*, y^*)$ does not satisfy the condition of the equilibrium point. According to the Lyapunov's (1992) criterion, a necessary and sufficient condition for the asymptotic stability of the system is that all eigenvalues of the Jacobian matrix are negative. Therefore, the stability of each equilibrium solution can be determined by bringing each equilibrium solution into the Jacobian matrix, which leads to the evolutionarily stable strategy (ESS). The Jacobian matrix of the bipartite game can be calculated as Eq. (8):

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} \tag{8}$$

where $\frac{\partial F(x)}{\partial x} = (1-2x)[R_2 - C_4 - C_5 + (1-y)(1-\rho)P_2 \times E - (1-y)R_1]$; $\frac{\partial F(x)}{\partial y} = x(1-x)[R_1 - (1-\rho)P_2 \times E]$; $\frac{\partial F(y)}{\partial x} = -y(1-y)[(1-h)R_1 + (1-\theta)(C_1 + C_2)]$; $\frac{\partial F(y)}{\partial y} = (1-2y)\{P_1 \times E_1 + P_2 \times (E - E_1) - [(1-\theta)x + \theta](C_1 + C_2) - [(1-h)x + h]R_1\}$.

Based on the system equilibrium points D_1, D_2, D_3, and D_4 into the Jacobian matrix. For D_1 *(0, 0)*, the Jacobian matrix is the following (See Eq. (9)):

$$J_1 = \begin{bmatrix} (1-\rho)(P_2 \times E) + R_2 - R_1 - (C_4 + C_5) & 0 \\ 0 & \begin{matrix} P_1 \times E_1 + P_2 \times (E - E_1) \\ -\theta(C_1 + C_2) - hR_1 \end{matrix} \end{bmatrix} \tag{9}$$

The eigenvalues of matrix J_1 are $\delta_{11} = (1-\rho)(P_2 \times E) + R_2 - R_1 - (C_4 + C_5)$, $\delta_{12} = P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2) - hR_1$. According to assumption 1, $\delta_{11} < 0$. Based on the Lyapunov criterion, when $\delta_{12} < 0$, then D_1 *(0, 0)* is the evolutionarily stable strategies (ESS).

Analogously, the Jacobian matrix at D_2 *(1, 0)* is the following (See Eq. (10)):

$$J_2 = \begin{bmatrix} -(1-\rho)(P_2 \times E) - R_2 + R_1 + (C_4 + C_5) & 0 \\ 0 & \begin{matrix} P_1 \times E_1 + P_2 \times (E - E_1) \\ -(C_1 + C_2) - R_1 \end{matrix} \end{bmatrix} \tag{10}$$

The eigenvalues of matrix J_2 are $\delta_{21} = -(1-\rho)(P_2 \times E) - R_2 + R_1 + (C_4 + C_5)$, $\delta_{22} = P_1 \times E_1 + P_2 \times (E - E_1) - (C_1 + C_2) - R_1$. According to assumption 1, $\delta_{21} > 0$. Based on the judgmental criterion, then D_2 *(1, 0)* is not stable.

For D_3 *(0, 1)*, the Jacobian matrix is the following (See Eq. (11)):

$$J_3 = \begin{bmatrix} R_2 - (C_4 + C_5) & 0 \\ 0 & hR_1 - P_1 \times E_1 - P_2 \times (E - E_1) + \theta(C_1 + C_2) \end{bmatrix} \tag{11}$$

The eigenvalues of matrix J_3 are $\delta_{31} = R_2 - (C_4 + C_5)$, $\delta_{32} = hR_1 - P_1 \times E_1 - P_2 \times (E - E_1) + \theta(C_1 + C_2)$. According to assumption 1, $\delta_{31} < 0$. Based on the Lyapunov criterion, when $\delta_{32} < 0$, then D_3 *(0, 1)* is the evolutionarily stable strategies (ESS).

Finally, the Jacobian matrix at D_4 *(1, 1)* is the following (See Eq. (12)):

$$J_4 = \begin{bmatrix} (C_4 + C_5) - R_2 & 0 \\ 0 & R_1 - P_1 \times E_1 - P_2 \times (E - E_1) + (C_1 + C_2) \end{bmatrix} \tag{12}$$

The eigenvalues of matrix J_2 are $\delta_{41} = (C_4 + C_5) - R_2$, $\delta_{42} = R_1 - P_1 \times E_1 - P_2 \times (E - E_1) + (C_1 + C_2)$. According to assumption 1, $\delta_{41} > 0$. Based on the judgmental criterion, then D_4 *(1, 1)* is not stable.

Based on the above analysis, we find that D_1 *(0, 0)* and D_3 *(0, 1)* are evolutionarily stable strategies (ESS) under certain conditions that are satisfied. D_2 *(1, 0)* and D_4 *(1, 1)* are not stable. The strategy choices in the bipartite game are the same for different types of firms. Due to a large amount of initial capital investment, choosing the C&O mode is the optimal strategy for small and medium-sized enterprises to enter the rooftop PV market. On the other hand, because local governments give priority to state-owned enterprises when choosing investors, there is a crowding-out effect on private PV companies. Extra and expensive costs lead to lower profits for the leading private enterprises, which seriously discourages the leading private enterprises to choose the ICO strategy.

Given that both the leading private enterprises and small and medium-sized enterprises choose the C&O strategy, the leading private enterprises crowd out the market share of the small and medium-sized enterprises due to scale and capital advantages. The small and medium-sized enterprises gradually withdraw from the rooftop PV market. Thus, under the bipartite evolutionary game rooftop PV market will gradually form a competitive layout of a two-party monopoly with state-owned enterprises taking the lead and leading private enterprises responsible for construction and operation. When the rural households choose the SIC strategy is more profitable, D_3 *(0, 1)* is the ESS. When the rural households choose the RL strategy is more profitable, D_1 *(0, 0)* is the ESS. (See Table 3)

4. Evolutionary game model for household PV development based on “enterprises + rural households+ rural PV cooperatives” mode

4.1. Tripartite evolutionary game model assumptions and construction

We now assume the household PV market has three economic agents: enterprises, rural households, and rural PV cooperatives, all three of which are bounded rationality groups with the ability to learn, imitate and innovate. Enterprises, rural households, and rural PV cooperatives all have two possible strategy choices, i.e., enterprises choose {ICO, C&O}, rural households choose {SIC, RL}, and rural PV cooperatives choose {participation, non-participation}. We use *x, y* and *z* to denote the proportion of enterprises, rural households, and rural PV cooperatives choosing ICO, SIC, and participation strategies with *x, y* and $z \in [0, 1]$, respectively.

To proceed, we assume that the development revenue received by the rural PV cooperatives is denoted as *M*, the guiding and integrating costs paid by the rural PV cooperatives are N_1. The profit effect coefficient is denoted as *g*, transaction cost effect coefficient is *m*, and market entry cost effect coefficient is *j*.

Consider the role of the intermediary organization in the household PV promotion. Rural PV cooperatives with rooftop equity play three main roles in the process of promoting household PV. First, the cooperatives can integrate the resources of rural households, form a scale effect, and improve bargaining power when communicating with enterprises, thus enhancing the profits of rural households. Second, the cooperatives reduce the transaction cost between enterprises and rural households. Third, the cooperatives create an equitable business environment for the rural household PV market and reduce the market entry cost of enterprises. Thus, we have the following assumption.

Assumption 2. *$g > 1$, $0 < m < 1$, and $0 < j < 1$.*

Consider the costs and revenues of the intermediary organization that is participating. The rural PV cooperatives receive the development revenue *(M)* and pay the guiding and integrating costs *(N_1)*. The payoff matrix and specific expected profits under the tripartite game are shown

Table 3
Stability analysis of equilibrium points.

Conditions	Equilibrium points	Matrix eigenvalues 1	Matrix eigenvalues 2	results
$P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2) \langle hR_1$	$D_1(0, 0)$	−	−	**ESS**
	$D_2(1, 0)$	+	uncertain	unstable
	$D_3(0, 1)$	−	+	unstable
	$D_4(1, 1)$	+	uncertain	unstable
$hR_1 < P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2)$	$D_1(0, 0)$	−	+	unstable
	$D_2(1, 0)$	+	uncertain	unstable
	$D_3(0, 1)$	−	−	**ESS**
	$D_4(1, 1)$	+	uncertain	unstable

Notes: Given the conditions, the positive and negative of the eigenvalues δ_{22} and δ_{42} are difficult to judge and therefore uncertain.

in Tables 4 and 5.

4.2. Tripartite evolutionary stable analysis

4.2.1. Replicator dynamic equations for PV enterprises, rural households, and rural PV cooperatives

The expected payoff of the enterprises when choosing the ICO strategy *(UC_1)* is (See Eq. (13)):

$$UC_1 = (1-z)[y\varphi_1 + (1-y)\varphi_2] + z[y\varphi_5 + (1-y)\varphi_6] = (2y-1)(C_1+C_2) + R_2 - C_4 + (1-y)(P_2 \times E - R_1) - [1-z(1-m)][y(1-\lambda)+\lambda]C_3 - [1-z(1-j)]C_5 \tag{13}$$

The expected payoff for the enterprises in choosing the C&O strategy *(UC_2)* is (See Eq. (14)):

$$UC_2 = (1-z)[y\varphi_3 + (1-y)\varphi_4] + z[y\varphi_7 + (1-y)\varphi_8] = (2y-1)(C_1+C_2) + (1-y)\rho(P_2 \times E) - [1-z(1-m)][y(1-\lambda)+\lambda]C_3 \tag{14}$$

Thus, the average expected payoff of the enterprises *($\overline{UC}$)* is (See Eq. (15)):

$$\overline{UC} = xUC_1 + (1-x)UC_2 \tag{15}$$

Taking the proportion of the ICO strategy as an example, the replicator dynamic equation of the enterprises can be expressed as Eq. (16):

$$F(x) = \frac{dx}{dt} = x\,(UC_1 - \overline{UC}) = x(1-x)\{R_2 - C_4 - (1-y)R_1 + (1-y)(1-\rho)(P_2 \times E) - [1-z(1-j)]C_5\} \tag{16}$$

Similarly, the replicator dynamic equation for rural households choosing to SIC strategy can be expressed as follows (See Eq. (17)):

$$F(y) = \frac{dy}{dt} = y(UD_1 - \overline{UD}) = y(1-y)[1-z(1-g)]\{P_1 \times E_1 + P_2 \times (E - E_1) - [x(1-\theta)+\theta](C_1+C_2) - [x(1-h)+h]R_1\} \tag{17}$$

The replicator dynamic equation for rural PV cooperatives choosing the "participation" strategy can be expressed as follows (See Eq. (18)):

$$F(z) = \frac{dz}{dt} = z\,(UE_1 - \overline{UE}) = z(1-z)(M - N_1) \tag{18}$$

The specific calculation process is detailed in Appendix B.

4.2.2. Equilibrium solution and asymptotic stability analysis

When $F(x) = \frac{dx}{dt} = 0$, $F(y) = \frac{dy}{dt} = 0$, $F(z) = \frac{dz}{dt} = 0$, the equilibrium points of the evolutionary game for enterprises, rural households, and rural PV cooperatives are *S_1(0,0,0), S_2(1,0,0), S_3(0,1,0), S_4(1,1,0), S_5(0,0,1), S_6(0,1,1), S_7(1,0,1), S_8(1,1,1), S_9(x_1*, y_1*, 0), S_{10}(x_1*, y_2*, 1)*. The two equilibrium points *S_9 (x_1*, y_1*, 0), S_{10} (x_1*, y_2*, 1)* may not be considered since they do not satisfy the sufficient and necessary conditions for achieving the evolutionarily stable strategy (ESS) according to the Lyapunov criterion. As a result, the Jacobian matrix of the tripartite game can be calculated as Eq. (19):

Table 4
The payoff matrix of the tripartite evolutionary game.

		Rural PV cooperatives			
		Non-participation *(1-z)*		Participation *(z)*	
		Rural households		Rural households	
		SIC *(y)*	RL *(1-y)*	SIC *(y)*	RL *(1-y)*
PV enterprises	ICO *(x)*	(φ_1,τ_1,ω_1)	(φ_2,τ_2,ω_2)	(φ_5,τ_5,ω_5)	(φ_6,τ_6,ω_6)
	C&O *(1-x)*	(φ_3,τ_3,ω_3)	(φ_4,τ_4,ω_4)	(φ_7,τ_7,ω_7)	(φ_8,τ_8,ω_8)

Table 5
Specific expected profits of enterprises, rural households, and rural PV cooperatives.

Expected profits	PV enterprises	Rural households	Rural PV cooperatives
(φ_1,τ_1,ω_1)	$C_1 + C_2 + R_2$-$(C_3 + C_4 + C_5)$	$P_1 \times E_1 + P_2 \times (E$-$E_1)$-$(C_1 + C_2)$	0
(φ_2,τ_2,ω_2)	$P_2 \times E + R_2$-R_1-$(C_1 + C_2 + \lambda C_3 + C_4 + C_5)$	R_1	0
(φ_3,τ_3,ω_3)	$C_1 + C_2$-C_3	$P_1 \times E_1 + P_2 \times (E$-$E_1)$-$\theta(C_1 + C_2)$	0
(φ_4,τ_4,ω_4)	$\rho(P_2 \times E)$-$(C_1 + C_2 + \lambda C_3)$	hR_1	0
(φ_5,τ_5,ω_5)	$C_1 + C_2 + R_2$-$(mC_3 + C_4 + jC_5)$	$g(P_1 \times E_1 + P_2 \times (E$-$E_1)$-$(C_1 + C_2))$	M-N_1
(φ_6,τ_6,ω_6)	$P_2 \times E + R_2$-R_1-$(C_1 + C_2 + \lambda mC_3 + C_4 + jC_5)$	gR_1	M-N_1
(φ_7,τ_7,ω_7)	$C_1 + C_2$-mC_3	$g(P_1 \times E_1 + P_2 \times (E$-$E_1)$-$\theta(C_1 + C_2))$	M-N_1
(φ_8,τ_8,ω_8)	$\rho(P_2 \times E)$-$(C_1 + C_2 + \lambda mC_3)$	ghR_1	M-N_1

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{19}$$

where $\frac{\partial F(x)}{\partial x} = (1-2x)\{R_2 - C_4 - (1-y)R_1 + (1-y)(1-\rho)(P_2 \times E) - [1-z(1-j)]C_5\}$; $\frac{\partial F(x)}{\partial y} = x(1-x)[R_1 - (1-\rho)(P_2 \times E)]$; $\frac{\partial F(x)}{\partial z} = x(1-x)(1-j)C_5$; $\frac{\partial F(y)}{\partial x} = y(1-y)[1-z(1-g)][-(1-\theta)(C_1+C_2) - (1-h)R_1]$; $\frac{\partial F(y)}{\partial y} = (1-2y)[1-z(1-g)]\{P_1 \times E_1 + P_2 \times (E-E_1) - [x(1-\theta)+\theta](C_1+C_2) - [x(1-h)+h]R_1\}$; $\frac{\partial F(y)}{\partial z} = -y(1-y)(1-g)\{P_1 \times E_1 + P_2 \times (E-E_1) - [x(1-\theta)+\theta](C_1+C_2) - [x(1-h)+h]R_1\}$; $\frac{\partial F(z)}{\partial x} = 0$; $\frac{\partial F(z)}{\partial y} = 0$; $\frac{\partial F(z)}{\partial z} = (1-2z)(M-N_1)$.

The stability of each equilibrium solution can be determined by the Jacobian matrix. Taking *S_8 (1, 1, 1)* as an example, the Jacobian matrix can be written as Eq. (20):

$$J_8 = \begin{bmatrix} C_4 + jC_5 - R_2 & 0 & 0 \\ 0 & g[C_1 + C_2 + R_1 - P_1 \times E_1 - P_2 \times (E - E_1)] & 0 \\ 0 & 0 & N_1 - M \end{bmatrix} \tag{20}$$

The eigenvalues of matrix J_8 are $\delta_{81} = C_4 + jC_5 - R_2$, $\delta_{82} = g[C_1 + C_2 + R_1 - P_1 \times E_1 - P_2 \times (E - E_1)]$, $\delta_{83} = N_1 - M$. According to assumption 2, as the rural PV cooperatives reduce the market entry cost *($0 < j < 1$)*, which causes the extra costs for firms when they choose the ICO strategy to be reduced and enhances the profit margin. When $C_4 + jC_5 < R_2$ is satisfied, $\delta_{81} < 0$, the enterprises will gain extra profits by choosing the ICO strategy. The rural PV cooperatives also increase the total profits of rural households. When the rooftop lease is less than the profits of rural households who invested in their own PV projects, i.e., $gR_1 < g[P_1 \times E_1 + P_2 \times (E - E_1) - (C_1 + C_2)]$ is satisfied, $\delta_{82} < 0$ and rural households will tend to choose the SIC strategy. Lastly, when the guiding and integrating costs of rural PV cooperatives input is lower than the development revenue, i.e., $M - N_1 > 0$ are satisfied, $\delta_{83} < 0$ and the choice of participation is the optimal strategy. As a result, *S_8 (1, 1, 1)* is the evolutionarily stable strategies (ESS).

Points *S_1 (0, 0, 0), S_3 (0, 1, 0), S_5 (0, 0, 1), S_6 (0, 1, 1), S_7 (1, 0, 1)*, and *S_8 (1, 1, 1)* can be realized under certain conditions (See Table 6). *S_1* and *S_3* have the same meaning as *D_1* and *D_3* expressions, and denote the evolutionarily stable strategy (ESS) without the rural PV cooperatives.

Table 6
Stability conditions of equilibrium solutions.

Scenario	ESS	Stability conditions of ESS
Intermediary organization choose not to participate	$S_1(0, 0, 0)$	$(1-\rho)(P_2 \times E) + R_2 < R_1 + C_4 + C_5$ $P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2) \langle hR_1$ $M < N_1$
	$S_3(0, 1, 0)$	$R_2 < C_4 + C_5$ $hR_1 < P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2)$ $M < N_1$
Intermediary organization choose to participate	$S_5(0, 0, 1)$	$(1-\rho)(P_2 \times E) + R_2 < R_1 + C_4 + jC_5$ $g[P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2)] \langle ghR_1$ $M > N_1$
	$S_6(0, 1, 1)$	$R_2 < C_4 + jC_5$ $ghR_1 < g[P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2)]$ $M > N_1$
	$S_7(1, 0, 1)$	$(1-\rho)(P_2 \times E) + R_2 > R_1 + C_4 + jC_5$ $g[P_1 \times E_1 + P_2 \times (E - E_1) - (C_1 + C_2)] \langle gR_1$ $M > N_1$
	$S_8(1, 1, 1)$	$C_4 + jC_5 < R_2$ $gR_1 < g[P_1 \times E_1 + P_2 \times (E - E_1) - (C_1 + C_2)]$ $M > N_1$

S_5, S_6, S_7, and S_8 show a diversity of organizational structures in the context of the rural PV cooperative introduced. To obtain high profits, ICO is the optimal strategy for the leading private enterprises to choose. To quickly enter the rooftop PV market and accumulate experience, small and medium-sized enterprises have chosen the C&O business mode, and gradually formed complementary cooperation with the state-owned enterprises in the industrial chain of upstream and downstream relations.

All types of firms find a better strategy choice in the tripartite game. The rooftop PV market will gradually form the state-owned enterprises, leading private enterprises, and small and medium-sized enterprises' win-win competition pattern. The various enterprises have their own responsibilities, with state-owned enterprises mainly acquiring assets, small and medium-sized enterprises responsible for implementing projects and undertaking downstream links such as construction and operation, and leading private enterprises transforming to the full industry chain coverage in terms of investment, construction and operation. There is a significant trend of industry integration. At the same time, as rural households have higher bargaining power after the rural PV cooperatives were involved, the profits of rural households will be improved, further enhancing the efficiency and equity of the organizational structure.

4.3. Comparative analysis for strategy choices and benefits of stakeholders before and after the participation of intermediary organization

From the perspective of behavioral strategy choices, the participation of rural PV cooperatives leads to the organizational structure to be more efficient, equitable, and diversified. The bridging role of rural PV cooperatives has led to clearer information communications between enterprises and rural households, reduced transaction cost, and more incentives for enterprises to participate in the project initially. When selecting investors, rural PV cooperatives take into account the income of rural households, and the positioning of state-owned enterprises and private enterprises is the same, which reduce the market entry cost of private enterprises, helping to create a fair business environment. Eventually, evolutionary stable strategies have increased from two to six. A diversified organizational structure and competitive layout of "enterprises mainly focusing on ICO or C&O mode, and rural households choosing to SIC or RL strategy" will be gradually formed.

From the perspective of benefits, the participation of rural PV cooperatives increases the expected profits of enterprises and rural households and total social welfare. Compare the evolutionary stable strategies D_1 *(0, 0)*, D_3 *(0, 1)* with $S_5(0, 0, 1)$ and $S_6(0, 1, 1)$. Rural PV cooperatives reduce the transaction cost, decrease the operating loss of enterprises, improve the overall bargaining level of rural households by the strength of integrating resources, and also enhance the economic benefits of rural households. In addition, rural PV cooperatives can generate income when they adopt the "participation" strategy. Thus, the increased benefits for enterprises, and rural households, and the net benefits gained by rural PV cooperatives in PV projects together lead to an increase in the total social welfare. (See Fig. 1.)

The key to the design of the organizational structure is to address incentive issues. By establishing or optimizing the mechanism of linking interests, the organizational structure is designed to balance the interests of different subjects, and finally achieve the overall goal of maximizing the total social welfare. The participation of an intermediary organization increases the expected profits of enterprises and rural households. If market entry cost is excluded, the enterprises adopt the business model that integrates investment, construction and operation is the most profitable, and ICO is a better strategy. Moreover, from the perspective of the overall operation of the PV market, the RL mode will lead to resource allocation in a sub-optimal balance and have Pareto improvement due to unclear rights and responsibilities and other issues, and therefore SIC is a better strategy. Thus, S_8 *(1, 1, 1)* is a more appropriate choice in the design of the organizational structure.

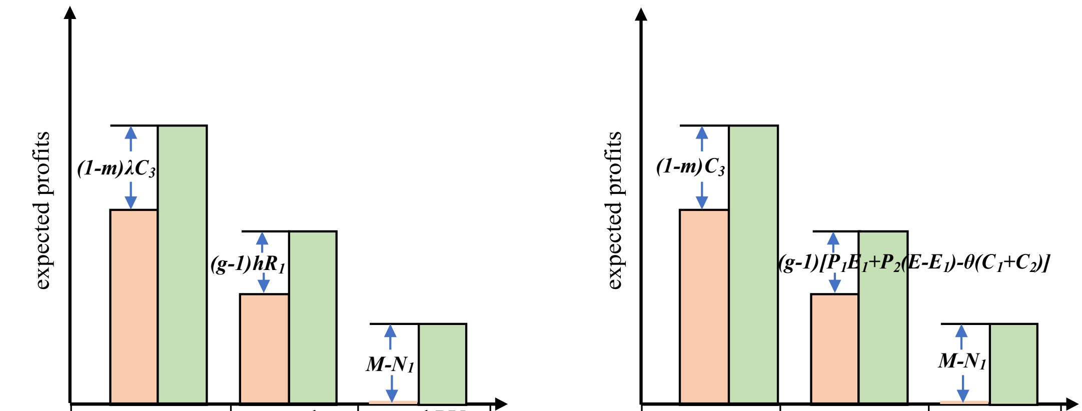
5. Simulation analysis

In the theoretical analyses above, six evolutionarily stable strategies are identified and can be realized under certain conditions. To show the evolutionary trajectory and explore the effective conditions for achieving the ESS, we simulate the six evolutionarily stable strategies and the sensitivity of the stakeholders to the relevant parameters using the MATLAB software.

5.1. Analysis of evolutionarily stable strategies

Scenario 1: The initial state is assumed to be 0.5 for enterprises, rural households and rural PV cooperatives. According to Table 6, when the conditions $(1-\rho)(P_2 \times E) + R_2 - R_1 - (C_4 + C_5) \langle 0$, $P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2) \langle hR_1$, and $M - N_1 < 0$ are satisfied, we assume $C_1 = 2$, $C_2 = 1$, $C_4 = 5$, $C_5 = 11$, $R_1 = 4$, $R_2 = 10$, $E = 15$, $E_1 = 3$, $P_1 = 0.50$, $P_2 = 0.30$, $M = 2$, $N_1 = 5$, $\rho = 0.5$, $h = 0.7$, and $\theta = 2$. The results are shown in Fig. 2(a1) and Fig. 2(a2), the final evolutionarily stable strategy is S_1 *(0, 0, 0)*, and the equilibrium was realized in descending order of speed for enterprises, rural households, and rural PV cooperatives, which indicates that the firm's group has a superior ability to learn and imitate than others. The reason for achieving S_1 is that when the income of rural PV cooperatives is lower than the cost of guiding and integrating, rural PV cooperatives lack the incentive to participate and fail to play a role in providing a fair business environment, resulting in lower profits for private enterprises choosing the ICO mode that covers the whole industry chain including investment, construction, and operation than the C&O mode that only undertakes the implementation links. Because rural households who choose to invest in the construction of their own household PV projects receive lower profits than rooftop leasing, the optimal strategies for enterprises, rural households, and rural PV cooperatives are C&O, RL and non-participation, respectively.

Scenario 2: When the conditions $R_2 - (C_4 + C_5) \langle 0$, $hR_1 < P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2)$, and $M - N_1 < 0$ are satisfied, assume $C_1 = 1$, $C_2 = 1$, $C_4 = 5$, $C_5 = 11$, $R_1 = 1$, $R_2 = 10$, $E = 15$, $E_1 = 3$, $P_1 = 0.50$, $P_2 = 0.30$, $M = 2$, $N_1 = 5$, $h = 0.7$, and $\theta = 1.2$. The results are shown in Fig. 2(b1) and Fig. 2(b2), and the final evolutionarily stable strategy is S_3 *(0, 1, 0)*. Firms achieve the equilibrium state first and rural households are the slowest to achieve equilibrium. The enterprises and rural PV cooperatives chose this strategy for reasons similar to Scenario 1. When the profits brought by "self-generation, surplus electricity feed-in" are higher, rural households who choose the SIC strategy will earn more than RL strategy. Without the participation of rural PV cooperatives, rural household groups have poor learning ability and weak incentives



	enterprises	rural households	rural PV cooperatives
$D_1(0,0)$	$\rho(P_2\times E)$-$(C_1+C_2+\lambda C_3)$	hR_1	0
$S_5(0,0,1)$	$\rho(P_2\times E)$-$(C_1+C_2+\lambda mC_3)$	ghR_1	M-N_1

	enterprises	rural households	rural PV cooperatives
$D_3(0,1)$	C_1+C_2-C_3	$P_1E_1+P_2(E$-$E_1)$-$\theta(C_1+C_2)$	0
$S_6(0,1,1)$	C_1+C_2-mC_3	$g[P_1E_1+P_2(E$-$E_1)$-$\theta(C_1+C_2)]$	M-N_1

Fig. 1. Comparative analysis for benefits to stakeholders.

to choose SIC strategy. The optimal strategies for the enterprises, rural households, and rural PV cooperatives are C&O, SIC, and non-participation respectively.

Scenario 3: When the conditions $(1-\rho)(P_2\times E)+\ R_2-\ R_1-(C_4+jC_5)\langle 0$, $g[P_1\times E_1+P_2\times(E-E_1)-\theta(C_1+C_2)]\langle ghR_1$, and $M-N_1>0$ are satisfied, assume $C_1=2$, $C_2=1$, $C_4=5$, $C_5=11$, $R_1=7$, $R_2=10$, $E=15$, $E_1=3$, $P_1=0.50$, $P_2=0.30$, $M=10$, $N_1=5$, $\rho=0.5$, $h=0.7$, $\theta=2$, $g=1.5$, and $j=0.8$. The results are shown in Fig. 2(c1) and Fig. 2(c2), where each evolutionary trajectory converges to S_5 *(0, 0, 1)*. With the significant increase in development income, rural PV cooperatives tend to choose the participation strategy. Due to a large amount of initial capital investment, small and medium-sized enterprises chose the C&O business mode to quickly enter the rooftop PV market and accumulate experience, and undertake the construction and operation of implementation links. In addition, the participation of rural PV cooperatives has accelerated the rate of equilibrium achieved in rural households, indicating that PV cooperatives can play an important role in guiding rural households and strengthen their ability to learn and imitate. When rural households earn less than the rooftop lease by investing in the construction of household PV projects, the optimal strategies of enterprises, rural households, and rural PV cooperatives are C&O, RL, and participation, respectively.

Scenario 4: When the conditions $R_2-\ (C_4+jC_5)\langle 0$, $ghR_1<g[P_1\times E_1+P_2\times(E-E_1)-\theta(C_1+C_2)]$, and $M-N_1>0$ are satisfied, we assume $C_1=1$, $C_2=1$, $C_4=7$, $C_5=11$, $R_1=1$, $R_2=4$, $E=20$, $E_1=3$, $P_1=0.50$, $P_2=0.30$, $M=10$, $N_1=5$, $h=0.7$, $\theta=1.2$, $g=1.5$, and $j=0.8$. The results are shown in Fig. 2(d1) and Fig. 2(d2), and the final evolutionarily stable strategy is S_6 *(0, 1, 1)*. The equilibrium between firms and rural households is achieved at a faster pace when PV cooperatives come in. Firms reach equilibrium around the time point of 0.5 and rural households reach equilibrium around the time point of 1. Enterprises and rural PV cooperatives choose this strategy similar to Scenario 3, SIC will be the optimal strategy for rural households when "self-generation, surplus electricity feed-in" brings higher returns.

Scenario 5: When the conditions $(1-\rho)(P_2\times E)+\ R_2-\ R_1-(C_4+jC_5)\rangle 0$, $g[P_1\times E_1+P_2\times(E-E_1)-(C_1+C_2)]\langle gR_1$, and $M-N_1>0$ are satisfied, assume $C_1=3$, $C_2=4$, $C_4=5$, $C_5=5$, $R_1=4$, $R_2=15$, $E=15$, $E_1=3$, $P_1=0.50$, $P_2=0.30$, $M=10$, $N_1=5$, $\rho=0.5$, $g=1.5$, and $j=0.1$. The results are shown in Fig. 2(e1) and Fig. 2(e2), where each evolutionary trajectory converges to S_7 *(1, 0, 1)*. Rural households and rural PV cooperatives choose their strategies for reasons similar to Scenario 3. As rural PV cooperatives choose their investors, they have the same positions of state-owned enterprises and private enterprises, which reduces the market entry cost of private enterprises. Thus, to obtain high profits and high-quality assets, ICO strategy becomes the optimal choice for the leading private enterprises.

Scenario 6: When the conditions $R_2-\ (C_4+jC_5)\rangle 0$, $gR_1<g[P_1\times E_1+P_2\times(E-E_1)-(C_1+C_2)]$, and $M-N_1>0$ are satisfied, assume $C_1=1$, $C_2=1$, $C_4=7$, $C_5=5$, $R_1=1$, $R_2=15$, $E=20$, $E_1=3$, $P_1=0.50$, $P_2=0.30$, $M=10$, $N_1=5$, $g=1.5$, and $j=0.1$. The results are shown in Fig. 2(f1) and Fig. 2(f2), and the final evolutionarily stable strategy is S_8 *(1, 1, 1)*. The firm group has a superior ability to learn and imitate than others, and the equilibrium was realized in descending order of speed for enterprises, rural PV cooperatives and rural households. The enterprises and rural PV cooperatives choose this strategy for reasons similar to scenario 5. As the profits from self-investment in constructing household PV projects increase, the final optimal strategies for enterprises, rural households, and rural PV cooperatives are ICO, SIC, and participation.

5.2. Sensitivity analysis

To maximizing the social welfare, S_8 *(1, 1, 1)* is a more appropriate choice in the design of the organizational structure. Therefore, it is necessary to explore the sensitivity of stakeholders in S_8 *(1, 1, 1)*, and to compare the effects of costs control, electricity prices, solar resources, and asset returns on the strategies of enterprises, residents, and rural PV cooperatives at different values, to derive the effective conditions for achieving this ideal evolutionarily stable strategy.

5.2.1. The effect of costs control on investment intention

The costs of rural households with PV cover fixed costs such as equipment investment and variable costs such as installation, operation cost, guiding and integrating costs, and market entry barriers. According to the China PV Industry Development Roadmap, the average annual investment cost of PV equipment (C_4) is RMB 3244 (discount rate of 8%), the average annual construction cost (C_1) is RMB 373, and the average annual operation cost (C_2) is RMB 510, according to the 25-year conversion to each year (Wang et al., 2021b). Limited by data availability, market entry cost (C_5) and guiding and integrating costs (N_1) will be simulated by numerical assumptions for sensitivity analysis. Different values of costs are set separately and substituted into the

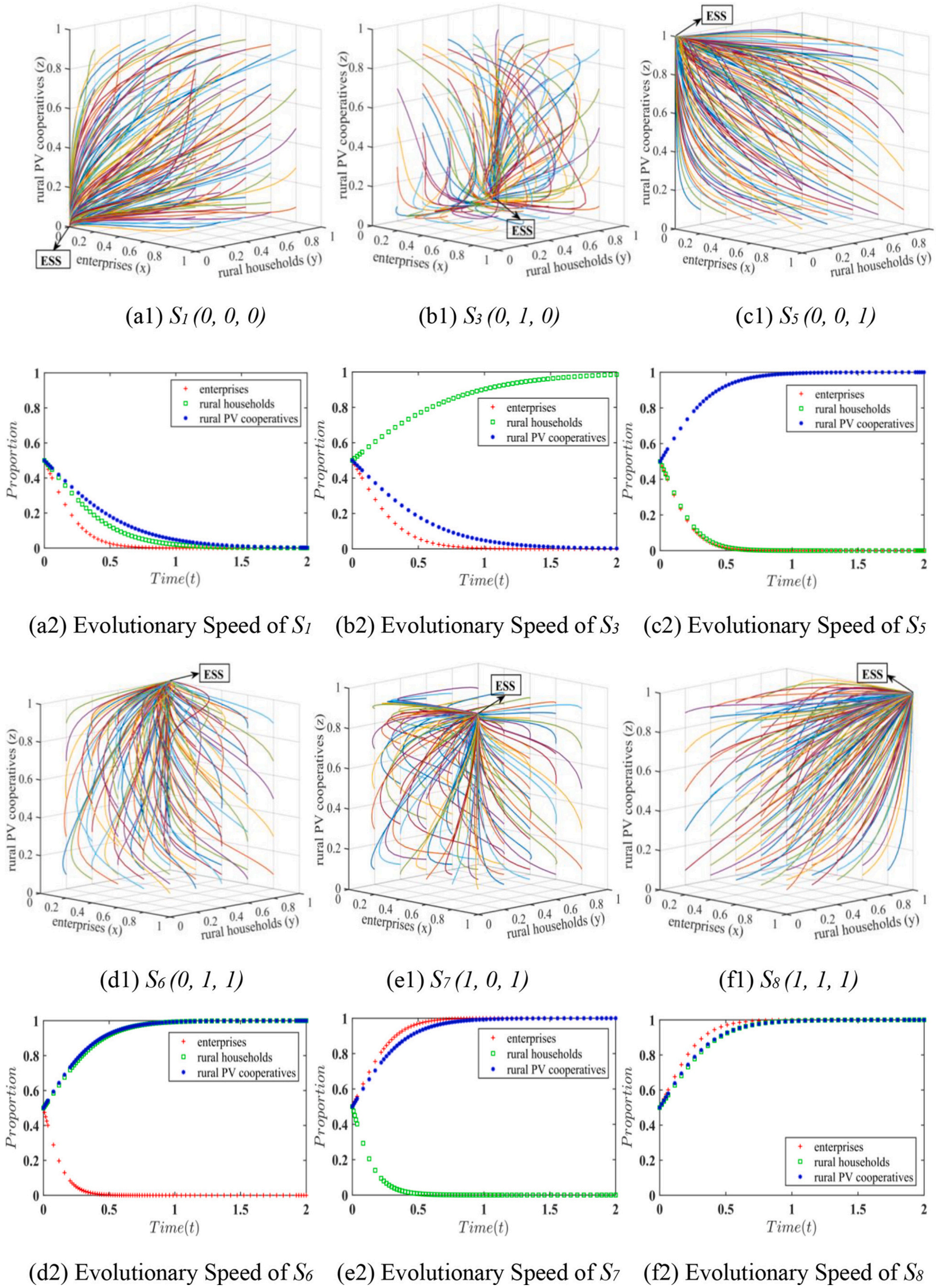


Fig. 2. Six evolutionarily stable strategies.

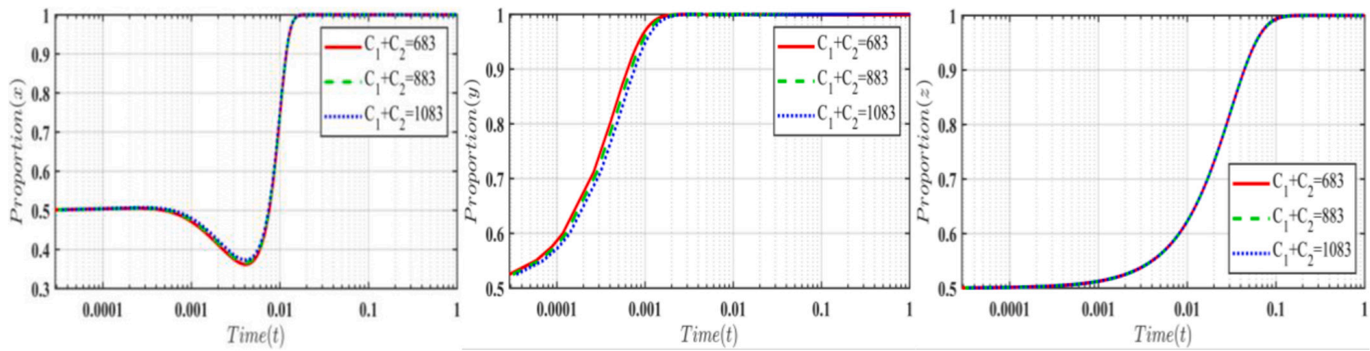


Fig. 3. Equilibrium evolution under changes in construction cost *(C_1)* and operation cost *(C_2)*.

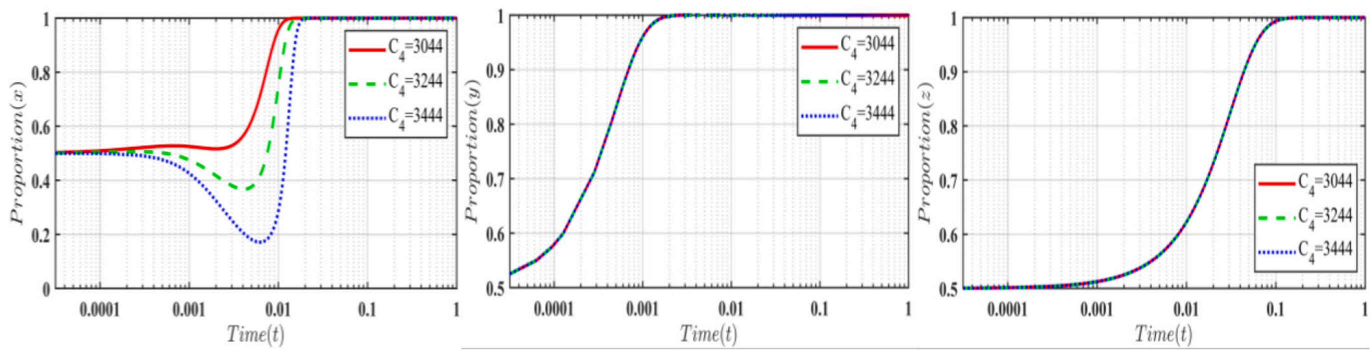


Fig. 4. Equilibrium evolution under changes in investment cost *(C_4)*.

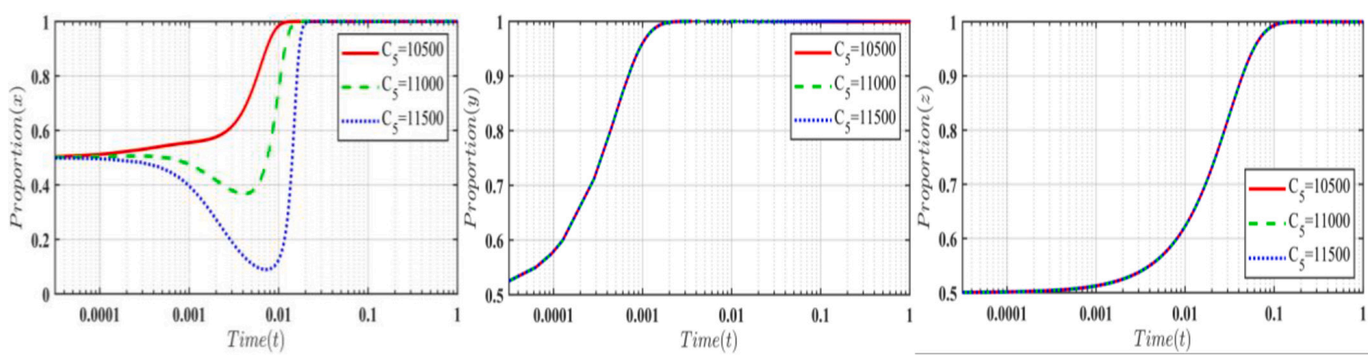


Fig. 5. Equilibrium evolution under changes in market entry cost *(C_5)*.

tripartite game model. The cost control is one of the effective ways to achieve Pareto improvement, and the influence of different types of cost changes on stakeholders' willingness to invest is different. The strategy choice of enterprises is mainly influenced by investment cost *(C_4)*, market entry cost *(C_5)*, and guiding and integrating costs *(N_1)*. As the investment cost *(C_4)* and market entry cost *(C_5)* increase, ICO strategy choice does not change, but the time to reach the stable state will be extended. The strategic choice of enterprises will gradually change to C&O mode as the cost of guiding and integrating costs *(N_1)* increases. The strategy choice of rural households is mainly influenced by the construction cost *(C_1)* and operation cost *(C_2)*, and the reduction of both will increase the willingness of rural households to choose SIC strategy. The strategy choice of rural PV cooperatives is influenced by the cost of guiding and integrating costs *(N_1)*. A higher cost is more likely to lead to "non-participation". Affected by the level of technology, equipment investment, and other fixed costs are limited by the decline in space. Local governments should adopt distinguished cost control measures, from installation and operation cost, guiding and integrating costs, market entry barriers, and other soft costs to strengthen the construction of rural household PV market system, to achieve the efficient equilibrium. (See Fig. 3-6)

5.2.2. *The effect of electricity price changes on investment intention*

Stakeholders are not only influenced by the feed-in tariff *(P_2)* but also by the electricity price in their region *(P_1)* when participating in a household PV project. According to the national electricity price monitoring system, the residential living electricity price in the suburbs of Beijing, for example, is 0.49 RMB/(KW-h), 0.54 RMB/(KW-h) and 0.79 RMB/(KW-h) respectively for the step electricity price in the area. According to the requirements of the PV subsidy withdrawal policy, the feed-in tariff *(P_2)* in Beijing is implemented according to the local coal-fired benchmark tariff, which would be RMB 0.36/(KW-h) in 2022. Different values of electricity prices are set separately and substituted into the tripartite game model. The feed-in tariff *(P_2)* and the electricity price in the area *(P_1)* have a positive impact on the investment decisions of rural households, i.e., a higher the electricity price increase leads to a

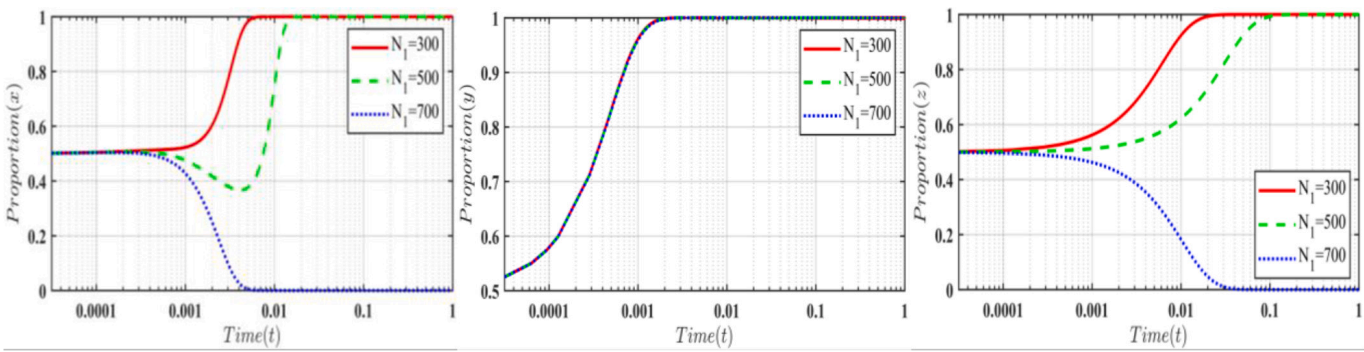


Fig. 6. Equilibrium evolution under changes of guiding and integrating costs *(N_1)*.

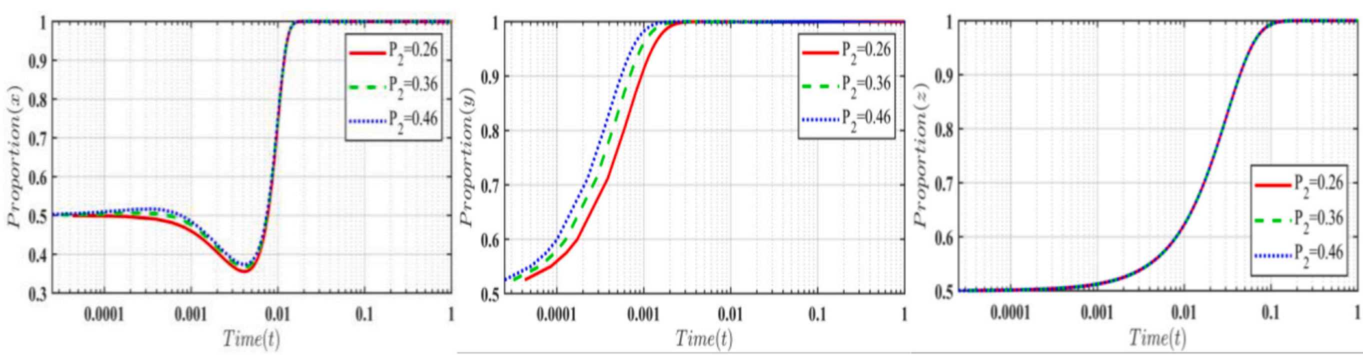


Fig. 7. Equilibrium evolution under changes of FIT *(P_2)*.

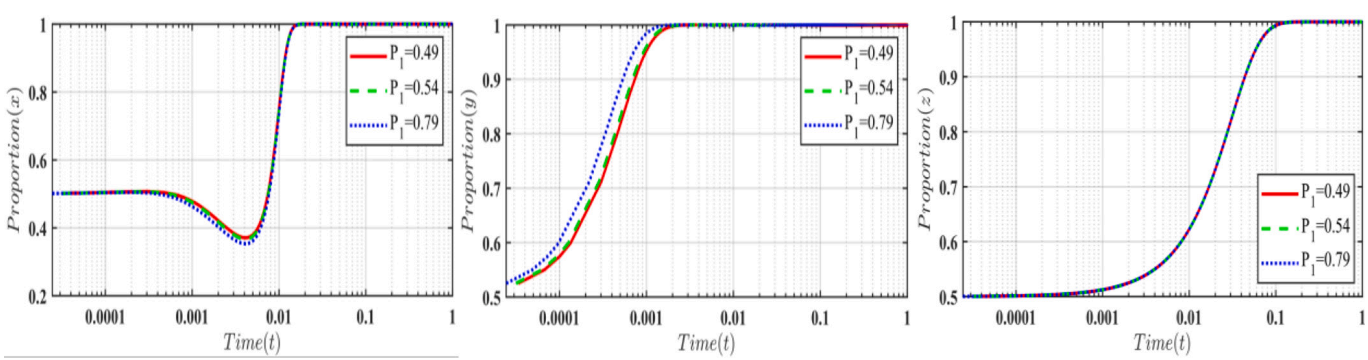


Fig. 8. Equilibrium evolution under changes in electricity price in the local area *(P_1)*.

faster the convergence rate for the rural households. The strategic choice of enterprises is also influenced by the feed-in tariff *(P_2)*. Since rural households usually generate more electricity than they consume, the electricity surplus will bring direct benefits to rural households. The feed-in tariff, which is linked to the balance of electricity, becomes a key factor affecting rural households' income. A higher the feed-in tariff will lead to more economic benefits of installing PV for rural households, which increase the demand in the rural PV market and effectively boost the supply rate of enterprises. On the other hand, the installation of household PV not only brings income from power generation but also forms benefits from electricity savings for rural households, which is positively correlated with the increase of electricity prices in the local area. As a result, a reasonable upward adjustment of the feed-in tariff *(P_2)* and the electricity price in the local area *(P_1)* will accelerate the advancement of the efficient equilibrium. (See Fig. 7 and 8)

5.2.3. The effect of solar resources on investment intention

China is a vast country with significant differences in solar resources endowment among regions, which will affect the investment decisions of stakeholders to a certain extent. According to the solar resource conditions in various regions, China divides solar resource zones into three categories. In this paper, by selecting typical cities in three resource zones, that is, Zhangye, Gansu (Class I), Beijing (Class II), and Hangzhou, Zhejiang (Class III), and using peak sunshine hours, based on 240 days of annual power generation (20 days of monthly power generation), the actual annual power generation *(E)* of a 10KW rooftop PV system installed in each of the three resource zones is calculated according to 90% power generation efficiency and substituted into a tripartite game model. The actual annual electricity production *(E)* has a significant positive impact on rural households' investment intention, with a near-zero impact on enterprises and rural PV cooperatives, showing that a richer the light resource endowment leads to a faster convergence of rural households' choice to invest. (See Fig. 9)

5.2.4. The effect of asset returns on investment intention

Asset returns are a necessary factor considered by the players in strategy selection. We set different values of potential asset value-added return *(R_2)* and development return *(M)* respectively, and substitute

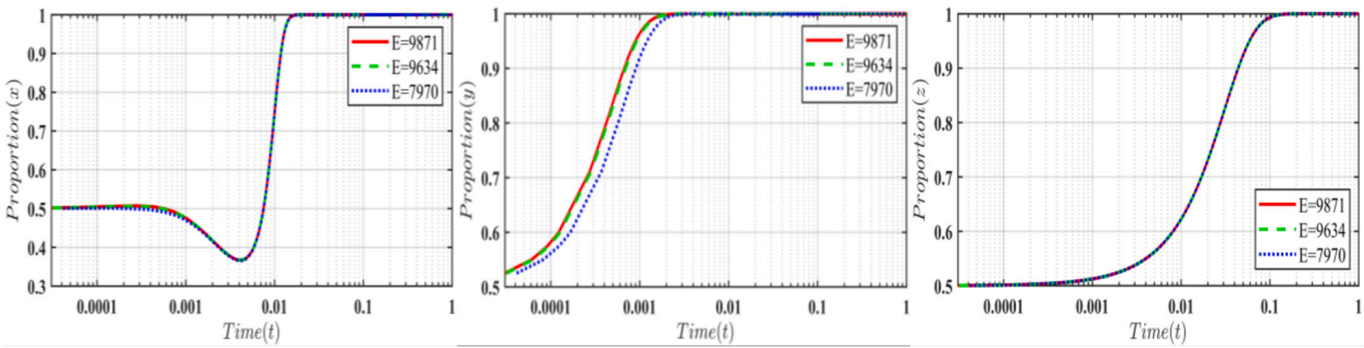


Fig. 9. Equilibrium evolution under changes of actual annual generation *(E)*.

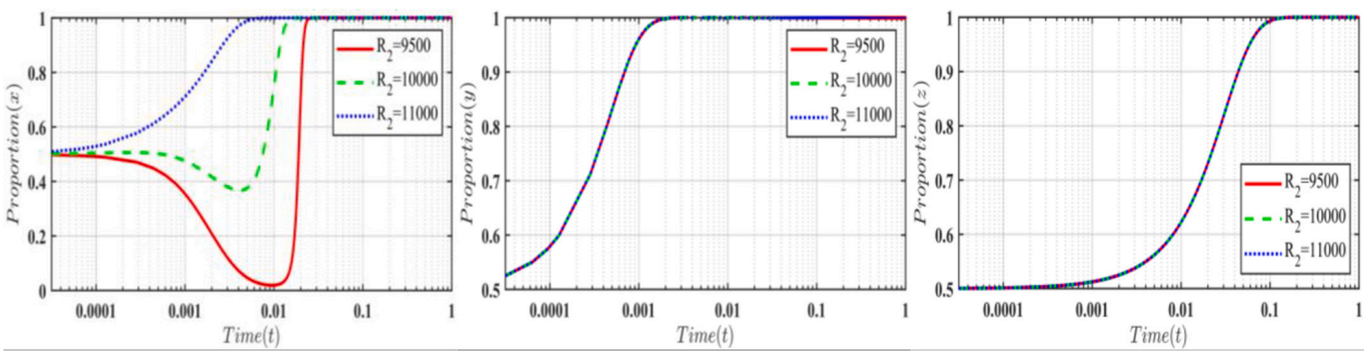


Fig. 10. Equilibrium evolution under changes of potential asset value-added income *(R_2)*.

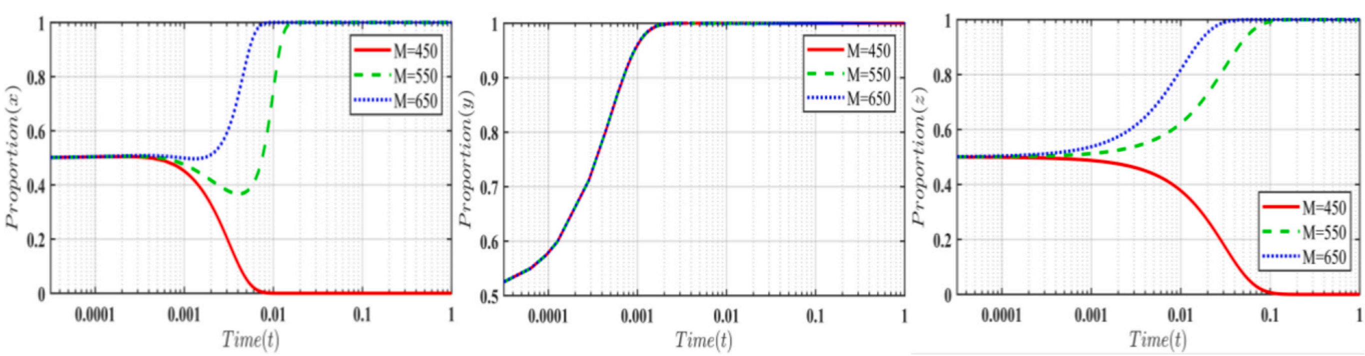


Fig. 11. Equilibrium evolution under changes of development revenue *(M)*.

them into the tripartite game model. Given the data limitations, the parameters can be set based on theoretical analysis and empirical outcomes. The investment intention of rural PV cooperatives depends more on the development revenue *(M)*, and the choice will gradually change to the "participation" strategy as the development revenue *(M)* increases. Enterprises may invest, construct and operate the whole process to obtain long-term and stable potential asset value-added income *(R_2)*, so it has an obvious positive impact on their investment decisions. In addition, the strategy choice of enterprises is also influenced by the development revenue *(M)*, which gradually changes to C&O mode as the development revenue *(M)* decreases. This result further indicates that the existence of rural PV cooperatives plays a significant role in the enterprise's choice process. (See Fig. 10 and 11)

6. Discussion

6.1. Applicability of our model

In the bipartite game as an example, the strategic choices and payoffs of rural households and enterprises are not symmetrical, and thus it is a bipartite asymmetric game. According to the payoff matrix and expected profits in Tables 1 and 2, there is only one Nash equilibrium strategy in different scenarios. When rural households are more gainful by choosing the SIC strategy than the RL strategy, it is a Nash equilibrium for enterprises to choose the ICO strategy and rural households to choose the SIC strategy, conversely, {C&O, RL} is a Nash equilibrium.

We discuss the process for the game subjects with bounded rationality. Assume that the proportion of enterprises adopting the ICO strategy is x, and the proportion of rural households adopting the SIC strategy is y. The expected payoffs and average expected payoff of enterprises are shown in Eqs. (2)–(4), respectively. The expected payoffs and average expected payoff of rural households can be obtained similarly and the detailed calculations and presented by Eqs. (B.5)-(B.7) in Appendix B. After obtaining replicator dynamics equations for enterprises and rural households respectively (i.e., Eqs. (5)–(6)), we find that dx/dt is zero for enterprises only for $x^* = 0$ and 1 according to assumption 1, and dx/dt is less than zero for all other conditions. According to the characteristics of an evolutionarily stable strategy (ESS), it must be stable in addition to being in an equilibrium. When subjects deviated from the ESS by chance, the replicator dynamic can still drive x to move towards x^*. The ESS requires that the derivative of dx/dt must be <0. The phase plot in Fig. 12 gives the dynamic trend and stability of x. For rural households, if $x = x^*$, then dy/dt is always 0, which means that all y levels are stable states, and if $x \neq x^*$, then $y^* = 0$ and $y^* = 1$ are two stable states. When rural households choose the SIC strategy to earn more than the RL, $y^* = 0$ is ESS for $x > x^*$, and $y^* = 1$ is ESS for $x < x^*$. Conversely, $y^* = 1$ is ESS for $x > x^*$, and $y^* = 0$ is ESS for $x < x^*$. The phase plots in Fig. 13 give the dynamic trend and stability of y for the two cases mentioned above, respectively.

The replicator dynamic process of the proportional change for both groups (enterprises and rural households) is represented in Fig. 14. The evolutionarily stable strategies have two points i.e., $x^* = 0, y^* = 1$ and $x^* = 0, y^* = 0$, and other points have no convergence and stability. This means that the game subjects with bounded rationality finally choose either {C&O, SIC} or {C&O, RL} strategy after the process of learning, repeatedly playing and adjusting their strategies. This also shows that in the pure strategy game, the ESS are obtained from the evolutionary game analysis is the same as the Nash equilibrium in the perfectly rational game, and subjects with bounded rationality are still able to achieve efficient strategy choices through learning and adjustment. The ESS has the robustness regarding the rational limitations of game subjects and small disturbances.

The dynamic process, uncertainty, and group behavior emphasized by the evolutionary game theory are sufficient to prove the rationality for analyzing stakeholders' behavioral strategies by using the evolutionary game model. Traditional game analysis fails to simulate realistic changes and uncertainties, and only reflects individual behavior decisions, making it difficult to predict long-term situations. The evolutionary game relaxes the assumption of the traditional game with perfect rationality. From the perspective of adaptability and dynamic evolution, the key to evolutionary game analysis is not the optimal strategy choices of stakeholders, but the strategy adjustment process and stability of bounded rational group members, which is reflected by group members' proportions (x, y, z). Evolutionary games focus on how uncertainty factors may influence the results, where uncertainty factors include potential changes in strategy choices and strategy gains from the game players. Thus, evolutionary games reveal long-term complex economic relationships by emphasizing the process of adaptability and dynamic evolution. Under uncertainty factors, the evolutionary results may highlight sub-optimal solutions which deserve our attention.

6.2. Comparison with existing literature

Existing studies concentrate on the development and evaluation of household PV incentive policies. These studies mostly analyze incentive policy formulation from an individual perspective, focusing on the production or consumption aspects. However, previous literature tends to overlook the conflicting interests between supply and demand and within the supply side. To maximize project benefits, it is crucial to address the incentive issues among individuals through organizational structure design. Previous studies have also explored the role of government in the vertical collaboration model. There is a need to address the information asymmetry between rural households and enterprises arising from government participation in household PV projects, and the potential inequality arising from government giving priority to state-owned enterprises. This paper proposes an innovative horizontal cooperative organizational structure incorporating rural cooperatives where the rural households may be members of the cooperative and have stronger decision-making power in the transaction. Rural cooperatives do not exhibit a clear bias towards the selection of investors and builders, which fosters a more equitable market environment.

In terms of research methodology, previous studies have primarily utilized a tripartite evolutionary game model to examine the dynamics of stakeholders. This approach lacks intuitive analysis regarding the influence of a third party on the behavioral strategies of stakeholders. To address this limitation, we propose a bipartite and a tripartite evolutionary game model to analyze the strategies and benefits of enterprises and rural households within rural PV cooperatives, which allows for a more comprehensive understanding of the changes in strategies and benefits.

Our research findings highlight the importance of implementing targeted policies to promote rural household PV adoption, consistent with current policy emphasized by the National Energy Administration. The administration has underscored the need to avoid the misconception of a uniform approach ("one size fits all") and monopoly in county-wide promotion policies. We explore an intensive development model for DPV that aligns with the specific regional development context, which encourages the promotion of rural household PV in a region-specific manner to match with the socioeconomic development of the region. Nonetheless, the evolutionary game model still has certain limitations and potential shortcomings. One notable limitation arises from the lack of realistic data support for certain parameters, such as market entry costs. Consequently, our analysis primarily relies on theoretical model and numerical simulations. Further empirical analysis would provide valuable insights into the practical application and validity of the model. We recognize this limitation and view it as an area for future improvement.

7. Conclusion

This paper constructs a bipartite evolutionary game model for the development of household PV under the "enterprises + rural households" model and a tripartite evolutionary game model with the additional inclusion of rural PV cooperatives. Based on the evolutionary equilibrium results comparing the strategy choices and benefit changes for enterprises and rural households before and after the participation of rural PV cooperatives, and discussing the effects of different parameter changes on the ideal equilibrium strategy.

Our results show that the rural PV cooperatives can provide a fair business environment in the rural household PV market by reducing the transaction cost and increase the diversification of enterprises' strategic choices. The rural PV cooperatives can also improve the bargaining power of rural households, contribute to an efficient, fair, and diversified organizational structure. The market changed from a two-party monopoly in which state-owned enterprises took the lead and large private enterprises were responsible for construction to a three-party competitive layout involving state-owned enterprises, large private enterprises, and small and medium-sized enterprises. The horizontal cooperation model in the household PV market mitigates the imperfect competition, reduces distortions in the price mechanism, and achieves efficient resource allocation.

After the participation in the rural PV cooperatives, the expected

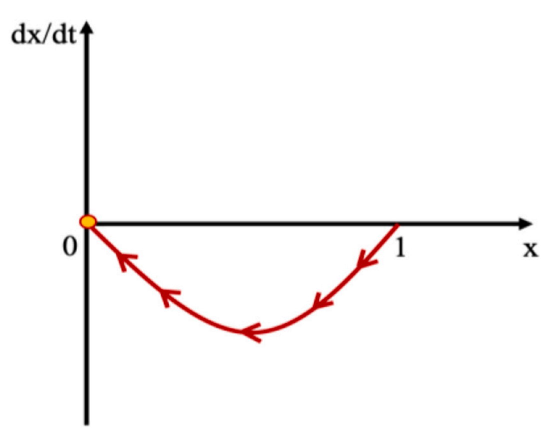


Fig. 12. Replicator dynamic phase plot of the enterprises.

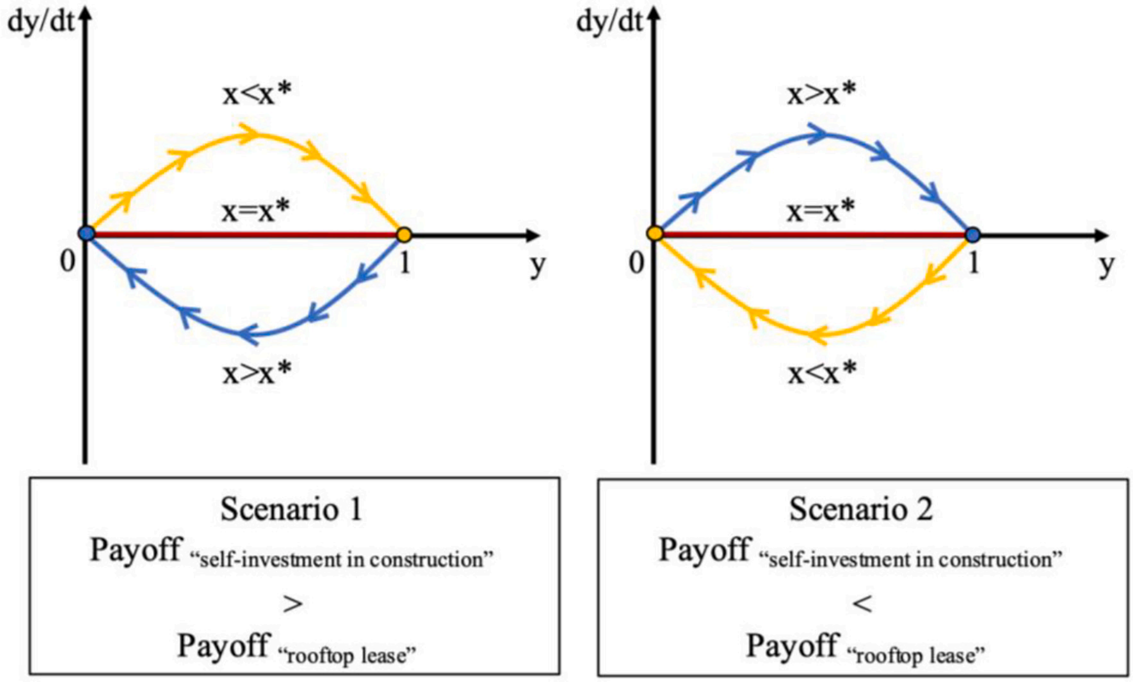


Fig. 13. Replicator dynamic phase plot of the rural households.

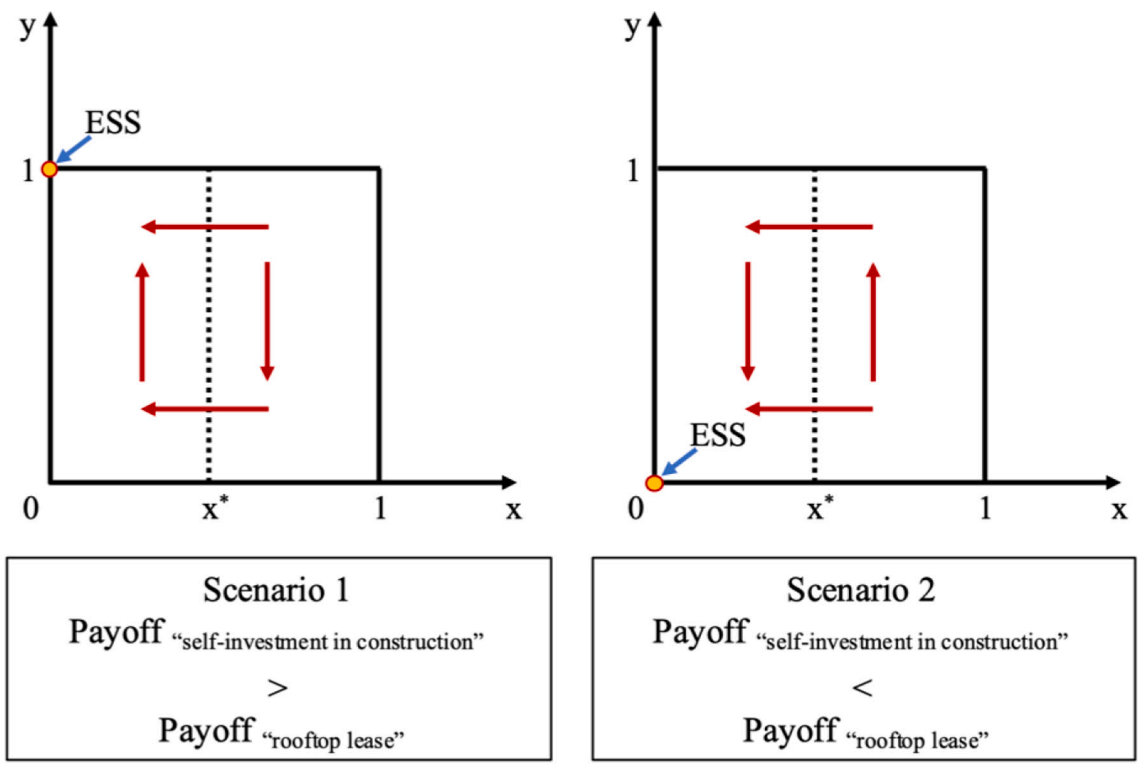


Fig. 14. The replicator dynamics relationship and stability of enterprises and rural households.

profits of enterprises, rural households, and the total social welfare increase significantly. *S8 (1, 1, 1)* is a more appropriate choice in the design of the organizational structure. The design of the organizational structure fosters participation incentives among stakeholders. By choosing to self-invest and construct household PV systems, rural households can effectively address the issue of unclear responsibilities, leading to potential Pareto improvements. From the perspective of enterprises, different types of DPV systems entail varying interests and maintenance requirements. State-owned enterprises are influenced by factors such as location, scale, and system complexity, making it challenging to cater to individual demands. Private enterprises, on the other hand, can overcome these limitations. Consequently, the household PV market necessitates collaboration between state-owned enterprises and private enterprises. However, the role of private enterprises should not be limited to undertaking downstream activities such as installation and maintenance. The market would determine the division of labor based on the diverse types and sizes of enterprises, thereby establishing a competitive market environment.

The cost control, electricity price changes, solar resources, and asset returns all have significant and differential effects on stakeholders' investment intentions. For the regions with abundant solar resources, enterprises can promote the ideal equilibrium by effectively controlling investment cost *(C_4)*, market entry cost *(C_5)* and guiding and integrating costs *(N_1)*, reasonably increasing the feed-in tariff *(P_2)*, and enhancing the potential asset value-added returns *(R_2)* and intermediary organization development revenue *(M)*. Rural households can achieve Pareto improvement by controlling construction cost *(C_1)* and operation cost *(C_2)*, and moderately increasing feed-in tariffs (P_2) and electricity prices in their areas *(P_1)*. Intermediary organization can achieve ideal equilibrium by saving guiding and integrating costs *(N_1)* and improving development revenue *(M)*. In the regions where solar resources are scarce, rural households reach the ideal equilibrium more slowly, thus it is important to implement distinguished regional subsidy policies according to different light resource areas.

Based on our results, it is important to develop rural photovoltaic cooperatives with rooftop equity, and actively explore the cooperative business and integrate individual rural households into the collective asset shares. The local government can increase the publicity of household PV, strengthen the skills training for rural households, and prompt rural households to be able to properly handle the common problems of household PV systems. Additionally, it is beneficial to encourage the establishment of more local PV operation and maintenance enterprises, which will generate additional employment opportunities and enhance the economic benefits for rural households.

CRediT authorship contribution statement

Xiaoning Su: Methodology, Data curation, Writing – original draft. **Pengfei Liu:** Conceptualization, Methodology, Writing – review & editing. **Yingdan Mei:** Conceptualization, Methodology, Writing – review & editing. **Jiaru Chen:** Writing – review & editing.

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Appendix A. Nomenclature

Abbreviations

PV	photovoltaic
DPV	distributed photovoltaic
ICO	investment, construction, and operation
C&O	construction and operation
SIC	self-investment and construction
RL	rooftop leases
ESS	evolutionary stable strategy
Parameters	
x	proportion of enterprises choosing the ICO strategy
y	proportion of rural households choosing the SIC strategy
z	proportion of rural PV cooperatives choosing to participate
C_1	household PV construction cost
C_2	operation cost
C_3	transaction cost
C_4	investment cost
C_5	market entry cost
P_1	electricity price in the area of rural households
P_2	price of the feed-in tariff
E	the annual electricity generation capacity of household PV
E_1	the annual electricity consumption of rural households
R_1	rooftop rent
R_2	potential value-added assets gains
M	the development revenue received by the rural PV cooperatives
N_1	the guiding and integrating costs paid by the rural PV cooperatives
λ	transaction cost coefficient
ρ	feed-in tariff revenue share coefficient
θ	cost control coefficient
h	income control coefficient
g	profit effect coefficient
m	transaction cost effect coefficient
j	market entry cost effect coefficient

Appendix B. Replicator dynamic equations for solving processes

B.1. Bipartite evolutionary stable analysis

Assume that the expected payoff is UA_1 when the enterprises choose the ICO strategy and UA_2 when they choose the C&O strategy. The expected payoff of the enterprises when choosing the ICO strategy *(UA_1)* is (See Eq. (B.1)):

$$\begin{aligned}UA_1 &= y\varphi_1 + (1-y)\varphi_2 = y(C_1 + C_2 + R_2 - C_3 - C_4 - C_5) + (1-y)(P_2 \times E + R_2 - R_1 - C_1 - C_2 - \lambda C_3 - C_4 - C_5) \\ &= (2y-1)(C_1 + C_2) + R_2 - [y(1-\lambda) + \lambda]C_3 - C_4 - C_5 + (1-y)P_2 \times E - (1-y)R_1\end{aligned} \tag{B.1}$$

The expected payoff for the enterprises in choosing the C&O strategy *(UA_2)* is (See Eq. (B.2)):

$$UA_2 = y\varphi_3 + (1-y)\varphi_4 = y(C_1 + C_2 - C_3) + (1-y)(\rho P_2 \times E - C_1 - C_2 - \lambda C_3) = (2y-1)(C_1 + C_2) - [y(1-\lambda) + \lambda]C_3 + (1-y)\rho P_2 \times E \tag{B.2}$$

the average expected payoff of the enterprises *($\overline{UA}$)* is (See Eq. (B.3)):

$$\overline{UA} = xUA_1 + (1-x)UA_2 \tag{B.3}$$

The replicator dynamic equation for the enterprises' choice of ICO strategy is (See Eq. (B.4)):

$$F(x) = \frac{dx}{dt} = x(UA_1 - \overline{UA}) = x(1-x)(UA_1 - UA_2) = x(1-x)[R_2 - C_4 - C_5 + (1-y)(1-\rho)P_2 \times E - (1-y)R_1] \tag{B.4}$$

Assuming that the expected payoff for rural households is UB_1 when they choose the SIC strategy and UB_2 when they choose the RL strategy. The expected payoff for rural households in choosing the SIC strategy *(UB_1)* is:

$$\begin{aligned}UB_1 &= x\tau_1 + (1-x)\tau_3 = x[P_1 \times E_1 + P_2 \times (E - E_1) - (C_1 + C_2)] + (1-x)[P_1 \times E_1 + P_2 \times (E - E_1) - \theta(C_1 + C_2)] \\ &= P_1 \times E_1 + P_2 \times (E - E_1) - [x(1-\theta) + \theta](C_1 + C_2)\end{aligned} \tag{B.5}$$

The expected payoff for rural households in choosing the RL strategy *(UB_2)* is:

$$UB_2 = x\tau_2 + (1-x)\tau_4 = xR_1 + (1-x)hR_1 = [x(1-h) + h]R_1 \tag{B.6}$$

The average expected payoff of the rural households *($\overline{UB}$)* is:

$$\overline{UB} = yUB_1 + (1-y)UB_2 \tag{B.7}$$

The replicator dynamic equation for the rural households' choice of SIC strategy is (See Eq. (B.8)):

$$F(y) = \frac{dy}{dt} = y(UB_1 - \overline{UB}) = y(1-y)(UB_1 - UB_2) = y(1-y)\{P_1 \times E_1 + P_2 \times (E - E_1) - [(1-\theta)x + \theta](C_1 + C_2) - [(1-h)x + h]R_1\} \tag{B.8}$$

B.2. Tripartite evolutionary stable analysis

Assume that the expected payoff is UC_1 when the enterprises choose the ICO strategy and UC_2 when they choose the C&O strategy. The expected payoff of the enterprises when choosing the ICO strategy *(UC_1)* is (See Eq. (B.9)):

$$UC_1 = (1-z)[y\varphi_1 + (1-y)\varphi_2] + z[y\varphi_5 + (1-y)\varphi_6] = (2y-1)(C_1 + C_2) + R_2 - C_4 + (1-y)(P_2 \times E - R_1) - [1 - z(1-m)][y(1-\lambda) + \lambda]C_3 - [1 - z(1-j)]C_5 \tag{B.9}$$

The expected payoff for the enterprises in choosing the C&O strategy *(UC_2)* is (See Eq. (B.10)):

$$UC_2 = (1-z)[y\varphi_3 + (1-y)\varphi_4] + z[y\varphi_7 + (1-y)\varphi_8] = (2y-1)(C_1 + C_2) + (1-y)\rho(P_2 \times E) - [1 - z(1-m)][y(1-\lambda) + \lambda]C_3 \tag{B.10}$$

The average expected payoff of the enterprises *($\overline{UC}$)* is (See Eq. (B.11)):

$$\overline{UC} = xUC_1 + (1-x)UC_2 \tag{B.11}$$

The replicator dynamic equation for the enterprises' choice of ICO strategy is (See Eq. (B.12)):

$$F(x) = \frac{dx}{dt} = x\,(UC_1 - \overline{UC}) = x(1-x)(UC_1 - UC_2) = x(1-x)\{R_2 - C_4 - (1-y)R_1 + (1-y)(1-\rho)(P_2 \times E) - [1 - z(1-j)]C_5\} \tag{B.12}$$

Assuming that the expected payoff for rural households is UD_1 when they choose the SIC strategy and UD_2 when they choose the RL strategy. The expected payoff for rural households in choosing the SIC strategy *(UD_1)* is (See Eq. (B.13)):

$$UD_1 = (1-z)[x\tau_1 + (1-x)\tau_3] + z[x\tau_5 + (1-x)\tau_7] = [1 - z(1-g)]\{P_1 \times E_1 + P_2 \times (E - E_1) - (C_1 + C_2)[x(1-\theta) + \theta]\} \tag{B.13}$$

The expected payoff for rural households in choosing the RL strategy *(UD_2)* is (See Eq. (B.14)):

$$UD_2 = (1-z)[x\tau_2 + (1-x)\tau_4] + z[x\tau_6 + (1-x)\tau_8] = [1 - z(1-g)][x(1-h) + h]R_1 \tag{B.14}$$

the average expected payoff of the rural households *($\overline{UD}$)* is (See Eq. (B.15)):

$$\overline{UD} = yUD_1 + (1-y)UD_2 \tag{B.15}$$

The replicator dynamic equation for the rural households' choice of SIC strategy is (See Eq. (B.16)):

$$F(y) = \frac{dy}{dt} = y(UD_1 - \overline{UD}) = y(1-y)(UD_1 - UD_2) = y(1-y)[1 - z(1-g)]\{P_1 \times E_1 + P_2 \times (E - E_1) - [(1-\theta)x + \theta](C_1 + C_2) - [(1-h)x + h]R_1\} \tag{B.16}$$

Assuming that the expected payoff for rural PV cooperatives is UE_1 when they choose to participation strategy and UE_2 when they choose to non-participation strategy. The expected payoff for rural PV cooperatives in choosing the participation strategy *(UE_1)* is (See Eq. (B.17)):

$$UE_1 = x[y\omega_5 + (1-y)\omega_6] + (1-x)[y\omega_7 + (1-y)\omega_8] = M - N_1 \tag{B.17}$$

The expected payoff for rural PV cooperatives in choosing the non-participation strategy *(UE_2)* is (See Eq. (B.18)):

$$UE_2 = x[y\omega_1 + (1-y)\omega_2] + (1-x)[y\omega_3 + (1-y)\omega_4] = 0 \tag{B.18}$$

the average expected payoff of the rural PV cooperatives *($\overline{UE}$)* is (See Eq. (B.19)):

$$\overline{UE} = zUE_1 + (1-z)UE_2 \tag{B.19}$$

The replicator dynamic equation for the rural PV cooperatives' choice of the participation strategy is (See Eq. (B.20)):

$$F(z) = \frac{dz}{dt} = z\,(UE_1 - \overline{UE}) = z(1-z)(UE_1 - UE_2) = z(1-z)(M - N_1) \tag{B.20}$$

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