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Research paper

Rooftop distributed photovoltaic development under the ”Whole-county promotion mode”: Based on farmers’ self-investment

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ABSTRACT

Rural China possesses abundant rooftop resources, making the development of rooftop distributed photovoltaics (RDPV) crucial for achieving national carbon neutrality goals. Under the "Whole-county promotion mode", self-investment by farmers has become a key financing channel. Based on a survey of 367 rural households in Shandong Province, this study combines econometric analysis and game theory simulations to explore the factors influencing farmers' willingness to invest in self-built RDPV systems. The results show that economic returns, environmental awareness, household characteristics, and rooftop conditions significantly affect their investment decisions. The findings highlight the importance of enhancing project profitability, providing financial support, and improving farmers' cognition through policy interventions. This research offers theoretical insights into renewable energy adoption behavior and practical implications for accelerating rural PV deployment under low-carbon strategies.

1. Introduction

Nowadays, the problem of global warming is intensifying, and the global environmental situation is becoming more and more severe. China is achieving its strategic goal of carbon neutrality by vigorously developing renewable energy (Liao et al., 2016). China has made great progress in the field of renewable energy (Chen et al., 2018a; Qiang et al., 2020a). In 2020, China's renewable energy utilization reached a peak equivalent to 680 million tons of standard coal, and carbon dioxide emissions decreased by 1.79 billion tons, making a great contribution to the realization of the "carbon neutrality" goal (Wang et al., 2021). In the promotion of the "carbon neutrality" strategy, farmers, as the main body of the countryside, are important parties (Qiang et al., 2020b). Mobilizing farmers' enthusiasm and making farmers embrace "carbon neutrality" will make the "carbon neutrality" in agriculture and rural areas better implemented.

The development of rooftop distributed photovoltaic(RDPV) in rural areas in China has great advantages. RDPV is combined with the rooftop of the house and used reasonably (AlAboosi and AlAboosi, 2021; Evangelos, 2019). It is a design method that directly uses the rooftop as the location of the main RDPV. Using the rooftop to build RDPV can not only increase the income of farmers, but also make the house warm in winter and cool in summer and prolong the service life of the rooftop. Chinese government is promoting a "Whole-county promotion mode" for RDPV in some counties. But to promote the project, financing channels are the most important part.

It is an important channel to solve the project financing by allowing farmers to actively participate in the project, so that they can build their own RDPV. At present, the national policy orientation is also actively encouraging farmers to actively participate in the project investment. It is necessary to understand the willingness of rural farmers to install RDPV power generation, find out the influencing factors of farmers' willingness to develop in self-built RDPV, and provide a breakthrough point for promoting farmers' self-built RDPV.

Therefore, this paper focuses on the research on farmers' willingness to develop in self-built RDPV. This study is based on two assumptions, that is, the project is first affected by market factors such as the project's investment return, and secondly, it will also be affected by some non-market factors (Qiang et al., 2019). So, first of all, farmers are most concerned about economic factors such as project self-construction

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willingness and project investment return. These economic factors are mainly solved by market factors. This article will first confirm this premise in the research. Secondly, other non-market factors other than market factors that can affect the willingness of farmers to build themselves, including but not limited to individual characteristics, family characteristics, housing conditions, energy use preferences, some behavioral characteristics, etc. These factors can provide important references for the government or project promoters. How to find the impact of these non-market factors on farmers' willingness will be the focus of this study.

The originality of this study is threefold. First, it moves beyond a singular focus on economic drivers by integrating both market and non-market factors within a unified analytical framework to explain farmers' investment decisions. Second, it introduces a novel methodological approach by combining empirical econometric analysis with a game theory simulation, thereby bridging the gap between identifying static influencing factors and modeling the dynamic strategic interactions between farmers and regulators. Third, it explicitly incorporates the concept of bounded rationality to provide a more realistic interpretation of farmers' decision-making processes under information and cognitive constraints, offering a fresh theoretical perspective on renewable energy adoption behavior in rural contexts.

This research aims to make contributions in both theoretical and practical dimensions. Theoretically, it enriches the understanding of renewable energy adoption behavior by integrating the perspective of bounded rationality with traditional econometric analysis. It introduces a game theory framework to model the strategic interaction between farmers and regulators, moving beyond a purely factor-identification approach to provide a dynamic simulation of policy impacts. Practically, the findings offer actionable insights for policymakers under the "Whole-county promotion mode". By identifying key market and non-market drivers, this study provides a evidence-based foundation for designing targeted policy interventions—such as tiered subsidies, tailored financing products, and cognitive enhancement campaigns—-that can effectively stimulate farmers' investment willingness, thereby accelerating the deployment of RDPV and contributing to rural carbon neutrality goals.

2. Literature review and hypotheses

2.1. Literature review

In terms of economic benefits, there are great differences in different countries and regions. Through the support policies for household RDPV in major European markets, using the net present value and internal rate of return indicators, a comprehensive evaluation, increasing the proportion of self-use can significantly increase the project income (Boeck et al., 2016). In China, regions with better solar energy resources or regions with higher sales prices also have higher incomes. From an investment point of view, this measure is obviously not attractive (Rodrigues et al., 2017). There is a strong correlation between the development of residential, industrial and commercial distributed photovoltaic in China and related policies (Zhao et al., 2015). Under the new technology and financing conditions, according to the calculation method of leveled power generation cost, grid parity can be achieved in selected typical areas (Branker et al., 2011).

In terms of environmental benefits, RDPV have significant potential for energy conservation and emission reduction. RDPV can reduce environmental pollution, which is in line with sustainable development research (Chen et al., 2018b). Through the promotion and application of RDPV technology, it is verified that RDPV can effectively reduce the use of fossil energy, thereby reducing the pollution to the surrounding environment (Wang and Wang, 2021). From the perspective of clean development mechanism, China should also vigorously develop clean energy (Fu, 2020). However, at present, rural energy is facing a prominent problem of consumption (Hong, 2020). The green construction of photovoltaic projects is of great significance in photovoltaic projects (Liu, 2020).

Comparison of international studies on rural photovoltaic applications. Globally, scholars have explored various drivers of household PV adoption. Studies in Germany and Australia have long highlighted the paramount importance of feed-in tariffs and investment subsidies as primary drivers, with adoption following a typical innovation diffusion curve influenced by income and education levels (Zhang et al., 2025; Deng et al., 2024). In contrast, research in developing countries, such as India and in Africa, often emphasizes the critical role of microfinancing and community-based models to overcome upfront cost barriers, alongside challenges of grid reliability (Yadav et al., 2019; Firoozi et al., 2025). A common thread across this literature is the recognition that financial incentives are necessary but often insufficient, with non-economic factors like environmental awareness and social influence (e.g., neighbor effects) playing a significant role (Kumar et al., 2025a).

Research on Rural PV Adoption in the Chinese Context. Within China, the literature on RDPV has evolved rapidly, reflecting its unique policy landscape. Early studies focused predominantly on large-scale, poverty-alleviation-focused photovoltaic (PV) projects (Wang et al., 2023). More recently, research has begun to examine distributed models. Studies have confirmed the influence of factors such as subsidy policy perception (Li et al., 2020) and household income (Liu et al., 2021). However, the literature often treats farmers as a homogeneous group and lacks a nuanced understanding of the behavioral mechanisms behind investment decisions under the innovative "Whole-county promotion mode". Furthermore, while game-theoretic models have been applied to energy policy (Yin et al., 2025), their application to model the strategic interactions between farmers, government, and companies in this specific context remains limited. There have been many good cases of RDPV in rural China being effectively integrated with other projects. "Photovoltaic + air source heat pump" combined heating system suitable for northern rural dwellings has good feasibility (Peng et al., 2019). The "photovoltaic + rural" model has important reference significance for realizing the dual goals of rural development and prosperity (Su and Sun, 2021). The "photovoltaic + electric heating" heating method is a method of optimizing the existing electric heating system by using RDPV (Zhang et al., 2020). Under the carbon trading model, household RDPV increase the competitiveness of the project. Considering the influence of urban and rural differences, the perception of subsidy policy has a significant impact on the willingness to purchase household RDPV (Wang et al., 2019). In order to meet the heating load demand of the house in winter, the electric energy generated by the distributed power source can be stored in the form of thermal energy through the thermal storage device (Mi et al., 2019). In remote rural areas, a multi-energy complementary power generation system with RDPV and new high-temperature solid oxide fuel cells as distributed power generation units and batteries as energy storage units is very feasible (Jiang et al., 2020). In addition, in recent years, many industrial development models of photovoltaic poverty alleviation have emerged, contributing China's strength to the realization of China's rural revitalization and global poverty reduction (Wang, 2018).

Related issues affecting the promotion of RDPV. A survey study on Malaysia shows that government policies have a greater impact on the implementation of RDPV (Muhammad-Sukki et al., 2011). There are four evolutionary stable strategies for the photovoltaic project, among which the initiative support of photovoltaic enterprises, the participation of poor households and less supervision of the government is a more appropriate choice (Shan and Yang, 2019). However, there are relatively few studies on the willingness of farmers to self-build RDPV, which are dual characteristics of investors and consumers. The usefulness perception and technical training had significant positive impacts on the adoption willingness, adoption behavior, and willingness-behavior consistency of the farmers, whereas the photovoltaic investment cost had a negative impact (Li et al., 2021). The effect estimation results show that increasing the initial willingness, financial subsidy, punishment taxes, and operating efficiency coefficient have positive effects on encouraging participants to actively promote distributed photovoltaics, while the additional costs and investment costs have negative effects (Chen et al., 2022). Positive associations between environmental concern and use intention, and between innovativeness and use intention, through the mediating of perceived benefits and harm. Residents' monthly electricity consumption also moderate part of the associations (Zhang et al., 2022).

Despite the valuable insights provided by existing literature, several research gaps remain. First, many studies focus on macro-level policy analysis or technical-economic potential, with less emphasis on the micro-level decision-making mechanisms of farmers as the primary investors and consumers. Second, while some studies identify influencing factors, there is a lack of integrated analytical frameworks that combine empirical econometric analysis with strategic interaction models (e.g., game theory) to simulate policy impacts dynamically. Third, the role of bounded rationality—where farmers' decisions are constrained by limited information, cognitive capacity, and risk aversion—is often overlooked in traditional economic models of energy adoption. Finally, within the specific context of China's "whole-county promotion" model, a comprehensive investigation into the synergistic effects of market and non-market factors on farmers' self-investment willingness is still needed.

In summary, scholars have conducted research on the economic, environmental or social benefits of RDPV from different perspectives. However, there are relatively few studies on the empirical analysis of farmers' willingness to develop of RDPV. Therefore, based on the research of existing RDPV, this paper selects typical areas, conducts research on farmers' willingness to develop, and conducts qualitative and quantitative empirical analysis of the data to understand farmers' willingness to develop in self-built RDPV. influencing factors. Finally find the driving factors that make farmers embrace "carbon neutrality".

Farmers studied in this study are defined as residents who live in rural areas for a long time. Self-built RDPV refer to RDPV installed according to the area of the family rooftop, also known as RDPV power generation. The willingness expressed in this paper refers to the willingness of villagers to participate in self-built RDPV, and the corresponding psychological activities of villagers before choosing whether to participate in self-built RDPV activities.

2.2. Utility maximization and constrained rationality

Farmers' decisions about whether to invest in self-built RDPV are essentially a process of maximizing their own utility under conditions of limited information, limited cognition, and limited computational capacity. Traditional rational choice theory assumes that individuals possess perfect information and unlimited computational capacity, enabling them to make optimal decisions. However, in reality, farmers often face constraints such as information asymmetry, cognitive limitations, and risk aversion, and their decision-making behavior is more consistent with the "bounded rationality" model proposed by Simon (1956) (Simon, 1956).

In this study, farmers' utility functions include not only economic benefits (such as return on investment and electricity savings) but also non-economic benefits (such as environmental contributions, convenience, and social recognition). Therefore, farmers' final decisions are formed through a constrained rational evaluation process, influenced by both market factors (such as electricity prices, subsidies, and investment costs) and non-market factors (such as individual characteristics, family structure, and environmental awareness).

The conceptual framework is shown in Fig. 1. It shows how market and non-market factors jointly influence farmers' investment willingness through the "utility evaluation" and "rational constraint" mechanisms. Market factors (such as investment returns and subsidy policies) directly affect farmers' evaluation of economic benefits, which in turn affects their investment willingness. Non-market factors (such as age, education, family structure, environmental awareness, etc.) influence decision-making through the following paths: (1) affecting information acquisition and processing capabilities (such as those with higher education levels find it easier to understand policies); (2) affecting the degree of emphasis on non-economic benefits (such as those with strong environmental awareness value environmental contributions more); (3) affecting risk perception and tolerance (such as those with higher incomes are more willing to bear investment risks). The rational constraint mechanism is manifested as: (1) information asymmetry: farmers have limited knowledge of policies, technologies, benefits, etc.; (2) cognitive biases: such as excessive optimism or pessimism, herd mentality, etc.; (3) risk aversion: tending to avoid investments with high uncertainty.

2.3. Hypothesis

Through investigation, it is found that with the increase of age, there

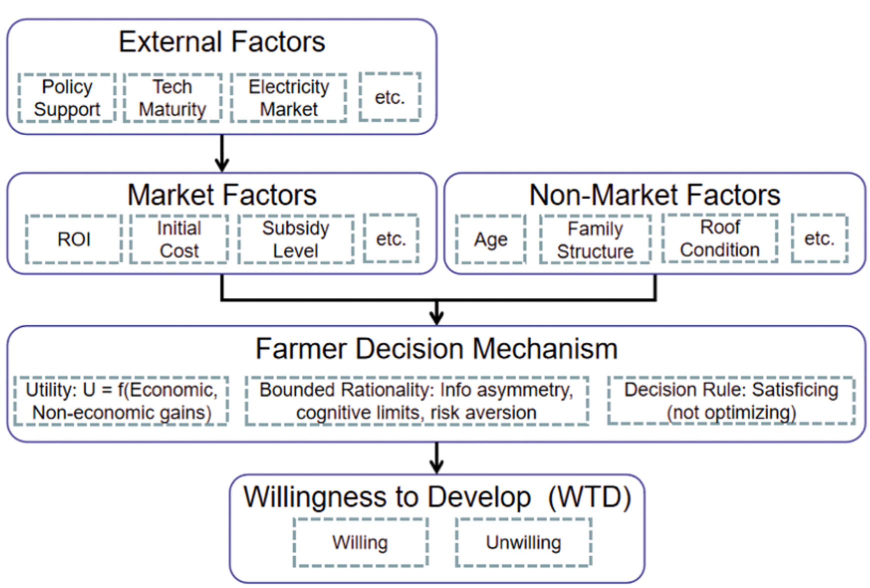

Fig. 1. Conceptual framework.

are fewer opportunities to work abroad, and the trend of returning to rural areas increases, so the willingness to invest in rural areas may increase. Therefore, Hypothesis 1 is proposed:

H1. The older the age, the greater the willingness of farmers to build their own RDPV.

Through investigation, it is found that with the popularization of compulsory education, the years of education of farmers increase, so the years of education of farmers may affect the cognitive level of participating in self-built RDPV. Therefore, Hypothesis 2 is proposed:

H2. The longer the years of education, the greater the willingness of farmers to build their own RDPV.

Through investigation, it is found that the operation of RDPV requires regular maintenance by farmers, which requires farmers to stay at home. The longer the time at home, the more convenient the project maintenance will be. Therefore, Hypothesis 3 is proposed:

H3. The longer the households spend at home each year, the more willing they are to build their own.

Through research, it is found that the elderly in rural areas generally choose to retire at home, and the left-behind elderly can ensure the daily maintenance of RDPV power generation. Therefore, there are left-behind elderly people at home who will increase their willingness to invest in self-built RDPV. Therefore, Hypothesis 4 is proposed:

H4. There are left-behind elderly people at home, and farmers are more willing to build their own RDPV.

Through investigation, it is found that the larger the population in the family, the greater the electricity consumption, so the number of population in the household may affect the willingness to develop in self-built RDPV. Therefore, Hypothesis 5 is proposed:

H5. The family has a large population, and the farmers are more willing to build their own RDPV.

Through the investigation, it is found that the level of household income determines the amount of funds that farmers can use for investment. As farmers pursue stable income projects, it is foreseeable that families with high annual income may increase their willingness to invest. Therefore, Hypothesis 6 is proposed:

H6. The higher the annual household income, the greater the willingness of farmers to build their own RDPV.

Through investigation, it is found that in recent years, with the continuous increase of farmers' income, young people have formed a trend of buying houses in cities. The houses are generally older, and most of them are middle-aged and elderly. Therefore, Hypothesis 7 is proposed:

H7. The longer the age of newly-built houses at home, the greater the willingness of farmers to build their own RDPV.

Through the investigation, it was found that the rooftop area is large, the installed photovoltaic modules are many, the power generation is large, and the income is high. Therefore, Hypothesis 8 is proposed:

H8. The larger the rooftop area of the family, the greater the willingness of farmers to build their own RDPV.

Through the survey, it is found that with the popularity of electrical appliances in the family, the higher the annual electricity consumption in the family, the higher the energy consumption of farmers. Self-built RDPV can hedge the energy consumption of households and reduce the cost of living. Therefore, Hypothesis 9 is proposed:

H9. The annual electricity bill for households is high, and farmers are more willing to build their own RDPV.

Through the investigation, it is found that the high utilization rate of solar water heaters in rural areas indicates that farmers' families have a high degree of acceptance of the convenience of modern life. Therefore, hypothesis 10 is proposed:

H10. The popularity of solar water heaters is high, and farmers are more willing to build their own RDPV.

Through the survey, it is found that with the publicity of environmental protection in recent years, farmers' cognition of environmental protection is getting higher and higher, and solar power generation is one of the relatively clean and environmentally friendly energy sources. Therefore, Hypothesis 11 is made:

H11. The higher the farmers' cognition of environmental protection, the greater the willingness of farmers to build their own RDPV.

Through investigation, it is found that with the increasing number of severe weather in recent years, farmers have become more and more aware that health and environmental protection are closely related. Therefore, Hypothesis 12 is proposed.

H12. The more positive the farmers' attitude towards environmental protection, the greater the farmers' willingness to build their own RDPV.

3. Game theory analysis

3.1. Theoretical framework

We introduce an evolutionary game theory framework to analyze the strategic interactions among three key stakeholders in RDPV adoption: rural investors (farmers), regulators (government), and PV companies. This multi-agent approach allows us to capture the complex dynamics and interdependent decision-making processes that characterize RDPV deployment under the "Whole-county promotion mode".

3.2. Model formulation

Building upon the foundational work of (Morris and Shin, 1996; Rabin, 1992) and incorporating the insights from the multi-agent framework (Yin et al., 2025), we develop an evolutionary game model involving three key stakeholders: Farmers (F), Government (G), and PV Companies (C) (Table 1).

Assumptions:

1) All players are bounded rational and continuously adjust their strategies based on observed payoffs.
2) The population of players is large, and the strategy evolution can be modeled through replication dynamics.
3) Information is imperfect and asymmetrical among different agents.

Strategy sets:

1) Farmers (F): {Invest (I), Not Invest (N)}
2) Government (G): {Subsidize (S), Not Subsidize (NS)}
3) PV Companies (C): {Provide High-Quality Service (H), Provide Low-Quality Service (L)}

Parameter definition and payoff matrices:

The payoffs for each player under different strategy combinations are

Table 1
Payoff matrix for the tripartite evolutionary game.

Strategy Combination	Payoff Functions
(I, S, H)	$U_F = R_f - C_{inv} + S_g$; $U_G = B_g - C_{sub} - S_g$; $U_C = R_c - C_h$
(I, S, L)	$U_F = R_f - C_{inv} + S_g - L$; $U_G = B_g - C_{sub} - S_g$; $U_C = R_c - C_l$
(I, NS, H)	$U_F = R_f - C_{inv}$; $U_G = B_g$; $U_C = R_c - C_h$
…	…
(N, NS, L)	$U_F = 0$; $U_G = 0$; $U_C = 0$

defined in Table 1. Key parameters include:

Rf: Farmer's revenue from electricity generation.
Cinv: Initial investment cost for the farmer.
Sg: Subsidy amount provided by the government.
Csub: Government's cost of administering subsidies.
Bg: Social and environmental benefits to the government.
Rc: Revenue for the PV company.
Ch, Cl: Cost for the company to provide high/low-quality service (Ch > Cl).
L: Loss suffered by farmers (e.g., reduced generation, maintenance cost) if the company provides low-quality service.

3.3. Replication dynamics and equilibrium analysis

The *evolutionary* stable strategies (ESS) are found by analyzing the system of replication dynamic equations. The proportion of farmers choosing to "Invest" is denoted by x, the proportion of governments choosing "Subsidize" is y, and the proportion of companies choosing "High-Quality" service is z.

The expected payoff for a farmer choosing "Invest" (U_{FI}) and "Not Invest" (U_{FN}), and the average payoff ($\bar{U}_F$) are calculated based on the payoffs in Table 3 and the strategy proportions (y, z).

The replication dynamic equation for farmers is:

$$F(x) = dx/dt = x(1-x)(U_{FI} - U_{FN}) \quad (3.1)$$

Similarly, we derive the equations G(y) = dy/dt for the government and H(z) = dz/dt for the PV company. The ESS candidates are the stable fixed points (x*, y*, z*) of the system where F(x) = 0, G(y) = 0, H(z) = 0. The local stability of these points is analyzed using the Jacobian matrix:

$$J = [\partial F/\partial x, \partial F/\partial y, \partial F/\partial z; \partial G/\partial x, \partial G/\partial y, \partial G/\partial z; \partial H/\partial x, \partial H/\partial y, \partial H/\partial z] \quad (3.2)$$

A fixed point is asymptotically stable if all eigenvalues of the Jacobian matrix have negative real parts (Srinivas and Fleuret, 2018).

3.4. Simulation and results

We simulate the strategy evolution of the three populations using R. Fig. 2 illustrates the evolutionary paths under different initial conditions and parameter values (e.g., varying the subsidy level S_g). The results identify the stable equilibria and the conditions under which the system converges to the desired state (High Investment, High Subsidy, High Quality).

4. Methodology

We chose Shandong Province as a typical province for investigation. The analysis proceeds as follows: we describe the sampling frame and data collection; descriptive analysis of the data; specify the empirical models by regression analysis; and implement robustness and heterogeneity analyses.

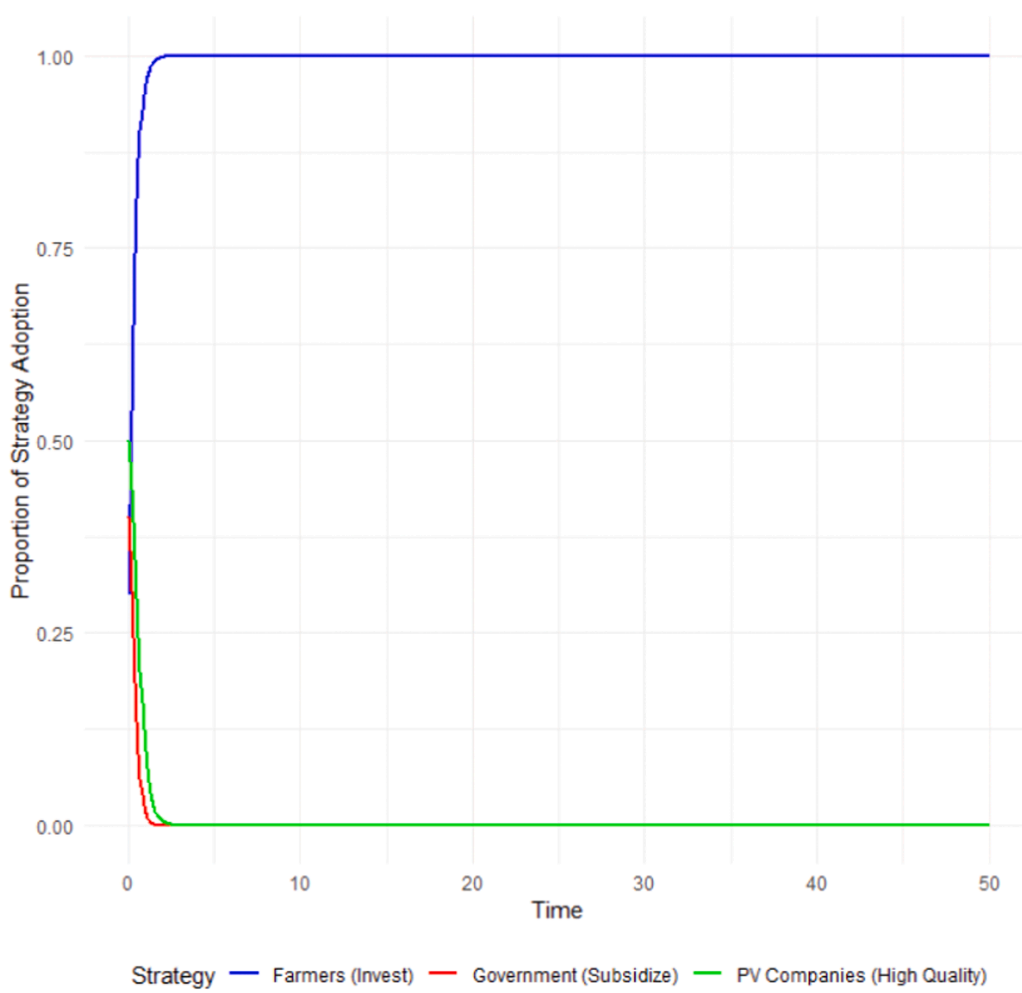

Fig. 2. Evolutionary dynamics of strategies in tripartite game.

4.1. Survey regions

This study chooses some countries of Shandong Province as the research area. First, The investment in RDPV in rural areas of Shandong mainly relies on market forces such as government procurement, enterprise investment, and farmer investment. As of April 2021, household photovoltaic installed capacity in Shandong Province reached 9.11 million kW, reaching 513,000, accounting for 57.3 % of the total distributed installed capacity (Statistics, 2021a). Second, the selected countries has great potential for developing and constructing RDPV. The selected countries belong the capital of Shandong Province, with an annual sunshine hour of 1870.9 h. By the end of 2020, these regions have installed solar capacity was 652,000 kW (Government n.d.).

4.2. Survey design

Combined with domestic and foreign research on farmers' behavior and RDPV, the specific factors that affect farmers' participation in self-built RDPV are included in the questionnaire.

Before officially entering the question, there is a stage of introducing the question, first asking the farmers whether they understand RDPV. According to the information, introduce the project to the respondents. Focus on the current investment cost and payback period of RDPV. Through interviews, it is confirmed that farmers attach importance to the project investment income. Tell the respondents in the most simple and easy-to-understand way, taking 100 m^2 of RDPV power generation as an example, a 5-kW household photovoltaic power station can be installed. According to the current market price, the estimated investment is 35,000–45,000 CNY, and it is estimated that 5000 CNY income can be obtained every year. This serves as an illustrative cost-benefit scenario.

To provide a scientifically-grounded estimate for this income projection, we calculated the potential energy yield based on the local solar resource. The average annual sunshine hours for Jinan from 2016 to 2020 was 2268 h (Statistics, 2021b). The annual energy output (E) of a 5 kW system was estimated using the following equation: E = System Capacity (kW) × Annual Sunshine Hours (h) × System Efficiency Assuming a conservative system efficiency of 75 % (accounting for losses from temperature, dust, and inverter inefficiency), the calculation is as follows (Liu et al., 2024): E = 5 kW × 2268 h × 0.75 = 8505 kWh Given the local feed-in tariff and provincial subsidies averaging approximately 0.59 CNY/kWh at the time of the survey, the estimated annual income would be: Annual Income = 8505 kWh × 0.59 CNY/kWh ≈ 5018 CNY This calculated value, rounded to 5000 CNY for simplicity, was used as the representative economic benefit communicated to the farmers during the interviews. Further threshold analysis will be conducted in follow-up studies.

The survey on the situation of farmers mainly sets the following basic elements: home address, gender, age, years of education, length of time at home in a year, number of family members, whether there are left-behind elderly people at home, main source of income of the family, annual family income, House age, rooftop area, annual electricity usage, whether there is a solar water heater at home, environmental awareness, environmental attitude, etc.

Regarding the acquisition of environmental protection knowledge variables, we adopt the form of common-sense questions, with a total score of 10 points. In terms of environmental attitudes, respondents were asked the importance of environmental protection compared to income and health, and then asked respondents to allocate between income, health, and environmental protection, scoring a total score of 10. If they choose the environmental protection score is 3, then the respondents' attitude score is 3 points.

During the research process, key interviews were also conducted with some farmers.

4.3. Variables setting

The variable settings of this survey are shown in Table 2.

The explained variable is whether farmers are willingness to self-investment in RDPV (WTS), and the answer is "Yes" or "No".

In the selection of explanatory variables, this study divides the influencing factors of farmers' participation in self-invest in RDPV into individual characteristic variables (ICV), family characteristic variables (FCV), house situation variables (HSV), energy consumption situation variables (ECSV), and behavior variables (BV).

4.4. Sample size determination

Prior to data collection, we calculated the minimum required sample size to ensure the statistical power and representativeness of our survey. The calculation was based on the formula for estimating a population proportion with a specified level of confidence and precision (Lohr, 1999; Bartlett et al., 2001). Given that the total number of rural households in the target counties is large (exceeding 100,000), we used the standard formula for an infinite population: $n = (Z^2 \times p(1\text{-}p))/e^2$

Where: n = required sample size; Z = Z-value (1.645 for the 90 % confidence level); p = estimated proportion of the population willing to invest in RDPV (conservatively set to 0.5 to maximize variability); e = desired margin of error (0.03)

Table 2
Variable setting and description.

Category	Name	Explanation
willingness to self-investment in RDPV	WTS	If the respondent is willing to self-invest in RDPV, then WTS= 1, otherwise WTS= 0
ICV	Gender	1 if the respondent is male, 0 otherwise
ICV	Age	Actual age as stated by the respondent.
ICV	Education	Actual years of education as stated by respondents.
FCV	Home time per year	Actual time spent at home per year, as stated by respondents.
FCV	Family size	The number of households living together as stated by the respondent.
FCV	Are there any left-behind elders at home?	Is there any elderly left behind in the family all the year round? 1 if yes, 0 otherwise.
FCV	Main source of income	Type of main source of income as stated by respondents. 0 if mainly relying on agricultural income, 1 otherwise.
FCV	Annual household income	Annual actual household income as reported by respondents.
HSV	House age	Actual age of current house as stated by respondents.
HSV	Roof area	Actual roof area of current house as stated by respondents.
ECSV	Annual electricity usage	Respondents' annual household electricity consumption as reported.
ECSV	Is there a solar water heater	Whether the respondent's household has installed a solar water heater. 1 if present, 0 otherwise
BV	Environmental awareness	Set up 10 routine questions about environmental protection, and asked the respondents to answer them. 1 question 1 point.
BV	Environmental attitude	Respondents were asked the importance of environmental protection compared to income and health, with a total score of 10, allocated between income, health and environmental protection.

Substituting the values, we obtained: $n \approx 752$

However, considering the feasibility of data collection and the homogeneity of the rural population within the same region, a minimum sample size of 128 was calculated using a finite population correction approach, which is consistent with the study of Adam et al (Anokye, 2020). To ensure robustness and account for potential invalid responses, we aimed for a larger sample size of 400 households.

4.5. Data collection

The survey was conducted from August 2021 to October 2021, a period selected to coincide with the summer and early autumn seasons when farmers are relatively less engaged in intensive agricultural activities and are more likely to be available for interviews.

A multi-stage random sampling technique was employed to ensure representativeness:

Stage 1 (County Selection): Five counties (Changqing, Zhangqiu, Jiyang, Pingyin, Shanghe) in Shandong Province were purposively selected based on their representativeness in terms of economic development level and RDPV development potential.

Stage 2 (Township and Village Selection): One township was randomly selected from each county. Within each township, two administrative villages were randomly chosen from the village roster.

Stage 3 (Household Selection): Within each selected village, a name list of all registered households was obtained from the village committee. A systematic random sampling method was used to select 40 households from each village (every k-th household, where k = total households/40). If the selected household was unavailable or refused to participate, the next household on the list was approached.

Trained enumerators from local universities conducted face-to-face interviews using a structured questionnaire. To ensure data quality, all enumerators underwent a comprehensive training program covering the research objectives, questionnaire content, and interview techniques. Each interview lasted approximately 10–30 min. To minimize response bias, the interviewers emphasized the anonymity and confidentiality of the survey at the beginning of each interview.

The questionnaire was designed based on an extensive literature review and preliminary field visits. Before the formal survey, a pilot test was conducted with 30 farmers in a non-sampled village to assess the clarity, comprehensibility, and contextual appropriateness of the questions. Ambiguous terms and complex expressions were simplified based on feedback from the pilot study. For example, the concept of “internal rate of return” was replaced with simpler language about “annual income from the investment.”

A total of 400 questionnaires were distributed. After the data collection phase, all retrieved questionnaires were checked for completeness and consistency on the same day. Questionnaires with over 20 % missing data, inconsistent answers (e.g., claiming zero electricity consumption while owning multiple high-power appliances), or clear patterns of straight-line responding were excluded. Ultimately, 367 valid questionnaires were retained, yielding an effective response rate of 91.8 %. The high response rate can be attributed to the face-to-face interview method and the prior coordination with local village committees, which helped in building trust with the respondents.

4.6. Model selection

In real life, we generally solve the regression problem of categorical variables by using the logistic regression model (Tan and Zeng, 2013). According to the classification of variables, this study expresses the factors affecting farmers' willingness to develop in RDPV construction as the following functional form:

$$Y_{WTP} = F(X_1, X_2 \ldots X_i) + \mu \tag{4.2}$$

Among them, Y_{WTP} represents the willingness of farmers to participate in the construction of RDPV, Xi is the factor of farmers' willingness to develop in the construction of RDPV, and μ is the random disturbance term. In this study, gender, age, years of education, number of people in the family, time spent at home by the main labor force, age of the house, rooftop area, annual electricity consumption in the home, whether there is solar energy, total family income, source of income, etc. are used as independent variables. Binomial classification was used in this study, which met the requirements of the binomial classification model for variables. Therefore, the model analyzes the influencing factors that affect the willingness of farmers to participate in the construction of RDPV power generation. The model is as follows:

$$Ln(P/1-P) = a + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i + \mu \tag{4.2}$$

Among them, P represents the probability that farmers are willing to participate in the construction of RDPV, and $1-P$ represents the probability that farmers are unwilling to participate in the construction of RDPV power generation. a represents the constant term of the regression model, X_i represents the i factor that affects farmers' willingness to develop, β_i represents the regression coefficient of the i factor that affects farmers' willingness to develop, and μ is the random disturbance term.

4.7. Reliability and validity test

We assessed the internal consistency of the multi-item scales (Environmental Attitude and Perceived Economic Return) using Cronbach's alpha. The results showed that both scales demonstrated good reliability. The Cronbach's alpha for the Environmental Attitude scale was 0.78, and for the Perceived Economic Return scale, it was 0.72, both exceeding the commonly accepted threshold of 0.70 (Nunnally, 1978). For the Environmental Awareness scale (true/false questions), the Kuder-Richardson Formula 20 (KR-20) coefficient was 0.71, also indicating acceptable internal consistency for dichotomous items (Kuder and Richardson, 1937).

Exploratory Factor Analysis (EFA) was conducted on the multi-item scales. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.81, and Bartlett's test of sphericity was significant ($\chi^2 = 210.5$, $p < 0.001$), confirming the suitability of the data for factor analysis. The analysis confirmed a single-factor structure for each scale, with all items loading above 0.6 on their respective factors.

5. Results and discussion

5.1. Descriptive analysis

In the problem introduction stage, 37 farmers said they did not know about RDPV, and 330 farmers knew about RDPV power generation. Through interviews, 100 % of the interviewed farmers confirmed that market factors such as project investment income, which was estimated based on the local solar energy potential (2268 annual sunshine hours) and a simplified calculation model, are the primary factors of farmers' investment willingness.

Among the farmers who knew about RDPV power generation, 126 households learned about RDPV through the introduction of relatives and friends, accounting for 34.3 %. 26.7 % of the 98 households got to know them through TV media and other publicity. 86 households accounted for 23.4 % through government propaganda.

In the survey on whether they understand the national RDPV policy, 65 households said they fully understand the state's policy on rural RDPV construction. 198 households said that they did not know much about some policies of the state for the construction of RDPV in rural areas. 47 households indicated that they did not understand some preferential policies of the state for the construction of rural RDPV.

Then, begin to formally enter the research question. There were 213 women and 154 men in the survey.

18 households are between 20 and 30 years old, accounting for 4.9 %. 65 households between 30 and 40 years old. 111 households aged 40–50 accounted for 30.2 %. 116 households between 50 and 60 years

old. 54 households aged 60–70 accounted for 14.7 %. In the survey, the number of farmers aged between 40 and 60 is the largest. Young people under the age of 40 are more likely to go out to work. Therefore, the number of surveys is relatively small. The survey found that at present, households in rural areas are willing to invest in self-built RDPV mainly based on the family unit, so it is not easy to intuitively judge the influence of gender differences of family members on the willingness of the project. However, as people grow older, opportunities to work abroad decrease and the tendency to return to rural areas increases, so their willingness to invest in rural areas may increase.

There are 15 rural households whose education level is below primary school, accounting for 4.1 % of the surveyed users. There are 127 households with primary school education, accounting for 34.6 %. There are 146 rural households with junior high school education, accounting for 39.8 %. There are 76 households with high school education and above, accounting for 20.7 %, and 3 households with college education or above, accounting for 0.8 %. The proportion of the population educated at the junior high school level is the highest, followed by the population at the primary school level. This also shows that farmers generally have insufficient knowledge, often have low acceptance of new things, and tend to follow the trend. This is not conducive to farmers' reasonable financial planning according to the actual situation of family income. The survey found that with the popularization of compulsory education, the number of years of education received by farmers has increased, so the number of years of education received by farmers may affect the level of awareness of participating in self-built RDPV.

There are 51 households with 1–3 members, 108 households with 4–5 members, and 204 households with 6–10 members, accounting for the highest proportion. There are 4 households with more than 11 family members. accounted for the least. The size of family members considered here is mainly based on household registration.

There are 36 households whose labor force stays at home for less than 60 days. 45 households stayed for 60–100 days. There are 26 households whose stay time is 100–150 days. There are 255 households whose stay time is between 150 and 200 days, accounting for 69.5 %. Five households stayed for more than 200 days. Among the 367 rural households, 324 households have left-behind personnel, and 43 households have no left-behind personnel. The survey found that the operation of RDPV requires regular maintenance by farmers, which requires farmers to spend a certain amount of time at home. The longer they are at home, the more convenient project maintenance will be.

There are 100 households whose income is mainly from agriculture. There are 267 households whose main source of income is non-agricultural, accounting for 72.8 %. Farmers are constantly expanding their economic channels, and the era of simply focusing on farming has passed. The development of urbanization and industrialization has increased the employment opportunities of farmers, enabling farmers to work in cities. The rural labor force has also formed seasonal characteristics. The left-behind rural labor force often chooses part-time jobs, and the income of the rural left-behind labor force is unstable due to the lack of a fixed occupation. The investigation found that the impact of the main source of income of the farmers on the willingness of the project cannot be directly judged.

There are 44 households with an annual household income of more than 100,000, accounting for 12 %. There are 188 households with an annual income between 10,000 and 30,000, accounting for 51.2 %. 97 households with an annual income between 30,000 and 50,000. 21 households between 50,000 and 100,000, accounting for 5.7 %. There are 17 households whose annual income is above 100,000. The proportion of annual income above 30,000 is nearly half. This shows that people's current income level has increased and their disposable income is high.

The roof area of most interviewed households is 121–150 square meters, accounting for 74.4 %. This is the mainstream roof area of rural households in China. 23.4 % of the households have an area of 80–120 square meters. Only very few homes exceed 150 square meters. This has an important relationship with the current strict homestead policy in rural China.

Regarding the age of houses, they are mainly concentrated between 11 and 20 years, accounting for 62.9 %. It can be seen that sub-new houses occupy the mainstream. The housing age within 10 years accounted for 28.6 %, and the proportion of new housing is relatively high. Homes over 20 years old accounted for only 8.4 %. From this aspect, we can see the rapid changes in rural areas brought about by China's economic growth. In recent years, with the continuous increase of farmers' income, young people have formed a trend of buying houses in cities. The houses are generally older, and most of them are middle-aged and elderly people. Therefore, the owners of old houses may be more willing to participate.

Most of the households surveyed spend between 601 and 900 CNY on electricity, accounting for 72.8 %, and the monthly electricity bill is about 50–75 CNY. This is the main electricity bill for rural households in China. 27.3 % of households spend less than 600 CNY a year on electricity. With the popularization of electrical appliances in households, the energy consumption of farmers is increasing. Self-built RDPV can offset household energy consumption and reduce household living costs.

Regarding whether there is a solar water heater, 75.7 % of the households have installed it, and less than 1/4 have not installed it. It can be seen that the popularity of solar water heaters in rural areas is relatively high. It reflects the importance farmers attach to solar water heaters. It shows that farmers have a high willingness for the convenience of life.

Regarding the acquisition of environmental awareness variables, due to the use of common sense questions, most farmers scored between 3 and 7 points, especially 4–5 points. It can be seen that farmers' cognition of environmental protection needs to be strengthened. With the promotion of environmental protection in recent years, farmers' cognition of environmental protection is getting higher and higher. RDPV is one of the relatively clean and environmentally friendly energy sources at present. Therefore, as the awareness of environmental protection increases, farmers' willingness to develop also increases.

In terms of attitude, most of them are between 2 and 4 points, especially 3 points. It reflects that farmers' cognition of environmental protection is weak, and guidance needs to be strengthened. The more positive the farmers' attitude towards environmental protection, the greater the farmers' willingness to build their own RDPV.

5.2. Measurement results

Before performing the regression analysis, we conducted a multicollinearity test on the variables. The results show that the mean VIF is 1.11, and the VIF of all variables are lower than 1.5. There is no multicollinearity between variables.

In this study, the econometric analysis software Stata 16.0 was used, and the Logistic econometric model was used to perform regression analysis on Y_{WTP} according to Equation 4.1 and Eq. 4.2. In the regression analysis, all variables were first introduced into the regression equation of farmers' willingness to develop in self-built photovoltaic construction, and then the corresponding model was obtained. The regression results showed that the χ value was 128.80 and the p value was 0.0000. The maximum likelihood estimate is -85.34. The overall fit is good.

Receiver Operating Characteristic (ROC) is a comprehensive indicator reflecting the sensitivity and specificity of continuous variables. AUC is the area under the ROC curve (Fig. 3), and the larger the AUC, the higher the correlation value of the factor (Fig. 4).

The measurement results are shown in Table 3. To enhance the interpretability of the statistical results, Table 3 presents a set of key indicators that reflect the predictive power of each factor influencing farmers' WTS. The AUC value derived from the ROC analysis indicates how well each variable can distinguish between those who are willing and those who are unwilling to pay a premium. An AUC value closer to

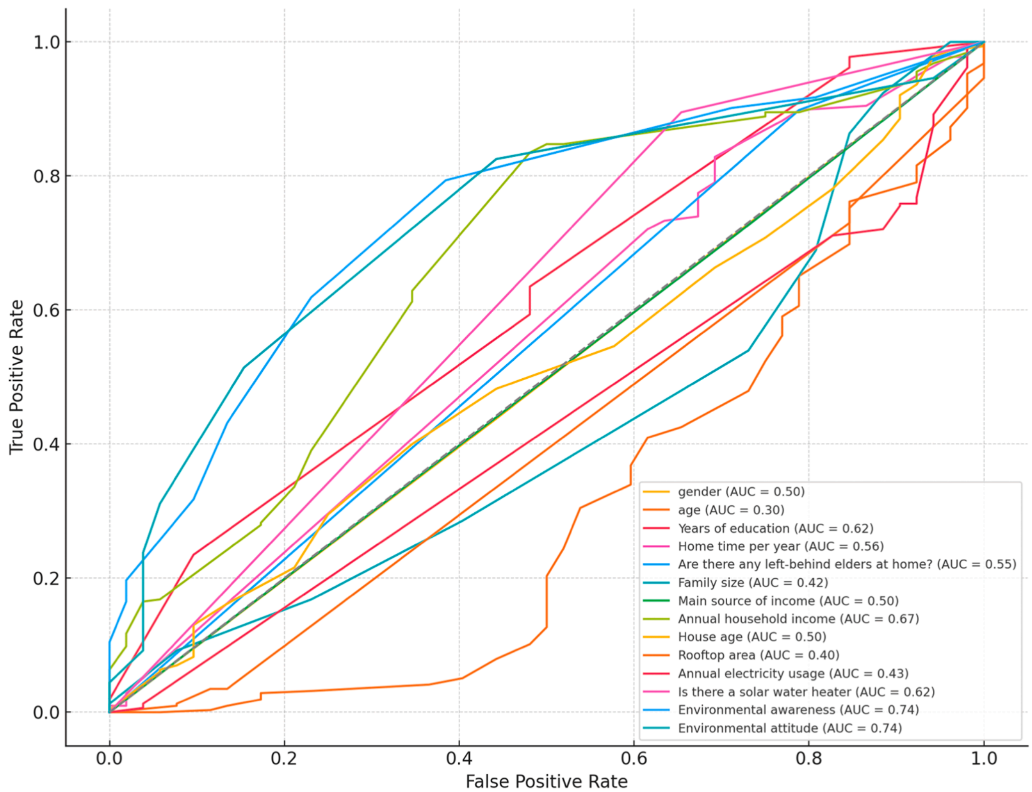

Fig. 3. ROC curves of individual predictors for WTS.

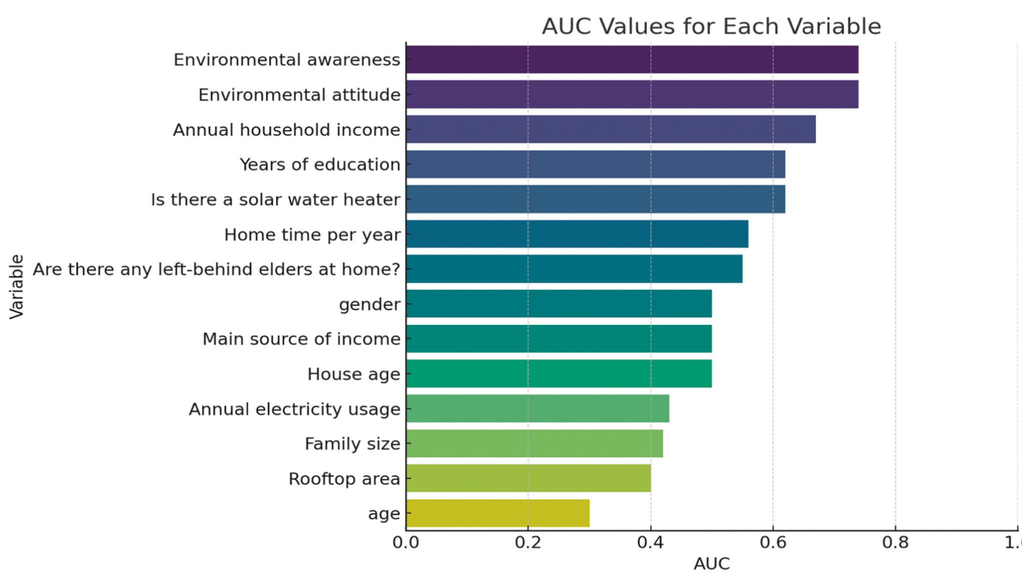

Fig. 4. AUC value of individual predictors for WTS.

1.0 suggests stronger discriminatory capacity, while a value around 0.5 indicates no better performance than random chance. For example, an AUC of 0.74 for environmental awareness implies a strong predictive effect on WTS. In addition, other statistical metrics such as the odds ratio, regression coefficient, and p-value are reported to assess the direction, magnitude, and statistical significance of each predictor. Together, these indicators provide a comprehensive evaluation of each variable’s explanatory strength within the logistic regression framework.

5.3. Result analysis

The measurement results show that the farmer's age, years of education, time at home each year, left-behind elderly people at home (over 65 years old), family population, annual family income, house age, rooftop area, annual electricity consumption, whether there is solar energy Water heaters, environmental awareness, and environmental attitudes have a significant impact on farmers' willingness to develop. Do not reject the null hypothesis.

The odds ratios provide a more intuitive measure of the magnitude and direction of these effects than regression coefficients alone.

Table 3
Measurement results and the significant variable AUC.

Variable	AUC	Odds Ratio	Coef.	*p*-value	Std.Err
Gender		1.499	0.405	0.340	0.636
Age	0.698	0.940	-0.061***	0.003	0.020
Years of education	0.615	1.220	0.199***	0.008	0.092
Home time per year	0.562	1.016	0.016***	0.001	0.005
Are there any left-behind elders at home?	0.555	5.064	1.622***	0.005	2.925
Family size	0.578	0.809	-0.212**	0.014	0.070
Main source of income		0.955	-0.046	0.921	0.439
Annual household income	0.675	1.000	0.000035***	0.006	0.000
House age	0.503	1.088	0.084*	0.054	0.047
Rooftop area	0.595	0.959	-0.036***	0.022	0.015
Annual electricity usage	0.574	0.994	-0.006***	0.008	0.002
Is there a solar water heater	0.621	4.434	1.489***	0.002	2.160
Environmental awareness	0.745	1.497	0.403***	0.000	0.151
Environmental attitude	0.740	1.488	0.397***	0.008	0.223
Cons.		9.468	2.248	0.372	23.839

Note: *, **, *** represent the significance levels of 10 %, 5 % and 1 %, respectively.

Age (OR = 0.940, $p < 0.01$): The odds ratio of less than 1 indicates a negative relationship. For each additional year of age, a farmer's odds of being willing to invest decrease by 6 % (1–0.940), holding other factors constant. This suggests that younger farmers, who may be more tech-savvy and have a longer investment horizon, are more likely to adopt RDPV.

Years of Education (OR = 1.220, $p < 0.01$): With one additional year of education, a farmer's odds of willingness to invest increase by 22 %. This underscores the critical role of education in enhancing cognitive ability and understanding of new technologies, making it a powerful lever for policy intervention.

Environmental Awareness (OR = 1.497, $p < 0.001$): This is one of the strongest predictors. A one-point increase on the environmental knowledge test (out of 10) is associated with a 49.7 % increase in the odds of investment willingness. This powerfully demonstrates that improving farmers' understanding of environmental benefits can be as influential as economic incentives.

Rooftop Area (OR = 0.959, $p < 0.05$): The negative sign was initially counterintuitive. However, post-hoc analysis and field interviews revealed that households with very large rooftops often belong to wealthier families who are less sensitive to the additional income from RDPV and more concerned about potential aesthetic impacts. This highlights a non-linear relationship where the middle-income group with adequate roof space is the primary target.

ROC-AUC Analysis: Beyond statistical significance, the Area Under the Curve (AUC) values assess the predictive power of each variable. Environmental Awareness (AUC = 0.745) and Environmental Attitude (AUC = 0.740) show the highest discriminatory power, meaning they are the most effective single variables for distinguishing between willing and unwilling farmers. In contrast, variables like Family Size (AUC = 0.578) and Home Time (AUC = 0.562), while statistically significant, have limited practical utility for targeted prediction on their own.

Women's family economic status has improved, and they have certain family resources and decision-making power in family affairs. The family relationship between husband and wife is more equal, and the role has changed from a dependent role to a more independent role (Bian, 2020). The age of farmers passed the significance level test, indicating that the age of farmers is a significant factor for participating in the construction of RDPV. With the increase of age and various reasons, the opportunities for farmers to work abroad gradually decrease, the trend of returning to the countryside increases, and the willingness to invest in the countryside will increase instead. Therefore, the age of the farmer is verified in the variable. The years of education of farmers passed the significance level test, indicating that the years of education of farmers had a significant impact on farmers' participation in RDPV construction. The reason is that the more years of education farmers have, the more knowledge about RDPV they can read through news or posters. Timely understanding of various environmental protection knowledge and RDPV policies, etc., can effectively improve the scientific and cultural quality of farmers and lay a solid cultural foundation for the construction of beautiful villages (Hao, 2021).

The main labor force of the family passes the significance level test every year, indicating whether farmers are willing to invest in self-built RDPV. Conventionally, RDPV require regular maintenance, and the longer you stay at home, the easier it is to maintain. Therefore, this is also an important factor for farmers to consider. Families with left-behind elderly people are more inclined to invest in self-built RDPV. The elderly left behind at home play an important role in the care and maintenance of RDPV. With the accelerated development of industrialization and urbanization, many young people choose to work in cities, which leads to an increase in the number of left-behind elderly people in rural areas (Wang et al., 2022a). There are left-behind elderly people at home who can carry out the daily operation and maintenance of the project. The AUC indicator shows that this factor has predictive value, but not much. The number of people in the household is a significant factor in the willingness to build RDPV. A larger population means that households use more energy. The increase in household size does increase household electricity and energy consumption. For each additional family member, household electricity consumption increases by about 2.7 % (Zhang and Wen, 2021). Therefore, families with a large population are more willing to participate in the construction of RDPV. But, the AUC indicator shows that this factor has predictive value, but not much. The annual household income has a direct impact on the willingness of farmers to participate in self-built RDPV. The higher the annual income of farmers, the stronger the willingness to develop in the construction of household power generation, and the impact is very significant. The rapid economic development has led to the continuous improvement of farmers' total income and the continuous improvement of farmers' quality of life. The increase in the proportion of labor income can promote the upgrading of the industrial structure through incentives for workers (Cai and Wang, 2012). The AUC indicator shows that this factor has a good predictive value.

There is a significant positive correlation between farmers' willingness to build RDPV and the age of their houses. According to the actual interviews in the survey, most of the farmers with older houses use farming at home as their main source of income, and they spend less time working outside and more time at home. Therefore, such people tend to increase investment projects at home to develop new revenue stream. The negative correlation between rooftop area and investment willingness (OR = 0.959, $p < 0.05$) appears counterintuitive at first glance, as a larger roof ostensibly allows for more panels and higher income. However, this simplistic economic intuition may be confounded by unobserved factors. We hypothesize that this result is driven by an omitted variable: household wealth. In rural China, a larger rooftop area often correlates with a larger, newer house, which is a proxy for higher overall wealth. Our qualitative interviews revealed that wealthier households: (1) are less motivated by the additional income from RDPV, as it constitutes a smaller portion of their total income; (2) may have higher aesthetic concerns about their newer properties; and (3) are more likely to have alternative investment opportunities. This suggests a non-linear relationship where the middle-income group with adequate (but not maximal) roof space is the most motivated. We test this hypothesis and address potential endogeneity through robustness checks in the following section. Photovoltaic power plants with small installed capacity do not have good economic benefits, and it is not suitable to build distributed photovoltaic power plants with too small available rooftop area. Therefore, the large area of the family rooftop can affect the willingness to install RDPV. The AUC indicator shows that this factor has a good predictive value. With the increasing degree of electrification, the electricity bill is also increasing year by year. The more electricity bills are used by farmers, the more they hope to offset the payment through RDPV. The AUC indicator shows that this factor has a good predictive value. Homes that install solar water heaters generally have a positive attitude towards convenience and a modern lifestyle. The AUC indicator shows that this factor has a good predictive value.

Farmers' cognition of environmental protection passed the significance level test. Taking farmers as the object to study farmers' information acquisition behavior, and analyze farmers' information acquisition behavior from the perspective of cognitive process of cognitive psychology, and discuss the interaction between farmers' cognitive process and information acquisition behavior (Huang et al., 2018). The research on farmers' information behavior is not only a necessary premise for long-term solution of rural informatization, but also a premise for the implementation and function of rural informatization construction (Chen et al., 2017). The AUC indicator shows that this factor has a good predictive value. Farmers' cognition of environmental protection determines their attitude towards installing RDPV. This is a good opportunity to promote RDPV. Similarly, there is an obvious positive correlation between the attitude towards environmental protection and whether farmers are willing to invest in self-built RDPV. The AUC indicator shows that this factor has a good predictive value. Therefore, by interfering with farmers' attitudes and strengthening environmental protection publicity, farmers' willingness to invest will be further increased.

5.4. Robustness checks

To further ensure the robustness of our empirical findings, we conducted additional analyses addressing potential endogeneity and omitted variable bias. First, we re-estimated the core logistic regression model including village-level fixed effects, which control for unobserved heterogeneity such as local leadership attitudes, infrastructure conditions, or village-level policy enforcement. The main coefficients of interest, including those for policy cognition, environmental attitude, and perceived economic return, remained statistically significant and consistent in direction.

Second, we introduced interaction terms to capture heterogeneous effects across household characteristics. For example, the effect of rooftop area on investment willingness was interacted with household income and education level. The results indicate that the previously observed negative correlation between rooftop area and investment willingness is most pronounced among lower-income households, suggesting that financial constraints outweigh physical resource endowments in shaping decision-making (Fig. 5). These robustness checks enhance the credibility of our results and provide a more nuanced understanding of heterogeneity in farmer investment behavior.

5.5. Discussion

It is necessary to strengthen the improvement of market factors such as project profitability and financing support. Although the promotion of the project needs to improve the residents' willingness to invest by intervening on key influencing factors, good profitability is required to fundamentally impress investors (Wang et al., 2022a). With the continuous advancement of technology and business models, as well as the continuous improvement of state support policies, farmers will become more and more motivated. Convenient financing support will have a very good role in promoting project investment (Wang et al., 2022a). The government can strengthen the financing channels of RDPV and reduce the problem of high initial investment costs for farmers, thereby promoting the installation and use of RDPV. In order to seek the balance of interests in the multi-party interest game in project promotion (Wang et al., 2022b).

Some non-market influencing factors need to be given full attention in order to improve farmers' willingness. In the promotion of distributed renewable energy projects, the variables of these non-economic factors

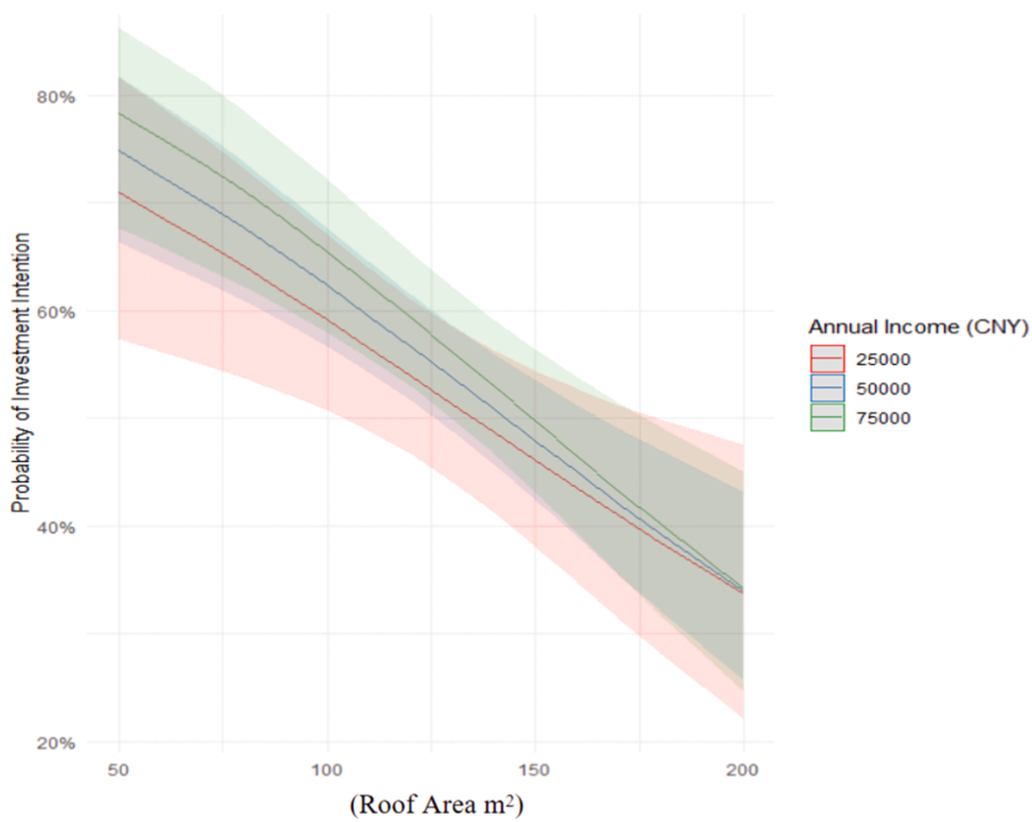

Fig. 5. Marginal effect of roof area on investment intention.

are important breakthroughs (Yazdanpanah et al., 2022). Taking the 11 significant variables found in this study as a reference, prescribing the right medicine will improve farmers' willingness and improve government or enterprise The difficulty of promotion has an important reference value. With the intensification of China's aging population, the improvement of rural education levels, and other factors, the relationship between farmers' willingness and the difficulty of promotion will continue to change, which will also be the direction of future research (Xu et al., 2022). It will also be an important reference for future public policy formulation (Bakhtiyari et al., 2017).

Strengthening the popularization and training of policies in the promotion process, especially the popularization of policies can greatly mobilize the enthusiasm of farmers. Farmers' cognition for self-built RDPV is an important internal driving force (Yaghoubi et al., 2019). Farmers are largely limited by their cognitive level when making decisions (Wang and Yang, 2022). With the diversification of farmers' information sources, farmers have easier access to knowledge and information. Most of them know about RDPV, but the level of understanding is still relatively low. This shows that farmers' cognition of RDPV is not high, and it is difficult to make scientific decision-making. Farmers' decision-making also needs to be driven by benefits at the level of strengthening cognition.

Effective financing mechanisms include microcredit, lease-based schemes, and direct subsidies, which have been proven to reduce upfront cost constraints in similar contexts (Li et al., 2024). Government-backed microloans and lease-to-own models are particularly beneficial for rural households with limited liquidity (Jadidi et al., 2025). Policy combinations such as subsidies coupled with awareness campaigns are expected to be more cost-effective in promoting RDPV adoption than standalone measures (Zaidan et al., 2025). These joint strategies improve both economic feasibility and farmer cognition.

Collaboration between local governments and PV companies can reduce investment risks through mechanisms such as guaranteed buyback schemes and post-installation service guarantees (Martin and Rice, 2013). Such arrangements improve trust and reduce the perceived risk among farmers. While our current simulation focuses on farmers and government, we recognize that stakeholders such as PV companies, banks, and grid operators also play essential roles (Chandel et al., 2022). Future game-theoretical models should include these actors to reflect a more realistic interaction system.

Social influence, such as neighbor adoption and community examples, is another important factor affecting decision-making (Chanda et al., 2025a). Although not measured in the current study, future research should incorporate peer effect variables into the analytical model. Stable pension income and elderly care subsidies could increase older farmers' confidence in investing in PV systems (Wu et al., 2024), as they reduce financial uncertainty. These demographic-economic interactions should be further explored. Information asymmetry is a common problem in rural energy projects (Chen et al., 2025). If farmers underestimate the long-term savings of PV systems, it could distort decision-making outcomes. Future studies may integrate behavioral assumptions or bounded rationality in the game model to capture such distortions.

China's RDPV adoption differs from countries like Germany and India. Germany promotes adoption through long-standing feed-in tariffs (Mueller et al., 2024), while India fosters growth via solar cooperatives and community models (Kumar et al., 2025b). Our findings highlight the importance of adapting policy tools to local institutional and cultural contexts.

Although our survey did not explicitly account for seasonal income fluctuations (e.g., from harvest cycles), this remains an important future research direction. Including temporal variables could further enhance the predictive accuracy of investment willingness models (Liu and Ling, 2025). Falling PV costs and the future integration of battery storage are likely to enhance the attractiveness of RDPV for farmers (Turnley et al., 2024). Storage systems can increase self-consumption and stabilize returns, making investment more appealing over the next 5–10 years (Bai et al., 2024). Peer-to-peer trading of excess solar power among farmers could provide additional income sources and enhance adoption incentives (Maya et al., 2025). Future pilot projects and policy trials are encouraged in this direction.

The findings move beyond mere statistical associations and offer concrete, actionable insights for policymakers. Firstly, targeting the "Willing but Unable" Segment. The strong positive effect of Annual Household Income (OR $= 1.000035$, $p < 0.01$) confirms that financial capacity is a fundamental barrier. While a single unit increase in income has a small effect, the difference between low and high-income households is substantial. This justifies targeted subsidy schemes or low-interest loan programs specifically designed for low and middle-income households who demonstrate high environmental awareness but lack capital. Secondly, investing in Education and Awareness Campaigns. The 22 % higher odds per year of education and the 50 % higher odds per point of environmental knowledge are not just statistics; they represent a clear policy pathway. Instead of generic propaganda, training programs should be designed to improve functional literacy around RDPV's economic and environmental benefits, directly tackling information asymmetry. Our ROC analysis confirms that environmental awareness is a key leverage point. Thirdly, reframing the Value Proposition for Different Audiences. The negative effect of rooftop area suggests a one-size-fits-all promotional approach is ineffective. For wealthy households with large roofs, the messaging should shift from pure economics to status, environmental leadership, and energy independence. For the broader audience, simplifying the installation process and providing reliable maintenance services (as indicated by the significance of Home Time and Left-behind elderly) is crucial to reduce perceived risks. Forthly, leveraging Social Proof and Demonstrations. The high predictive power of Environmental Attitude suggests that farmers who value sustainability are early adopters. Policies should identify and incentivize these "green champions" to serve as local demonstrators, leveraging community influence to overcome the inertia of their peers, thereby reducing the government's direct promotional costs (Wang and Yang, 2023).

Our findings both confirm and extend the existing body of knowledge. The significant influence of economic factors like income and perceived return aligns with foundational research globally (Chanda et al., 2025b)and within China (Li et al., 2025; Ma, 2025). Similarly, the powerful role of environmental awareness reinforces findings from European contexts (Geoghegan and Donoghue, 2023), suggesting that this driver may have universal importance, even in developing economies where economic pressures are more acute. However, our study reveals nuances specific to the Chinese context. The counterintuitive relationship between rooftop area and WTS, which we found was moderated by income, highlights a form of behavioral heterogeneity that is often overlooked in the literature, which tends to assume uniform economic rationality. This finding necessitates a more segmented policy approach than is commonly proposed.

Our primary theoretical contribution lies in the integration of bounded rationality with evolutionary game theory. This approach moves beyond the standard economic models prevalent in the literature by acknowledging that farmers make decisions under cognitive constraints and that policies evolve through strategic interaction. By simulating these interactions, we provide a dynamic tool for policy testing, a methodology advocated in international research but still underutilized in the Chinese PV context.

5.6. Limitations

This study also has many limitations. Firstly, the data collected in this study is subject to funding and manpower constraints, and the amount of data has certain limitations. Although we incorporated regional average solar data (sunshine hours) to ground our economic estimates, future research could utilize high-resolution satellite-derived irradiance data or on-site measurements for individual households to achieve more precise energy yield predictions. This study did not further explore the mechanism of action of some control variables found in the study. These are to be realized in further research. Secondly, this study focuses primarily on the demand-side (farmer) willingness. The actual large-scale deployment of RDPV is also contingent on technical feasibility and grid-side constraints, including grid absorption capacity, voltage stability, and interconnection standards. Future research should integrate these crucial supply-side technical factors into a comprehensive multi-agent model to provide a more holistic assessment of RDPV integration pathways. Thirdly, grid-side Constraints. Although this study focuses primarily on farmer-side willingness to invest in distributed PV, the eventual success of large-scale adoption also hinges critically on the absorptive capacity and technical constraints of the rural power grid. In practice, issues such as voltage stability, connection standards, and grid integration costs may limit the effective deployment of PV systems, even when farmers demonstrate strong investment intentions. The omission of these grid-side constraints represents a limitation of our current analysis.

6. Conclusions and policy recommendations

6.1. Conclusions

This paper takes farmers' self-built RDPV as an example to understand farmers' willingness to develop in order to formulate corresponding project promotion strategies, so as to promote the realization of "carbon neutrality" in rural areas through energy improvement in rural areas. The economic benefits presented to farmers were derived from a calculation model based on Jinan's proven solar irradiance data (2268 annual sunshine hours), providing a realistic foundation for assessing investment returns. First, through interviews and investigations, the importance of economic factors such as project investment income to farmers' decision-making was confirmed. Secondly, through the analysis of the survey data of non-economic factors, the study found that the age of the farmers, the level of education, the time at home each year, whether there are left-behind elderly people in the home, the number of family members, the annual family income, the age of the house, the rooftop area, and the household electricity expenses. whether there are solar water heaters, environmental protection knowledge and environmental protection attitude and other variables can significantly affect the willingness of farmers to participate in the construction of self-built RDPV power generation. The hypotheses proposed in this study were verified. Third, through further interviews, the farmers' demands were discovered, and important qualitative analysis suggestions were formed. Finally, based on the above research findings and conclusions, combined with China's current national conditions, in order to better develop rural RDPV. It is necessary to strengthen the improvement of market factors such as project profitability and financing support, to fully understand and utilize the effect of non-market factors on farmers' wishes, and to improve farmers' cognition of projects, so as to finally realize the vision of farmers' initiative to embrace "carbon neutrality".

6.2. Policy recommendations

Based on the findings of this study, the following streamlined policy recommendations are proposed to enhance the effectiveness of the "Whole-county promotion mode" for rooftop distributed photovoltaic (RDPV) development:

Develop Differentiated Subsidy Programs. Design tiered subsidy levels and low-interest loan options based on key household characteristics (e.g., income level, rooftop area). This precision targeting maximizes the impact of financial support and alleviates initial investment burdens for the most viable yet financially constrained households.

Simplify Information and Enhance Cognitive Accessibility. Launch clear, localized information campaigns that use simple cost-benefit examples and leverage the most effective communication channels (e.g., community champions, TV/media). This strategy is crucial for overcoming information asymmetry and bounded rationality, helping farmers make informed decisions.

Establish Localized Service and Maintenance Networks. Incentivize PV companies to set up local operation and maintenance (O&M) service points within counties. This provides farmers with reliable, accessible technical support, mitigating perceived risks and long-term maintenance concerns, which is especially important for households with left-behind elderly members.

Streamline Procedures and Foster Collaboration. Create a "one-stop" service platform to simplify the processes of application, grid connection, and subsidy collection for farmers. Furthermore, foster collaboration between governments, PV companies, and financial institutions to establish a supportive ecosystem with clear benefit-sharing mechanisms.

In summary, moving beyond uniform subsidies towards a holistic package of precision financing, simplified information, reliable service, and streamlined procedures is essential for motivating widespread farmer investment in RDPV and achieving rural carbon neutrality goals.

CRediT authorship contribution statement

Qiang Wang: Writing – review & editing, Writing – original draft, Project administration, Data curation, Conceptualization. **Yueling Yang:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Liang Meng:** Visualization, Software, Resources, Data curation. **Guocai Yu:** Supervision, Resources, Project administration, Funding acquisition. **Jiachen Wang:** Writing – original draft, Validation, Resources, Investigation. **Ye Li:** Writing – original draft, Validation, Supervision, Software, Methodology, Investigation.

Declaration of Competing Interest

No potential conflict of interest was reported by the authors.

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Data availability

Data will be made available on request.

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