Research on the investment decisions of PV micro-grid enterprises under carbon trading mechanisms

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Abstract
Achieving carbon neutrality targets requires substantial financial support. Effective utilization of renewable energy is an essential means of promoting energy-saving and emission reduction to realize a green and circular economy. This paper combines carbon trading mechanisms with the operational mode of Chinese micro-grid enterprises. This method uses the real options theory to construct an investment decision model for photovoltaic (PV) micro-grid enterprises. The study aims to analyze the impact of carbon trading revenue on a numerical simulation of PV micro-grid enterprise investment decisions. The findings demonstrate that when projected growth rates, volatility standard deviations, and risk-free interest rates rise in the carbon trading market, the carbon price threshold rises, causing businesses to seek out investment opportunities with higher future carbon prices. The increase of micro-grid generation technology acceptance probability, the availability of resources to meet generation investment requirements, and the generation project cycle will decrease the carbon price threshold and accelerate enterprise investment. Studying the influence of carbon trading prices on micro-grid investment has specific guidance and practical significance for future government subsidy policies and the investment strategies of grid enterprises.

Keywords
carbon trading mechanism, investment decision, PV micro-grid, real option theory, renewable energy

1 | INTRODUCTION

The increasing prominence of global climate change, reducing carbon emissions, optimizing the energy mix, and reducing fossil energy consumption is currently among the most important concerns of countries worldwide. The achievement of carbon neutrality targets requires large investment, and although the process is diverse and complex, the aim is to achieve green development. China’s commitment to the world to reach the “double carbon” goal of peak carbon and carbon neutrality will not be easy and will require a substantial financial investment. The existing forecasts vary, but investment is forecast to exceed 15 trillion dollars. For such a large investment, government funds can only cover a small portion, and the gap must be made up through social capital, which will be guided by market-based approaches. The carbon market can play the role of...
providing a signal of the carbon price in the market, stimulating, and attracting resources to low-carbon green projects.\(^1\)

The State Council’s “Notice of the State Council on Issuing the Work Plan to Control Greenhouse Gas Emissions during the 13th Five-Year Period” (the “Greenhouse Gas Control Plan”) means that China’s market will start to implement nationwide carbon emissions trading. The PRC government should increase carbon emission reduction to expand China’s micro-grid industry’s market scale and industrialization. This will then promote the development of new energy, energy conservation, environmental protection, and other strategic emerging industries, as well as cultivating new economic growth points, and encouraging investment in micro-grid power generation projects.

Government-driven investment in micro-grid projects increases, resulting in more resources from other industries and an increase in the factor prices of resources. When costs rise, micro-grid companies’ profitability falls, and thus rely solely on subsidies from government-led investments. More government-led investments will cause a decline in overall efficiency and bring further downward pressure on the economy, creating a vicious circle. When government subsidies increase and electricity prices remain at the same level or rise, the cost of electricity does not fall, leading to a decline in the profitability of traditional enterprises. Therefore, the government should not have unlimited subsidies but should encourage the market to play a leading role so that renewable energy enterprises themselves lead investment projects.

China’s investment ratio in clean energy and new energy has increased significantly. Photovoltaic (PV) power generation is one of the most energy-efficient and consumption-reducing energy acquisition methods. It has become one of the crucial paths to enhancing the reliability and safety of electricity consumption in China. Smart micro-grid supplies reliable and inexpensive power with low carbon emissions.\(^2\) Statistics show that by the end of 2020, the cumulative installed capacity of PV power generation in China reached 253 GW, up 23.5% year-on-year, with a growth rate up from 17% in 2019. Despite the impact of COVID-19, China’s cumulative installed PV power generation scale has still ranked first in the world for six consecutive years. Fully leveraging the coordinated development of PV and grid technology can effectively solve the dilemma. The PV micro-grid then becomes an essential mode of layout for many domestic micro-grid companies. The experience of developed countries demonstrates that the combination of PV power generation and micro-grid energy storage mode creates, opportunities for innovation and gain in

many aspects Thus, the PV micro-grid has gained considerable corporate attention for investment and management. The emergence of the PV micro-grid meets the demand for government energy saving and emission reduction policy, and also effectively develops a low carbon economy, realizing the coordination of both social and economic benefits.

Compared to traditional thermal power generation projects, the investment in power generation in PV micro-grid projects is riskier and more complex. The investment decision generally has the following three characteristics: first, the future return on investment is uncertain; the investor can choose the timing of the investment. Second, the capital is less liquid. Thirdly, the capital cannot be revoked in whole or in part.\(^3\) These three characteristics of investment decisions give PV micro-grids option value. In this study, taking PV power generation projects in micro-grid power projects as an example, we apply real options theory to the investment characteristics of PV micro-grid power projects, and then study the impact of relevant policies on the investment decision of micro-grid power enterprises. The next step is to determine the investment option value of enterprises. Finally, we need to determine the best time to invest and provide policy recommendations for the government to develop incentives for PV micro-grid investments and derive more insightful policy implications. This can serve as a possible solution to help the Chinese government promote further development of the microgrid industry.

The remaining sections of this paper are organized as follows: Section 2 reviews related literature. Section 3 introduces the real options model and describes three kinds of uncertainty factors when micro-grid companies invest in photovoltaic power generation projects. We establish the value model of the PV power project investment decision and solve the decision model. In Section 4, we conduct a numerical simulation to analyze the impact of factors such as the fluctuation of the carbon price on investment decisions and find the optimal investment timing. We then test the prediction accuracy of the model. In Section 5, we summarise the conclusions and provide recommendations.

2  |  LITERATURE REVIEW

This section reviews research closely related to this paper. It consists of two streams. The first stream of literature is related to carbon trading market mechanisms and implementation of carbon trading policy, and
the second stream of literature reviews investment decisions of PV micro-grid and renewable energy.

### 2.1 Carbon trading market mechanism and implementation of carbon trading policy

In terms of carbon trading market mechanisms, the gradual deepening of the global industrialization of carbon emissions trading and the severe impact of global human over-consumption of fossil fuels has become a problem that cannot be ignored. Foreign scholars have conducted in-depth and accomplished research in this area. Pigou, Coase, and Ostrom are among the best and provide important theoretical models. Research on the price of carbon emissions trading, and carbon emissions trading mechanisms of countries worldwide have greatly enriched international social practices and promoted new developments in the international legal system. The ETS is generally considered effective. As a market-based mechanism that controls emissions by providing incentives for reductions, it is cost-effective with minimum social costs, thus enabling firms to develop their mitigation strategies to cope with climate change through free trade between businesses. Since its first introduction, researchers have regularly suggested that the ETS plays or will play a significant role in achieving a low-carbon society and promoting green growth. Xia and Tang conduct a comparative analysis of different global carbon trading market mechanisms. On one hand, the results indicate that direct trading of carbon emission reduction credits between supply and demand parties is more efficient and effective than trading through intermediaries with better prices. On the other hand, when cross-regional transactions of carbon emission rights are realized, the transaction price can be best adjusted through the marginal abatement cost. It can also improve the transaction efficiency of the supply and demand sides, which is contributed to energy saving and reduction. Rannou starts with the industrial sector with the most significant carbon emissions and explores the effect of change mechanisms on the industrial output value of the price of carbon emission reduction allowances. He finds that among the various industrial sectors selected by E.U. member states, only the industrial output value of individual industries plays an essential role in the price of carbon emission reduction allowances.

In terms of the implementation of carbon trading policy, based on a simulation approach, Zhang et al. investigated the actual impact of carbon emission reductions resulting from the implementation of carbon trading policy in China when considering the national day constraint. used a three-stage DEA to analyze the carbon emission efficiency before and after the implementation of carbon trading. The carbon emission intensity was reduced to a certain extent through carbon trading policies. Zhao et al. conducted an empirical analysis using a quantile double difference research method to test the synergistic emission reduction effect of the implementation of carbon trading policy on regions in the postindustrial stage of economic development. This synergistic effect includes carbon emissions, haze, sulfur dioxide, and other air pollution. The study uses the mediating effect approach to test the transmission mechanism of environmental improvement by carbon trading policy. It is also suggested that the implementation of a carbon trading policy can effectively force the improvement of science and technology, optimize the energy structure, and produce the synergistic effect of air pollution reduction. Lu et al. collected relevant provincial panel data from 2006 to 2017 in China for empirical analysis based on a counterfactual analysis. They used the synthetic control method to explore the effect of China’s carbon trading pilot policy measures on the intensity of transportation carbon emission reduction in the test region. The mediating effect method was used to analyze the transmission mechanism of “improved transport structure.” Lu and Luo collected relevant panel data from thirty provinces and cities during 2005 to 2016 and investigated the effect of carbon trading policy implementation on CO2 emissions using the D-in-D. The study indicates that the policy can contribute to a significant and sustained reduction in CO2 emissions. At the same time, they tested the adaptability of the D-in-D to this problem. Zhou and Liu used the PSM-DID based on data from a sample of prefecture-level cities between 2010 and 2016. The study explored the effect of the implementation of the carbon trading policy in China on carbon emissions of prefecture-level cities and its mechanism from a meso perspective of cities. According to the study, carbon trading can significantly reduce carbon emissions through industrial restructuring and energy savings. Hu and Ding collected relevant historical data from listed enterprises in China during 2006–2017. Using the Difference-in-differences method, they evaluated the effect of the implementation of a carbon trading policy on firm effectiveness and green performance. Their study used the mediating and moderating effect models to detect the effects of green innovation, marketization, and government subsidies.

### 2.2 PV micro-grid and renewable energy investment

With respect to the impact of photovoltaic energy costs and tariffs on investment, Liu et al. proposed a
Energy trading decision model with the objective of minimizing the cost of power purchase by the power sales company. This study uses distributed photovoltaics as an example of distributed power sources that can participate in the market through the agency of a power sales company. A two-agent “dual-price” contract pricing mechanism is designed to determine the optimal decision price and settlement price based on forecast and actual electricity prices, respectively. The former is used for model optimization and the latter is used for contract settlement, thus achieving a balance of interests between the two agents. Lu et al.'s research is based on a non-cooperative game model of smart electricity optimization in distributed PV residential communities. In the study, PV power generation was predicted, and then a cluster analysis was performed based on the load profile of urban communities. Finally, a non-cooperative game model between PV energy providers and community users is constructed. Zhong et al. focused on the impact of discharge frequency and depth on the lifetime of energy storage. This study established a power optimization model with the objective of minimizing the total cost of investment operation and maintenance.

Regarding energy market incentives for investments in renewable energy, Jiang et al. examined the economic interactions between community energy suppliers and PV consumers from a cooperative viewpoint. They proposed a bargaining model of cooperation with a non-master-slave relationship. The Community's energy suppliers are prepared to offer incentives for consumers to participate. PV consumers may act as producers or consumers to maximize utility by negotiating with community energy providers to determine the energy exchanged. Compared with the Stackelberg game approach, both PV consumers and community energy managers can benefit more from the Nash bargaining cooperative model. Wu et al. focused on the characteristics of the new electrical power architecture. The research highlights that the energy storage industry should accelerate technological innovation around high resilience, universality, technical flexibility, and resource sharing. It should also be tightly integrated with the relevant business models. Zhang et al. proposed a hierarchical system architecture model to identify and classify the key links in the process of trading small-scale distributed energy directly with local energy producers and consumers. The study also proposed the idea of a P2P energy trading platform and used the theory of game theory to mimic the process of trading. Morstyn et al. formed the overall demand by coordinating small-scale distributed energy sources. A new scalable peer-to-peer energy trading market is designed based on a network of bilateral contracts. This is done to alleviate the need for investment in upstream generation and transmission infrastructure and to improve network efficiency and energy security.

These summarized studies provide important references for the investment decisions of microgrid enterprises under the carbon trading mechanism. In recent years, the carbon trading market mechanism has been maturing and flourishing, and at the same time, its financialization has become increasingly prominent. Scholars have been focusing on the impact of carbon allowances on carbon markets and enterprises, with research focusing on the impact on costs and emission effects with or without allowances or under different allowance approaches. The pricing of carbon allowances is a key focus of carbon trading research. Researchers have suggested that carbon trading impacts the investment decision of microgrid companies. Focusing on the influencing factors of the carbon price and the influencing mechanism among them, we can predict the future direction and trend of the carbon price.

When considering uncertainties, existing studies have focused on the role of carbon trading systems on macroeconomic regions or cities, meso-industries, and micro-enterprise perspectives. They have mainly considered the potential of renewable energy, the ability of renewable energy to replace traditional energy sources, and the benefits of renewable energy generation. Uncertainties such as PV feed-in tariff, PV power cost, and carbon price fluctuations are less involved in the investment process. The interaction between micro-grid enterprise investment decisions and related influencing factors has also received less attention. The carbon price, PV generation cost, and PV feed-in tariff are factors that can directly or indirectly affect the income of renewable energy investors. Research methods involving carbon trading policies and PV microgrid project investments are mostly studied using scenario simulation analysis methods and double-difference methods. There are few Chinese and international studies involving investment decision models for microgrid enterprises based on the above factors.

In this study, we propose a model for PV micro-grid power generation project investment. We establish a decision value model by combining three uncertainties: PV feed-in tariff, PV power generation cost, and carbon price. Micro-grid enterprises need to consider these factors when making PV power project investments. All these factors are considered together to ensure the feasibility and accuracy of the results, and the investment threshold for photovoltaic micro-grid power generation projects.
3 | METHODS

3.1 | Theoretical framework

3.1.1 | Real option model

Real options were first introduced by Professor Stewart C. Myers and refer to options that investors have or create throughout the future process of investing. Real options theory is an extension of financial options theory to tangible assets, using the concept of options to define a firm’s options on an investment. When a firm is faced with an investable project, the firm has the right, but not the obligation, to decide to invest. Real options theory has been applied to the power industry since the late 1990s, mainly in power generation investments.

3.1.2 | Influencing factors analysis

Micro-grid enterprises must consider three uncertainties when investing in PV power projects: PV feed-in tariff, PV power generation cost, and carbon emission trading mechanism.

**PV feed-in tariff**

PV power generation enterprises need more considerable investment in the early construction stage and maintenance and development in the later operation stage. According to the low efficiency of PV power generation at the present stage, the PV feed-in tariff cannot yet compete with the thermal power tariff in a fully market-based manner. The National Development and Reform Commission in June 2021 issued a “notice on matters related to the new energy feed-in tariff policy in 2021,” for the newly approved (for the record) solar thermal power generation project feed-in tariff by the local provincial price authorities to develop. This regulation also encourages the introduction of targeted support policies around the country to support the sustainable and healthy development of new energy industries such as photovoltaic power generation. Currently, Zhejiang, Jiangsu, Beijing, Shanxi, Guangdong, and other provinces in 18 areas still give distributed PV subsidies. Investors are uncertain about the amount of feed-in tariff subsidies from various provinces and municipalities as a factor affecting investment decisions in PV power projects before the project is implemented.

**PV power generation cost**

There are still many uncertainties in developing new and renewable energy sources, and the cost of PV power generation is one of the critical factors. PV power generation costs include installed costs, financial costs and operation, and maintenance costs, and so on. Companies consider PV power generation costs to be poorly measured when making PV power generation investment decisions. In contrast, the breakdown costs in PV power generation costs are closely related to the technological attack, government policies, equipment depreciation life, operation and maintenance costs, and loan status. Therefore, the uncertainty of PV power generation cost is a factor that affects the investment decision of PV power generation projects.

**Carbon emission trading mechanism**

To promote global greenhouse gas emission reduction, the Kyoto Protocol set up three-carbon emission trading mechanisms, namely Clean Development Mechanism (CDM), Joint Implementation (JI), and Emissions Trading (ET). China draws on the carbon offset mechanism in the Kyoto Protocol Clean Development Mechanism (CDM) to build a voluntary certified emission reduction mechanism (CCER) applicable to the country. Since 2013, the number of domestic CDM projects has dropped sharply due to the EU's restrictions on CDM projects, and China has started to establish a carbon trading market system—Carbon Emission Trading (ETS) Pilot Market + Voluntary Certified Emission Reduction (CCER). Carbon Emissions Trading (ETS) pilot market + Voluntary Certified Emission Reduction (CCER) mechanism. As the rules of CCER offsetting are different in each pilot market, the value of CCERs varies from region to region, and the current trading is still based on offline negotiation, with prices fluctuating between 10 and 30 RMB/ton. The international carbon trading market influences the price in the carbon trading market, so the uncertainty of carbon price is a factor affecting the investment decision of PV power projects.

3.2 | Model description

3.2.1 | Model hypothesis

Based on the above study, micro-grid enterprises must consider three uncertainty factors when investing in PV power generation projects: PV feed-in tariff, PV power generation cost, and carbon price. The total PV power project plan is T. Referring to Zhang, Zhou P, Zhou DQ's approach to PV investment decision and Pingping Yu's approach to strategic investment in renewable energy, the value model of PV power project investment decision is established.
Hypothesis 1. Micro-grid enterprises investing in PV power projects are rational and risk-neutral, and $m$ is the risk-free rate.

Hypothesis 2. According to Dixit and Pindyck’s model, the carbon price for the sale of approved carbon emission reductions from PV power projects based on CCER is $P$. In the market environment, the carbon price $P$ is a random variable and obeys geometric Brownian motion:

$$dP = \alpha P dt + \sigma P dz. \quad (1)$$

In the equation, $P$ refers to the expected growth rate of the carbon price, $\sigma$ refers to the standard deviation of carbon price fluctuations, and $dz$ refers to the standard Wiener process increment.

Hypothesis 3. The total planned period of the PV power project is $T$. The decision-making right of the PV power project can be made at any point of the total planned period, which is divided into the pre-project planning period, the project construction period, and the operational power generation period, respectively, which are denoted as $T_1$, $T_2$, $T_3$.

$\xi$ refers to total project investment, and $V(P)$ is the total investment value. $\xi_1$ refers to pre-planning period investment, and $V_1(P)$ is pre-planning period investment option value. $\xi_2$ refers to the project construction period investment, and $V_2(P)$ refers to the project construction period investment option value. $\xi = \xi_1 + \xi_2$.

Hypothesis 4. $t_1$ is the pre-planning completion time node of the project. If the project goes through pre-planning and the results meet the project investment requirements, it can move to the next phase, the probability of this happening is $p$. If for some reasons, such as uncertainty of resources that lead to no further investment in the project, the loss is $\xi_1$, the probability of this happening is $1 - p$. $t_2$ is the project construction period completion time node, $t_3$ is the project operation end node.

Hypothesis 5. During the total project planning period, the price of electricity and the level of power generation technology for PV power projects are fixed, both based on the approved price and technology level during the pre-planning period. The expressions of the feed-in tariff $P_r$ and the unit generation cost $c$ of the PV power project as a function of:

$$P_r(t_i) = e^{-\vartheta t_i} P_r^0, \quad (2)$$

where $P_r^0$ is the feed-in tariff level in the pre-planning period, and $\varphi$ is the average annual decline in feed-in tariff ($0 \leq \varphi < 1$). $c_0$ is the level of power generation cost during the pre-planning period, $\theta$ is the probability of acceptance of power generation technology after the pre-planning period, $\theta \in (0, 1)$ follows the standard normal distribution, $\delta$ is the rate of cost reduction per unit of power generation after the acceptance of power generation technology ($0 < \delta < 1$).

3.2.2 Decision-making model

When studying the investment decision problem of PV power generation enterprises, it is necessary to find the best time to invest to obtain the maximum return on investment. There are two primary sources of revenue for PV power projects: the revenue earned from the sale of electricity and the revenue earned from the carbon emission reductions approved by CCERs. Here, it is assumed a conversion factor $\lambda$ of CCER-approved carbon emission reductions and electricity generation,

$$\lambda = \frac{\text{CCER-approved average annual carbon emission reductions of PV power projects}}{\text{Average annual power generation capacity of PV power projects}},$$

which converts the revenue per unit of carbon emission reductions approved by CCER into revenue per unit of electricity generation. The total revenue of the PV power project is shown as follows:

$$G(P) = (P + P_r - c)Q = \left[\lambda P + e^{-\vartheta T_1} P_r^0 \right]Q - (1 - \delta \theta) c_0 Q. \quad (4)$$

Factors such as technological progress, industrial structure, energy composition and policies have important impacts on the baseline, so the emission reductions generated by CCER project activities will differ with changes in these factors. This creates uncertainties and risks associated with CCER project investments and abatement benefits, which are difficult to define in advance. In this case, a proposed CDM carbon emission reduction project would have an operational lifetime of 10 years. The total revenue of the PV power project is converted to the present value of...
\[
\int_{t_0}^{t_{i+10}} G(P)e^{-\delta t}dt = \int_{t_0}^{t_i} (\lambda Pe^{\delta t})Qe^{-\delta t}dt \\
+ \int_{t_0}^{t_i} \left[e^{-\varphi T_i}P^0 - (1 - \delta \delta)c_0 \right]Qe^{-\delta t}dt.
\]

Further,
\[
\int_{t_0}^{t_i} G(P)e^{-\delta t}dt = P \\
\frac{\lambda e^{-(m-a)(T_i + T_j)}}{m - \alpha} \left[1 - e^{-10(m-a)} \right]Q \\
+ \frac{\left[e^{-\varphi T_i}P^0 - (1 - \delta \delta)c_0 \right]Q}{m} \left[1 - e^{-mT_i} \right]e^{-m(T_i + T_j)}.
\]

Let \( \mu = \frac{\lambda e^{-(m-a)(T_i + T_j)}}{m - \alpha}P \cdot \mu = V \), where \( V \) is the value of revenue obtained from the sale of carbon emission reductions from PV power projects, which fluctuates randomly with the carbon price. \( V \) is the value of the revenue obtained by the PV power project through the sale of electricity.

### 3.3 Model analysis

In the next stage, we are about to solve the value of the PV power projects. Let \( V(P) \) express the total value of the PV power project. \( V(P) \) refers to the function of the carbon price. Applying the Bellman equation\(^27\) with Ito’s Lemma\(^28\) to derive the differential equation satisfying. Applying the dynamic programming method, the Bellman equation in the continuous period is found as

\[
dP = \alpha P dt + \sigma P dz. \tag{7}
\]

The above equation shows that the expected total return of the investment opportunity in \( t \) period is equal to the expected rate of appreciation of the invested capital. According to Ito Lemma, obtain

\[
\frac{1}{2} \sigma^2 P^2 V''(P) + \alpha PV'(P) - mV(P) + G(P) = 0. \tag{8}
\]

Here, after the construction of the PV power generation project is completed, the enterprise will operate and generate electricity immediately, and there is no delay in production. Therefore, the project value of the PV power enterprise is the discounted value of the total project return, namely:

\[
V(P) = \frac{\mu P + V_0}{\lambda P e^{-(m-a)(T_i + T_j)}} \left[1 - e^{-10(m-a)} \right]Q \\
+ \frac{\left[e^{-\varphi T_i}P^0 - (1 - \delta \delta)c_0 \right]Q}{m} \left[1 - e^{-mT_i} \right]e^{-m(T_i + T_j)}. \tag{9}
\]

Due to the presence of three uncertainties, PV project feed-in tariff, PV power generation cost, and carbon price, PV power generation companies need to weigh the benefits from two strategies, that is, investing immediately or waiting for a period until the information is revealed.\(^29\) Waiting for a period to invest is similar to the American option and is a right granted to the power producer. This option reduces the risk of project failure and is referred to as a delayed investment option.\(^30\)

Power generation enterprises must find the best time to invest, that is, the investment threshold of the project when making investments. Therefore, the investment decision problem of power generation companies is transformed into finding the optimal carbon price \( P^* \). When \( P \geq P^* \), power generating companies invest in PV projects, and when \( P < P^* \), power generating companies will choose to wait and will not invest immediately.\(^31\)

Since both the pre-planning and construction phases of a PV project involve option estimates of carbon prices, to find the investment threshold value, that is, \( P^* \), in addition to the total value of the PV project, that is, \( V(P) \), it is necessary to find the value of the investment option for the pre-planning phase of the PV project, that is \( V_1(P) \) and the value of the investment option for the construction phase of the PV project, that is \( V_2(P) \).\(^32\) Only if \( V_1(P) \) is executed, \( V_2(P) \) can be enjoyed. \( V_1(P) \) is equivalent to a compound option, its value depends on whether to invest more capital to buy the underlying option of the composite option, that is \( V_2(P) \). It can only be obtained \( V_1(P) \) by solving for \( V_2(P) \).\(^33\)

According to Ito Lemma, obtained the differential equation satisfying the \( V_2(P) \):

\[
\frac{1}{2} \sigma^2 P^2 V''(P) + \alpha P \cdot \frac{\partial V_2}{\partial P} - mV_2(P) = \frac{1}{2} \sigma^2 P^2 V''(P) + \alpha PV_2(P) - mV_2(P) = 0. \tag{10}
\]

Equation \(10\) converted to a general solution:

\[
V_2(P) = M_1 P^\kappa + M_2 P^{\kappa}. \]
\( M_1 \) and \( M_2 \) are undetermined constant, \( \chi_1, \chi_2 \) are two roots of the quadratic equation below, let \( \chi_1 > \chi_2 \):

\[
\frac{1}{2} \sigma^2 \chi (x - 1) + \alpha x - m = 0
\]

\[
x_1 = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{\alpha}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2m}{\sigma^2}}.
\]

\[
x_2 = \frac{1}{2} - \frac{\alpha}{\sigma^2} - \sqrt{\left(\frac{\alpha}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2m}{\sigma^2}}.
\]

Observing the nature of the image of the function corresponding to Equation (11), there is \( \chi_1 > 1, \chi_2 < 0 \). The critical value of the carbon price for making investments during the project's construction period is \( P_2^* \), when \( P = 0 \), \( V_2(P) = 0 \), when \( P \to 0 \), \( P \chi \to \infty \), and the value of the investment option tends to 0. Thus \( M_2 = 0 \), \( V_2(P) = M_1 P \chi \), hence, the value of the investment during the construction period of the project is

\[
V_2(P) = \begin{cases} 
M_1 P \chi, & P < P_2^*, \\
\mu P + V' - \xi_2, & P \geq P_2^*.
\end{cases}
\]

(12)

By the value matching condition of the critical point and the smoothing paste condition required, on the critical value of the carbon price \( P_2^* \) for investing in the project construction period, \( \psi \) the value of the investment option in the project construction period \( V_2 \) is equal to the value of the termination return \( V(P) - \xi_2 \), that is \( V_2(P_2^*) = V(P_2^*) - \xi_2 \). The two function derivatives are also equal, that is \( V_2'(P_2^*) = V'(P_2^*) \), it is deduced that:

\[
\begin{cases}
M_1 P_2^* P \chi = \mu P + V' - \xi_2, \\
\chi_1 M_1 P_2^* P \chi - 1 = \mu,
\end{cases}
\]

(13)

obtained:

\[
\begin{cases}
M_1 = \frac{\mu P_2^* P \chi - 1}{\chi_1}, \\
P_2^* = \frac{\chi_1}{\mu (\chi_1 - 1)} (\xi_2 - V').
\end{cases}
\]

(14)

Similarly, the critical value \( P_1^* \) of the carbon price for the investment made during the pre-planning period of the project, in which the enterprise does not generate any profit, along with uncertainties such as resource availability, therefore, a parameter \( \psi \) is set indicating the probability that the measured resource availability meets the investment requirements for power generation. \( \psi \)

According to Ito Lemma, obtain the differential equation satisfying \( V_1(P) \):

\[
\frac{1}{2} \sigma^2 P^2 \cdot \frac{\partial^2 V_1}{\partial P^2} = \alpha P \cdot \frac{\partial V_1}{\partial P} - m V_1(P) = \frac{1}{2} \sigma^2 P^2 V_1''(P) + \alpha P V_1'(P) - m V_1(P) = 0.
\]

(15)

Equation (15) converted to a general solution:

\[
V_1(P) = N_1 P \psi \chi, \text{ where } N_1 \text{ is an undetermined constant, } \chi_1 \text{ is the root, } \chi_1 > 0.
\]

The critical value of the carbon price for investment in the pre-planning period of the project is \( P_1^* \), when \( P = 0 \), \( V_1(P) = 0 \), when \( P \to 0 \), the value of the investment option tends to 0. By the value matching condition of the critical point and the smoothing paste condition requirement, the value of the investment option in the construction period of the project \( V_1 \) is equal to the termination return value \( \psi [V(P) - \xi_2] - \xi_1 \), on the critical value \( (P_1^*) \) of the carbon price for investment in the construction period of the project, which considered to be

\[
V_1(P_1^*) = \psi [V(P_1^*) - \xi_2] - \xi_1 = \psi (\mu P_1^* + V_1 - \xi_2) - \xi_1, \text{ the derivatives of the two functions are also equal, then:}
\]

\[
V_1(P) = \begin{cases} 
N_1 P \psi \chi, & P < P_1^*, \\
\psi (\mu P + V_1 - \xi_2) - \xi_1, & P \geq P_1^*,
\end{cases}
\]

obtained:

\[
\begin{cases}
N_1 = \frac{\psi \chi_1}{\chi_1}, \\
P_1^* = \frac{\chi_1}{\psi (\chi_1 - 1)} (\xi_2 + \xi_2 - \psi V_1),
\end{cases}
\]

(16)

\[
P_1^* - P_2^* = \frac{\chi_1}{\psi (\chi_1 - 1)}> 0, \text{ obtained } P_1^* > P_2^*. \text{ It indicates that the critical value of the expected carbon price is higher than the critical value of the expected carbon price during the project construction period when companies make investment decisions in the pre-planning period due to the uncertainty of the number of profits and resources not generated in the pre-planning period.}
\]

4 | RESULTS AND DISCUSSION

In this section, we use numerical simulation to analyze the impact of factors such as fluctuations in carbon prices on the investment decision of PV power projects to find the optimal investment timing. We perform the analysis by giving an example of a 174 MWp grid-connected PV project.
4.1 Data source and processing

In this paper, we take Tianjin, China, as an example, and select a 174 MWp grid-connected PV project located in the Huanggang area of Tianjin Binhai New Area. The project is developed by Xinyi Solar Energy (Tianjin) Co., Ltd (after this referred to as “the project owner”), using the relatively abundant solar energy resources in the area, and using solar PV technology to produce electricity, which will be connected to the North China Grid. The project activity will achieve greenhouse gas emission reduction by replacing fossil fuel power generation in the North China Grid.

Our data in this paper is based on the data in China Emission Accounts and Datasets database. The expected growth rate of the carbon price and its volatility are estimated, and the results are taken as integer values, that is \( \alpha = 0.02, \sigma = 0.1 \), and the risk-free rate \( m \) is 0.05. Considering the small carbon emission reduction and power generation conversion factor, it is assumed that \( \lambda = 0.00098 \text{ton/kWh} \). The total installed capacity of the project is 174 MWp. The project PV, power generation system, adopts block power generation and centralized grid connection. The system is divided into 150 power generation units; each 1.16 MWp PV module comprises one power generation unit, all adopting the best tilt angle, and fixed bracket. The average annual utilization hours of the PV power generation project are 2000 h, the unit power generation cost is 0.35 RMB/kWh, and the total investment is 318.6 million RMB. The level of the feed-in tariff for PV project pre-planning is 1 RMB/kWh. According to the actual situation, the construction period of the PV project is 2 years, and the project operation and power generation period is 20 years. The relevant parameters are substituted into functions (9), (14), and (17) to find out the carbon price for the carbon pre-planning period and project construction period, that is, the critical investment values are \( P^*_1 = 24.5610 \) and \( P^*_2 = -53.7964 \), respectively. This shows that when the carbon price \( P \) in the market is more significant than \( P^*_1 \), PV power generation companies will choose to invest immediately; when the carbon price \( P \) is less than \( P^*_1 \), PV power generation companies will choose to delay investment.

In 2016, 38 countries or regions worldwide (including different provinces within countries) introduced carbon pricing systems, including carbon trading markets and carbon taxes. The price of carbon in the EU is around 50 Euros per ton. From the perspective of the Chinese pilot, the weighted average carbon price in the past 2 years is about 40 RMB/ton. The carbon price level in China is higher than the carbon price threshold for investment in PV power generation project pre-planning. It indicates that it makes sense to invest in PV power projects, and PV power projects can gain revenue through the carbon trading market, and PV power projects will invest in PV power projects at carbon price levels higher than 24.5610 RMB/ton.

4.2 Simulation results under different scenarios

This section is a sensitivity analysis of carbon price fluctuations for PV power projects.

(1) Assume the acceptance probability \( \theta = 0.5 \), and other parameter conditions remain unchanged, and the expected growth rate of the carbon price \( \alpha \) fluctuates between 0% and 4% (Figure 1, it indicates that \( \alpha \) takes the interval from 0 to 0.04 is in line with the actual meaning), the impact of carbon price growth rate on the critical value of carbon price is shown in Figure 1.

As shown in Figure 1, the value of carbon price growth rate \( \alpha \) increases from 0% to 4%, and the carbon price critical value increases from 24.5610 to 72.2845. This indicates that the carbon price critical value of the investment in PV power projects will increase at a more significant rate as the carbon price growth rate increases, and when the carbon price critical value is higher, companies will tend to delay investment and wait for the carbon price reaches a higher price before investing to gain more revenue, and it can be seen that the carbon price growth rate has a more significant impact on the investment threshold.

(2) Assume other parameter conditions remain unchanged, and the expected growth rates of a carbon price are \( \alpha = 1\% \), \( \alpha = 2.5\% \), \( \alpha = 4\% \). The impact of the standard deviation of the carbon price on the carbon price threshold when the range is between 0 and 1 is shown in Figure 2.

As shown in Figure 2, as the carbon price volatility \( \sigma \) increases, the carbon price critical value also increases gradually and at an increasing rate. When \( \sigma = 0.1, \alpha = 0.01, P^*_1 = 20.3152, \alpha = 0.025, P^*_1 = 28.8621, \alpha = 0.04, \) and \( P^*_1 = 60.0883 \), that is, the greater the
carbon price growth rate, the greater the carbon price critical value for the same carbon price volatility. This indicates that the greater the magnitude of carbon price volatility, the faster the carbon price critical value will increase, and the risk borne by firms will be more significant, and firms will choose to delay their investment and wait for a higher carbon price to invest.

(3) Assume other parameter conditions remain unchanged, and the expected growth rates of a carbon price are $\alpha = 1\%$, $\alpha = 2.5\%$, $\alpha = 4\%$. The impact of the probability of acceptance of micro-grid generation technology $\theta$ between 0 and 1 on the carbon price threshold is shown in Figure 3.

As shown in Figure 3, the carbon price threshold is a straight line because it is a primary function of the probability of R&D on PV generation technologies. With all other parameters constant, the carbon price critical value becomes smaller and smaller as the probability of acceptance of the power generation technology increases. When the acceptance probability is at the same level, the larger the value of $A$, the
faster the carbon price threshold will fall. When \( A = 0 \), the carbon price threshold is 0, when \( A > 0 \), the carbon price threshold is negative. This indicates that the power generation technology acceptance probability is significant, the level of power generation technology will improve, and when the R&D probability reaches a certain level, it represents a certain degree of decrease in the cost of power generation, which also represents an increase in the revenue of enterprises, and enterprises are more willing to make investments, thus facilitating investors to make investments in PV power generation projects, and helping to promote the development of PV industry.

(4) Assume other parameter conditions remain unchanged, and the expected growth rates of a carbon price are \( \alpha = 1\% \), \( \alpha = 2.5\% \), \( \alpha = 4\% \). The impact of the risk-free interest rate \( m \) between 0 and 0.1 on the carbon price threshold is shown in Figure 4.

As shown in Figure 4, as the risk-free rate increases, the carbon price threshold becomes progressively larger.
at an increasingly lower rate. At the same risk-free rate, the higher the expected growth rate of the carbon price, the larger the carbon price’s critical value. As the carbon price critical value increases, the corresponding investment option value increases, and the increase in option value make firms more inclined to delay their investment until the carbon price reaches a higher level to obtain more returns.

(5) Assume other parameter conditions remain unchanged, and the expected growth rates of a carbon price are $\alpha = 1\%$, $\alpha = 2.5\%$, $\alpha = 4\%$. The impact of the probability of resource availability to meet the investment requirement for power generation $\psi$ in the range of 0 to 0.1 on the carbon price threshold is shown in Figure 5.

As shown in Figure 5, the carbon price threshold decreases as the probability of resource availability meeting the investment requirements for power generation increases, which means that the investment threshold decreases. The carbon price threshold decreases at an approximately constant rate as the probability that the resource availability meets the investment requirement for power generation increases from 0 to 1 when $\alpha = 1\%$, $\alpha = 2.5\%$, $\alpha = 4\%$. This indicates that investors are more willing to invest if the higher probability that the resource availability meets the investment requirements for power generation represents a guarantee of stable investment returns for the investing firm. Comparing the two plots, when $\alpha$ is larger, the slope of the carbon price threshold curve becomes larger, and investors are increasingly sensitive to the resource availability to meet the investment requirements for power generation. Therefore, investors can be motivated to invest by increasing resource availability to meet the investment requirements for power generation.

(6) Assume other parameter conditions remain unchanged, and the expected growth rates of a carbon price is $\alpha = 1\%$, $\alpha = 2.5\%$, $\alpha = 4\%$. The impact of the PV project power generation cycle between 0 and 20 on the carbon price threshold is shown in Figure 6.

As shown in Figure 6, the longer the generation cycle of PV power projects, the smaller the carbon price threshold, the lower the investment threshold, and the more willing investors to make investments. When $\alpha = 1\%$, $\alpha = 2.5\%$, $\alpha = 4\%$, and the PV power project cycle increases from 1 year to 20 years, the carbon price threshold also decreases gradually at an approximately constant rate. Comparing the two graphs, when $\alpha$ is larger, the slope of the carbon price critical value curve is getting more prominent, and investors are more sensitive to the PV power project generation cycle. It is necessary to increase the project generation cycle to motivate investors to invest by extending the project generation cycle.

(7) Assume other parameter conditions remain unchanged, and the expected growth rates of a carbon price are $\alpha = 1\%$, $\alpha = 2.5\%$, $\alpha = 4\%$. The impact of the decline in power generation costs between 0 and 1 on the carbon price threshold is shown in Figure 7.

![Figure 5](image1.png) ![Figure 6](image2.png) ![Figure 7](image3.png)

**Figure 5** The impact of the probability of resource availability to meet the investment requirement for power generation on the carbon price threshold and the impacts with different expected growth rates of the carbon price.
As shown in Figure 7, the carbon price threshold is a primary function of the cost of power generation, so the carbon price threshold is a straight line. The carbon price critical value decreases as the decrease in the cost of electricity generation accelerates. When the growth rate of the carbon price is 0.01, 0.025, or 0.04, the faster the cost of electricity generation decreases, the faster the carbon price threshold decreases. When the cost of power generation decreases at the same level, the larger the $\alpha$ is, the smaller the carbon price threshold is, and when the carbon price threshold is the same, the larger the $\alpha$ is, the larger the cost decrease is. The above shows that the lower cost of power generation will motivate the investment in PV projects. Companies can increase the conversion efficiency of photovoltaic cells and increase the installed capacity of photovoltaics. Establish power stations in areas with abundant solar energy resources, increase power generation, and use polycrystalline silicon or amorphous silicon panels to reduce the production cost of photovoltaic panels. To reduce the cost of power generation, promote the investment of photovoltaic projects and the development of the industry.
5 | CONCLUSIONS

This paper introduces carbon price as a critical factor in the investment of PV micro-grid power generation based on the micro-grid power generation market under carbon trading mechanisms and the real options theory. It then establishes the investment decision model of the PV micro-grid power generation project. Finally, this paper solves the PV micro-grid power generation project’s investment threshold, that is., the critical carbon price value. According to MATLAB’s numerical simulations, many factors affect the investment decisions of a PV micro-grid power project, such as the expected growth rate of the carbon price, the standard deviation of the carbon price fluctuation, and the acceptance probability of power generation technology. The risk-free interest rate and the probability of resource availability to meet power generation’s investment requirements are included.

In addition, the power generation cycle of power generation projects and the annual decrease of power generation costs also impact the investment decisions of PV micro-grid power generation projects. The increase in the acceptance probability of power generation technology, the probability of resource availability to meet the investment requirements of power generation, and the power generation cycle of power generation projects will make enterprises invest first. Moreover, the increase in the expected growth rate of the carbon price, the standard deviation of the carbon price fluctuation, and the risk-free interest rate will ensure enterprises choose to invest in the future when the carbon price is higher to obtain more benefits. Investors will benefit from the conclusions drawn by this study when choosing whether and when to invest. It also provides policy support to the government to encourage the development of PV microgrid projects.

We suggest that the government needs to further improve the carbon trading market mechanism, design reasonable fiscal incentives, and make full use of the linkage between the electricity market and the carbon trading market. The carbon trading mechanism can improve the investment value of projects. The carbon price can truly reflect the value of emission reduction. With the continuing improvement of China’s carbon trading market mechanism, PV power generation technology will become more sophisticated, the share of carbon trading revenue will increase, and the investment costs will decrease. A higher carbon price and a more stable carbon trading market will encourage market participants to make construction investments. As a result, this will contribute to boosting investment in PV microgrids, further accelerating the development of new energy on a large scale and of high quality, and contributing toward the achievement of carbon neutrality.

NOMENCLATURE

Variables and parameters

\[ c \] \quad \text{unit generation cost}
\[ c_0 \] \quad \text{level of power generation cost during the pre-planning period}
\[ m \] \quad \text{risk-free rate}
\[ P \] \quad \text{carbon price (variable)}
\[ P_r \] \quad \text{PV power project feed-in tariff}
\[ P_r^0 \] \quad \text{feed-in tariff level in the pre-planning period}
\[ P^* \] \quad \text{critical value of the carbon price}
\[ P^*_1 \] \quad \text{critical value of the carbon price for making investments during the construction period of the project}
\[ T \] \quad \text{total planned period}
\[ T_1, T_2, T_3 \] \quad \text{pre-project planning period, project construction period, operational power generation period}
\[ V \] \quad \text{value of revenue obtained from the sale of carbon emission reductions from PV power projects}
\[ V_r \] \quad \text{value of the revenue obtained by the PV power project through the sale of electricity}
\[ V(P) \] \quad \text{value of the investment option for the pre-planning phase of the PV project}
\[ V_1(P) \] \quad \text{value of the investment option for the construction phase of the PV project}
\[ \alpha \] \quad \text{expected growth rate of the carbon price}
\[ \varphi \] \quad \text{average annual decline in feed-in tariff}
\[ \sigma \] \quad \text{standard deviation of carbon price fluctuations}
\[ \theta \] \quad \text{probability of acceptance of power generation technology after the pre-planning period}
\[ \delta \] \quad \text{rate of cost reduction per unit of power generation after the acceptance of power generation technology}
\[ \lambda \] \quad \text{conversion factor of CCER-approved carbon emission reductions and electricity generation}
\[ t_1, t_2, t_3 \] \quad \text{pre-planning completion time node, project construction period completion time node, project operation end node}
\[ \xi \] \quad \text{total project investment}
\[ \xi_1 \] \quad \text{pre-planning period investment}
\[ \xi_2 \] \quad \text{project construction period investment}
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CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

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