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Unleashing the wind: The role of carbon reduction revenue in Shanghai's distributed wind power investments

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A R T I C L E I N F O

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A B S T R A C T

Distributed wind power has the potential to contribute significantly to China's carbon neutrality goals. However, the recent policy shift away from wind power subsidies necessitates a thorough examination of alternative revenue streams, such as carbon emission reduction benefits. In response to this need, our paper aims to assess the impact of carbon reduction revenue on the investment viability of distributed wind power projects. Employing the Monte Carlo method, we construct investment models for a case study based in Shanghai, incorporating variables like feed-in tariffs and carbon trading prices. Our analysis reveals that, although distributed wind power investments are generally feasible, optimal investment should be deferred until 2031 according to real options analysis. We further note that carbon reduction revenue can enhance the investment value and shorten the dynamic payback period of these projects; however, current low trading volumes and prices for carbon credits do not sufficiently compensate for the absence of subsidies.

1. Introduction

China, as the world's largest industrial nation, is under intense pressure to reduce carbon emissions and has established carbon peaking and neutrality goals to demonstrate its commitment to this objective. The large-scale development of renewable energy sources, including wind power, will aid China in achieving its carbon reduction targets. The country has made remarkable progress in the development of wind power in recent years, as shown in Fig. 1. As of 2021, China's installed wind power capacity was approximately 330 million kW, accounting for 13.8 % of the total installed power capacity of 2.38 billion kW[1]; wind power represented 30.9 % of the renewable power capacity in China.[2] In 2021, the vast majority of wind power generation systems in China were centralized systems, with less than 4 % being distributed systems. However, the number of distributed systems has been growing steadily since 2017, with a surge in growth in 2021. Compared with centralized systems, distributed systems have a number of advantages; they require smaller development areas, shorter construction periods, and less investment. Thus, distributed systems are superior in terms of economy and flexibility, and there is considerable potential for their future development.

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[1] http://www.nea.gov.cn/2022-01/26/c_1310441589.htm.
[2] http://www.gov.cn/xinwen/2022-01/29/content_5671076.htm.

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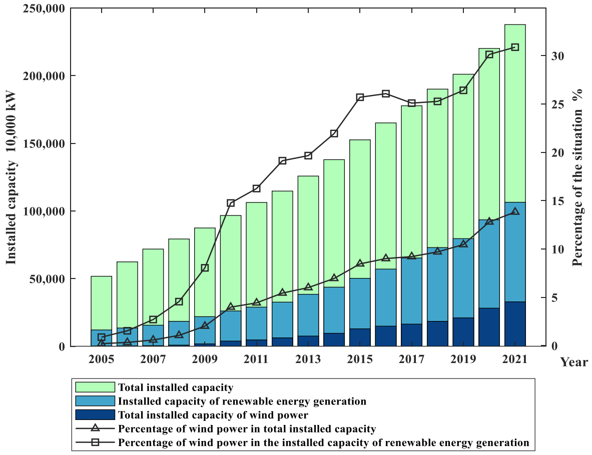

Fig. 1. Total installed capacity and proportion of wind power (2005–2021).

To encourage large-scale development of renewable energy, including distributed wind power, the Chinese government has introduced a series of policies,[3] including tax preferences and funding subsidies. However, in 2021, the National Development and Reform Commission announced a new policy related to the 'complete removal of subsidies for newly approved onshore wind power projects and implementation of grid parity.'".[4] This policy has led to wind power companies shifting towards installing alternative systems, such as distributed rather than centralized wind power. The resulting drastic increase in installed capacity of distributed wind power is shown in Fig. 2. In 2021, the cumulative installed capacity of distributed wind power was close to 10 million kW, with a year-on-year increase of 414.6 %, while the newly installed capacity was 8.027 million kW, showing a dramatic year-on-year growth of 702 %.[5] Despite the surge in distributed wind power project investments between 2020 and 2021, Wu and Zhang [1] noted that the substantial subsidy reductions might lead to decreased investment in the wind power industry.

In an effort to preserve the stability of the wind power investment market, the government initiated a national carbon trading market in 2021. This allows wind power companies to earn revenue from carbon emission reductions through trading, which can offset their investment expenses and boost their economic gains. However, this policy shift raises several critical questions. What will the investment returns on distributed wind power projects be, considering the full removal of wind power subsidies and the introduction of grid parity? Is the revenue from carbon reduction sufficient to make up for the loss of wind power subsidies? These questions warrant thorough investigation and serve as the driving force behind our study. Consequently, we examine the impact of carbon reduction revenue on investments in distributed wind power projects within the context of wind power subsidy cancellation and grid parity implementation. Our findings hold significant practical implications for the widespread and sustainable growth of distributed wind power in China.

The research contributions of this paper are twofold: First, this paper incorporates carbon emission reduction gains into the investment return model for wind power projects. It examines the impact of these gains on the investment returns of distributed wind power projects following the complete removal of wind power subsidies, thereby offering actionable insights for promoting the large-scale development of distributed wind power. Second, the paper employs the real options research method to evaluate the economic benefits of distributed wind power. It integrates uncertainty factors such as wind power feed-in tariffs and carbon trading prices into the investment return model. This approach refines the assessment of the investment value of wind power projects, providing a more reliable investment basis for distributed wind power enterprises.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature on investment in renewable energy generation projects, focusing on wind power. Section 3 presents the investment return model for distributed wind power projects. Section 4 provides an in-depth analysis using a specific arithmetic example, with Shanghai serving as the case study. Section 5 concludes the paper, offering corresponding policy recommendations and outlining future research directions.

2. Literature review

Recent years have seen a surge in scholarly attention focused on investments in projects aimed at generating renewable energy, such as wind power. Accordingly, this paper presents a review of existing literature from related fields. Specifically, we examine the factors that influence investment in renewable energy projects, the economic value derived from investment in wind power projects,

[3] Notice of the National Energy Administration on the Issuance of *Interim Measures for the Management of Development and Construction of Distributed Wind Power Projects*. http://www.gov.cn/zhengce/zhengceku/2018-12/31/content_5433876.htm.

[4] Notice of the National Development and Reform Commission on *Matters Related to the Policy on the Feed-In tariff of New Energy in 2021*. https://www.ndrc.gov.cn/xwdt/tzgg/202106/t20210611_1283089.html?code=&state=123.

[5] http://www.cres.org.cn/art/2022/8/2/art_6900_334522.html.

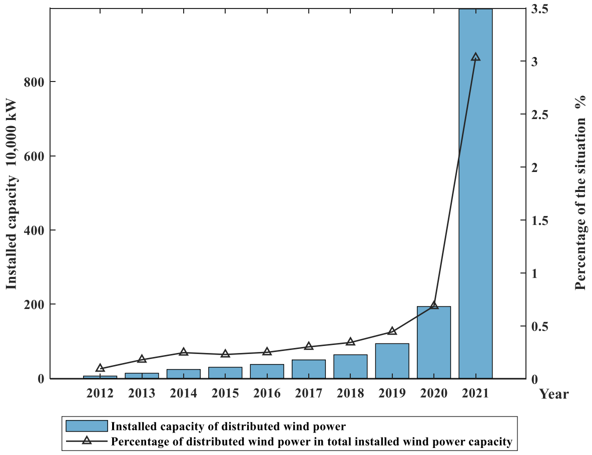

Fig. 2. Installed capacity of distributed wind power and percentage of total installed wind power capacity (2012–2021).

and the impact of carbon revenue on investment in wind power projects.

2.1. Research on factors affecting investment in renewable energy projects

China's abundant renewable energy resources have established a robust foundation for the development of its electricity industry [2]. However, the costs associated with investing in renewable energy generation projects are relatively high, compelling enterprises to evaluate the potential return on investment when strategizing their investments [3]. The decision-making process of investors is also influenced by numerous other factors, including various government incentives (such as price- and cost-based incentives), changes in the market, and shifts in the investment environment [4].

Several studies have analyzed investors' optimal investment timing and strategies from the perspective of return on investment of renewable energy generation projects [5–7]. For example, Zhang et al. [6] examined the impact of market price and loan rate fluctuations and uncertainties on the investment value of solar PV projects in China, employing an extended trinomial tree model. Their findings indicated that a continually varying volatility is more conducive to driving investment in renewable energy generation projects than a fixed volatility. Ofori et al. [7] assessed the optimal timing of investment in renewable energy projects in Ghana, considering their investment and options values under a scenario of delayed investment. Their research found that firms could maximize their returns on investments when fluctuations in uncertain factors, such as the market, the economy, and technology, were minimized in the context of delayed investment.

Further research has evaluated the influence of various government incentives [8–10], market supply and demand dynamics [11, 12], environmental regulations [13], and green finance [14,15] on investment in renewable energy generation projects. For instance, Gong and Li [8] investigated the impact of government subsidies on the investment timing of renewable energy and found a positive role of government subsidies in prompting renewable energy investments. Kong et al. [11] analyzed the relationship between the optimal investment scale of renewable energy capacity and the levels of supply and electricity demand using a bilateral trading model. They found an overall positive correlation between the optimal investment scale of renewable energy capacity and other factors. Tan et al. [13] investigated the relationship between two types of environmental regulations (order-controlled and market-incentivized) and the level of investment in renewable energy enterprises, identifying a significant inverted U-shaped relationship in both cases. These studies offer a comprehensive analysis of the myriad factors that influence renewable energy projects, including return on investment, incentive policies, market dynamics, and environmental considerations. Their findings contribute to the promotion of investment in renewable energy projects.

2.2. Research on the economic value of investment in wind power projects

China, endowed with rich wind energy resources, stands to make significant strides toward its carbon peak and neutrality goals by developing large-scale wind power generation systems and expanding the use of wind energy [16]. In October 2018, the National Development and Reform Commission and the National Energy Administration released the Action Plan for Clean Energy Consumption (2018–2020). This plan set specific targets for wind power consumption, aiming for a national average wind power utilization rate higher than 90 % and an abandonment rate lower than 10 % by 2019. Additionally, the plan aimed for the national average wind power utilization rate to reach the internationally advanced level of approximately 95 % by 2020, essentially resolving the issue of

clean energy consumption.[6] In December 2020, the State Council released a white paper titled 'China's Energy Development in the New Era,' which emphasized the need to comprehensively and coordinately advance the development of wind power. The paper also called for the orderly promotion of the development and utilization of wind power, along with the construction of large-scale wind power bases.[7] Indeed, wind power is currently a major contributor to renewable energy generation in China, accounting for approximately one-third of its installed renewable energy generation capacity in 2021.

The Chinese wind power industry encompasses both onshore and offshore wind power, in addition to centralized and distributed wind power. However, studies exploring the economic value of investments in wind power projects have predominantly focused on offshore and centralized wind power projects, leaving onshore and distributed projects relatively under-examined. For instance, Liu et al. [17] investigated the economic feasibility of investing in offshore wind power projects, taking variable investment costs into account. They concluded that the existing investment climate in China is not conducive to attracting direct investment in offshore wind power projects and suggested that increasing subsidies and fostering technological progress could bolster investment. Kim et al. [18], studying the impact of wind speed variation on the economic feasibility of offshore wind power project investment using the real options (RO) theory, discovered that investment decisions based on the RO approach were highly flexible and could effectively minimize the risk associated with investing in offshore wind power projects, thereby improving their long-term profitability. He et al. [19] developed a life-cycle cost pricing model for offshore wind power project investment, predicting a future decrease in the price of offshore wind power, which would make it a competitive player in the energy market.

While wind power generation is primarily centralized in China, the investment costs associated with centralized wind power plants are relatively high, and these plants are unable to meet the electricity needs of smaller towns and cities, which are constrained by available space. Distributed wind power systems, on the other hand, offer a promising alternative, with their flexibility, smaller spatial requirements, and lower investment costs. In 2021, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA), along with other departments, outlined in the Notice on the Issuance of the '14th Five-Year Plan' for Renewable Energy Development that the distributed and localized development of wind power should be actively promoted to enhance the efficiency of wind energy utilization.[8] A few studies in recent years have explored the economic value of investment in distributed wind power projects. For example, Huang et al. [20]constructed an options pricing model to determine the optimal investment timing and sizing decisions for distributed wind power projects with uncertain contributions to gross profits. Their findings suggested that the threshold value of the contribution to gross profits, the optimal investment size, and the expected waiting time prior to the initiation of the distributed wind power project were positively correlated with the expected drift rate and volatility rate of the contribution to gross profits during the investment term. However, as noted, most studies have primarily focused on offshore and centralized wind power projects. Thus, a detailed examination of the economic value of investment in distributed wind power projects is of significant importance.

2.3. Research on the effect of carbon revenue on investment in wind power projects

Wind power enterprises in China can earn carbon reduction revenue through the nation's carbon trading market as a form of compensation for the positive environmental externalities they produce. These external economic benefits, specifically the reduction in carbon emissions associated with the transition to renewable energy, are represented in the carbon price within the trading market. However, fluctuations in carbon trading prices can affect the carbon reduction revenue that wind power enterprises can secure. Some studies have evaluated the influence of carbon pricing [21,22] and carbon taxation [23] on wind power project investment in China. Tu et al. [22], for instance, probed the role of carbon trading prices in China's carbon trading market by contrasting the impact of having, or not having, a carbon trading price on the levelized cost of electricity from wind power projects. Their findings indicated that the carbon trading price in each of China's emissions trading pilot schemes was too low to fully compensate wind power companies for their loss of revenue. Nevertheless, the national carbon emissions trading system presents a new economic incentive for Chinese enterprises to invest in renewable energy projects. Zhao et al. [23] examined the effects of two policies, a carbon tax and emissions trading, on the investment value of wind power projects in China under uncertain conditions, using the RO approach. They found that both policies positively influenced future investment in wind power projects and the development of renewable energy, albeit with limited impact. Given this, there is ample room to enhance the analysis of the impact of carbon revenue on investment in wind power projects, particularly in terms of the role of carbon revenue in wind power project investment in the context of the total elimination of wind power subsidies. This paper endeavors to address this gap in the literature.

Our literature review provides a relatively comprehensive analysis of prior studies on the factors influencing investment in renewable energy generation projects, viewed from the perspectives of return on investment, government policies, market factors, environmental regulations, and green finance [5–15]. This provides a robust theoretical foundation for subsequent studies. However, research on the returns on investment in wind power projects is scarce and primarily centered on offshore and centralized wind power projects, with insufficient attention given to distributed wind power projects, as previously noted [17–20]. Specifically, in the context

[6] Circular of the National Development and Reform Commission and the National Energy Administration on the issuance of *the Action Plan for Clean Energy Consumption (2018–2020)*. https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/201812/t20181204_960958.html.

[7] The State Council Information Office of the People's Republic of China *White Paper on China's Energy Development in the New Era*. https://www.gov.cn/zhengce/2020-12/21/content_5571916.htm.

[8] Notice of the National Development and Reform Commission, the National Energy Administration and other departments on *the issuance of the Renewable Energy Development Plan for the Fourteenth Five-Year Plan*. http://zfxxgk.nea.gov.cn/2021-10/21/c_1310611148.htm.

of the official launch of China's carbon trading market, no studies have analyzed the impact of carbon reduction revenue earned through the carbon trading market on investment in wind power projects, following the complete elimination of wind power subsidies. Therefore, in this study, we aim to construct an investment value model for distributed wind power projects that incorporates carbon reduction revenue, measure the options value of distributed wind power projects based on RO theory, and analyze the optimal investment strategy for wind power projects.

3. The distributed wind power project investment value model

We construct an investment value model for wind power projects by analyzing the model variables impacted by uncertain conditions, and simulating the path changes of these uncertainties, drawing on real-world construction and operation of wind power projects in China.

3.1. Description of main variables

(1) Wind power feed-in tariff

In 2021, as noted earlier, the Chinese government introduced policies for the complete elimination of wind power subsidies and the implementation of grid parity. The change in the wind power feed-in tariff obeys a geometric Brownian motion, which can be represented by equation (1):

$$dP_t^e = \mu_e P_t^e dt + \sigma_e P_t^e dz_t^e, \tag{1}$$

where P_t^e is the wind power feed-in tariff at time t, μ_e and σ_e are the expected drift rate and volatility rate, respectively, of the wind power feed-in tariff, dz_t^e is the standard Wiener process increment, and $dz_t^e = \varepsilon_e\sqrt{dt}$, ε_e is a random variable that obeys the standard normal distribution.

(2) Carbon trading price

The carbon reduction revenue that wind power companies receive through the carbon trading market is mainly influenced by the carbon trading price. The variation in the carbon trading price also obeys a geometric Brownian motion [24], and can be represented by equation (2):

$$dP_t^c = \mu_c P_t^c dt + \sigma_c P_t^c dz_t^c, \tag{2}$$

where P_t^c is the carbon trading price at the time t, μ_c and σ_c are the expected drift rate and volatility rate, respectively, of the carbon trading price, dz_t^c is the standard Wiener process increment, and $dz_t^c = \varepsilon_c\sqrt{dt}$, ε_c is a random variable that obeys the standard normal distribution.

(3) Initial cost of investment in wind power projects

Wind power technology fits the learning curve model [25,26], such that the cost of investment decreases with improvements in wind power technology. Equation (3) represents the initial cost of investment in a wind power project (I_t) at the time t, :

$$I_t = \theta_i \cdot IC \cdot \exp(-\tau t), \tag{3}$$

where θ_i is the unit investment cost of the wind power project and τ is the learning curve coefficient.

3.2. Monte Carlo simulation

We simulate variations in uncertainty using the least-squares Monte Carlo method and the inverse dynamic programming algorithm. The accuracy of this method is largely influenced by the simulation scale (i.e., the number of simulation paths M and project investment decision points N). The greater the number of simulation paths, the less accurate is the simulation. To address the shortcomings of this approach, we use a dual variable variance reduction technique to reduce fluctuations in the variance of the data simulation while ensuring that the dimensionality remains unchanged, thereby improving the simulation accuracy. Suppose that the number of simulated paths and the number of decision points on each simulated path are M and N, respectively, where $N = \frac{t_e}{\Delta t}$, and Δt is the step length. Ito's Lemma states that the sample paths obtained by the Monte Carlo simulation method are as follows:

$$P_{t+\Delta t,j}^e = P_t^e \cdot \exp\left(\left(\mu_e - \frac{1}{2}\sigma_e^2\right)\Delta t + \sigma_e\sqrt{\Delta t} \cdot \varepsilon\right) \tag{4}$$

$$P_{t+\Delta t,j}^c = P_t^c \cdot \exp\left(\left(\mu_c - \frac{1}{2}\sigma_c^2\right)\Delta t + \sigma_c\sqrt{\Delta t} \cdot \varepsilon\right), \tag{5}$$

where path j satisfies $0 \le j \le M$.

3.3. Model construction

3.3.1. Revenue function of the distributed wind power project

We construct a value function for distributed wind power projects based on the whole life-cycle theory as follows:

$$\pi_t = R_t - C_t, \tag{6}$$

where π_t is the net cash flow of the wind power project at time t, and R_t and C_t are the total revenue and total cost, respectively, of electricity generation by the wind power project at time t.

Wind power providers can earn revenue from their carbon reductions by selling their carbon emissions rights in the carbon trading market. Therefore, we consider both revenue from energy sales (ER_t) and revenue from carbon reductions (CR_t) for the wind power project at time t, as follows:

$$R_t = ER_t + CR_t = P_t^e Q_t^e + P_t^c Q_t^c. \tag{7}$$

P_t^e and P_t^c represent the wind power feed-in tariff and the carbon trading price, respectively, at time t, and Q_t^e and Q_t^c represent the energy generation capacity and the carbon emissions reduction, respectively, at time t, where $Q_t^e = q_t^e IC$, $Q_t^c = \xi Q_t^e$, in which IC is the total installed capacity of the wind power project, q_t^e is the hours of wind turbine generation of the wind power project at time t, and ξ is the carbon emissions reduction coefficient.

The whole-of-life costs, represented in the equations below, largely consist of operating and maintenance costs (OMC_t), income tax costs (TCI_t) and value added taxes (TCV_t). Thus, for the wind power project at time t, we have:

$$C_t = OMC_t + TC_t \tag{8}$$

$$OMC_t = \theta_{om} q_t^e IC \tag{9}$$

$$TC_t = TCV_t + TCI_t \tag{10}$$

$$TCV_t = (ER_t + CR_t) \cdot r_v \tag{11}$$

$$TCI_t = [(ER_t + CR_t) \cdot (1 - r_v) - OMC_t] \cdot r_i, \tag{12}$$

where θ_{om} represents the unit operation and maintenance costs of the wind power project, and r_v and r_i represent the value added tax rate and the income tax rate.

3.3.2. Investment value of the distributed wind power project

Suppose that an investor in a wind power project invests at time t_1. Then, the investment validity period, that is, the maximum period for which investment in the wind power project can be delayed, is $t_1 \le t_e$, t_e. Because the life cycle of the wind power project is T, the operation time of the project is t_1 to $t_1 + T$.

(1) Investment value of distributed wind power projects based on the net present value (NPV) method

Net Present Value (NPV) represents the difference between the discounted value of future cash flows generated by an investment and the initial cost of the project. The NPV method accounts for both the time value of money and the profitability of the invested projects, providing a comprehensive view of investment outcomes. Scholars have commonly used the NPV method to calculate and evaluate the investment value of wind power projects, when random variations in the elements affecting the investment value are not being considered. The investment value of a distributed wind power project based on the NPV method (NPV_{t_1}) at time t_1 is calculated as follows:

$$NPV_{t_1} = E\left[\sum_{t=t_1}^{t_1+T} \pi_t (1+r)^{-(t-t_1)} - I_{t_1}\right], \tag{13}$$

where $E[\cdot]$ is the expected value operator, T is the life cycle of the wind power project, and r is the risk-free interest rate. Using the NPV method, if the investment value of the project is positive, investment in the project is feasible; otherwise, potential investors should avoid the project. However, as noted, the NPV method does not consider the effect of uncertainties, such as changes in wind power feed-in tariffs and carbon trading prices, on the investment value of wind power projects. Thus, the NPV method is only applicable under deterministic conditions, and it may mislead investors as to the investment value in the presence of uncertainties.

(2) Investment value of distributed wind power projects based on the real options (RO) method

In reality, there is a high degree of uncertainty in the energy market, with fluctuations in energy prices and feed-in tariffs affecting the investment value of energy projects. Therefore, to overcome the limitations of the NPV method, Myers [27,28] developed RO theory by applying options pricing theory to the field of project investment. RO models have been applied to energy projects to determine optimal investment strategies based on investment decision rules [4,29].

We use the RO method in this paper to overcome the deficiencies of the NPV method, reduce evaluation errors regarding the investment value of wind power projects, and provide a more reasonable basis for investment decisions. The investment value of a distributed wind power project based on the RO method (*ENPV*) is calculated as follows:

$$ENPV = NPV + ROV, \tag{14}$$

where *ROV* is the options value, that is, the flexible economic value under uncertain conditions, also known as the opportunity value.

(3) The optimal investment choice for distributed wind power projects

The primary goal of distributed wind power companies is to maximize the value of their investments. To do this, investors need to choose the optimal time to invest in a project within its validity period. Using the RO method, we can measure the project investment value at each possible investment time. When the wind power project value satisfies the optimal investment condition, the investors will decide to either invest immediately or delay their investment. An investor will only choose to invest in a wind project immediately if the value of that immediate investment is greater than the value of deferred investment. Thus, the optimal investment choice for a distributed wind power project can be represented as follows:

$$ENPV_{optimal} = \max ENPV = \max_{0<t_o<t_e} [\max(NPV_{t_o}, 0) \cdot \exp(-rt_o), NPV_{t_o}], \tag{15}$$

where $ENPV_{optimal}$ is the investment value of the distributed wind power project based on the RO method under stochastic optimal investment timing and t_o is the stochastic optimal investment timing for the wind power project. The specific decision rules for investment in distributed wind power projects are presented in Table 1.

4. Numerical example

The Yangtze River Delta region is relatively advanced in terms of distributed energy within China, with Shanghai being the most representative city. During the 13th Five-Year Plan period, the total installed capacity of wind power in Shanghai reached 1.4 million kW, with a newly installed capacity of between 0.8 and 1 million kW.[9] On April 16, 2022, the Shanghai Municipal People's Government released the Shanghai Energy Development 14th Five-Year Plan. This plan aims to promote the development of distributed wind power in Shanghai, Chongming, Pudong, Jinshan, and other coastal areas along the river, based on local conditions. It also aims to explore the implementation of an onshore distributed wind power demonstration pilot, and strives to add 1.8 million kW of wind power to China's energy mix. As such, we have chosen Shanghai as a case study to delve deeper into the investment value of distributed wind power projects. The data used in this study were obtained from the National Energy Administration website, the National Development and Reform Commission website, the China Carbon Trading website, and the Wind database.

4.1. Data sources and parameter settings

4.1.1. Parameters related to the wind power project

The National Energy Administration regulations state that a distributed wind power project is a wind power project located near a load centre that is not for the purpose of large-scale, long-distance power transmission, with the generated power being fed into the local grid for local consumption. Most distributed wind power projects in China are small-scale, with capacities of 6–50 MW and their output can be absorbed locally without the need for large-scale export.

We selected a new distributed wind power plant in Shanghai with a total installed capacity (*IC*) of 10 MW as the research object for numerical analysis. The Wind database showed that the average annual use q_t^e of wind power in Shanghai from 2017 to 2021 was 2274 h. The National Development and Reform Commission regulations state that the feed-in tariff for new wind power projects in 2021 and beyond is based on the local benchmark price for coal-fired power generation. Therefore, we use the benchmark price for coal-fired power generation in Shanghai in 2022 (0.4155 yuan/kWh) as the initial feed-in tariff, P_t^e. In addition, we set the expected drift rate, μ_e, and the volatility rate, σ_e, of the wind power feed-in tariff at 0.4 % and 2.7 %, respectively [17]. Based on the relevant national regulations, we use a value-added tax rate, r_v, of 8.5 %[10] and an income tax rate, r_i, of 15 %.[11] We set the risk-free interest rate, *r*, which

[9] https://www.shanghai.gov.cn/shssswzxgh/20200820/0001-22403_51932.html.

[10] The value added tax on wind power projects in China enjoys a preferential policy of '50 % refund after taxation' and is levied at 50 % of the taxable amount.

[11] Wind energy is clean renewable energy, and wind power technology is included in new energy and energy-saving technology. The *Management Measures for the Designation of High and New Technology Enterprises* state that enterprises using wind power generation technology, wind farm matching technology, and so on, belong to high and new technology enterprises. The *Law of the People's Republic of China on Enterprise Income Tax* states that the state will give priority support to high and new technology enterprises by reducing income tax to 15 %.

Table 1
Decision rules for distributed wind power project investment.

Investment value based on NPV method	Investment value based on RO method	Investment decision
$NPV > 0$	$ENPV > NPV$	Delay investment
$NPV > 0$	$ENPV = NPV$	Immediate investment
$NPV \leq 0$	$ENPV > 0$	Delay investment
$NPV < 0$	$ENPV = 0$	Quit investment

is the return on investment without credit or market risks, at 5 % [30].

Generally, the life cycle of distributed wind power projects is 20–30 years. After considering objective factors, such as the accelerated depreciation of machinery and equipment, we selected a life cycle, T, of 20 years and an investment validity period, t_e, of 10 years (i.e., the maximum delay in investment is 10 years). Furthermore, based on the operation of distributed wind power plants in Shanghai under the same scale conditions, we set the unit operation and maintenance costs of the distributed wind power plants, θ_{om}, at 0.1 yuan/kWh, the unit investment cost, θ_i, at 6000 yuan/kW and the learning curve coefficient, τ, at 1 %/year [31] We do not consider the construction cycle of the wind power facilities or the transformation between the operational states of the wind power equipment. The parameters related to the investment and construction of the wind power project are shown in Table 2.

4.1.2. Parameters related to the carbon trading market

We based our carbon trading price changes on the Shanghai carbon trading market, which is one of eight carbon emissions trading markets being trialled in China. As noted, the benefits gained by distributed wind power enterprises from positive environmental externalities are mainly reflected in the carbon trading price. The carbon reduction revenue received by enterprises from trading in the carbon market can partially offset the costs of power generation, thereby enhancing the return on investment in wind power projects. Statistics from the *China Carbon Market Review and Prospect (2022)* showed that the average transaction price on the Shanghai carbon trading market in 2021 was 39.46 yuan/ton. Based on historical data related to the carbon trading price on the Shanghai carbon trading market from 2017 to 2021 obtained from the CSMAR database, we set the expected drift rate, μ_e, and the volatility rate, σ_e, of the carbon trading price at 4.91 % and 5.39 %, respectively, using the method proposed by Zhang et al. [32] Furthermore, we used the method proposed by Gong and Li [8] to measure the carbon emissions reduction coefficient, ξ, which we set at 0.8615 kg/kWh. This was used to calculate the carbon reduction revenue for distributed wind power projects. The initial carbon trading price, P_t^e, was set at 0.0340 yuan/kWh. The parameters related to the carbon trading market are shown in Table 3.

4.2. Simulation of uncertainty factors

As noted earlier, we use the least-squares Monte Carlo method to simulate the path of change of wind power feed-in tariffs and carbon trading prices from the initial values. To reduce the error between the simulated value and the actual value and improve the prediction accuracy, we conducted 25 Monte Carlo simulations (i.e., $M = 25$) using MATLAB software. The path diagrams for the Shanghai wind power feed-in tariff and carbon trading price were derived by simulating the change paths of the uncertainties (shown in Figs. 3 and 4). It is evident that the wind power feed-in tariff and carbon trading price show an upward trend. To reduce the effect of calculation errors on the investment value of distributed wind power projects, we used the arithmetic means of the values obtained from the 25 simulations for the wind power feed-in tariff and carbon trading price.

4.3. Analysis of the numerical example

4.3.1. Effect of carbon revenue on the investment value of distributed wind power projects

In this section, we substitute the parameters presented in Tables 2 and 3 and the arithmetic means of the wind power feed-in tariff and carbon trading price derived from the Monte Carlo simulation into the investment value model of distributed wind power projects. Then, we measure the investment value and options value of distributed wind power projects in Shanghai within the valid investment period based on the NPV and RO methods. We also compare these scenarios to a case without carbon benefits to reflect the effect of carbon reduction revenue on the investment value of distributed wind power projects, as shown in Figs. 5 and 6.

As Fig. 5 shows, both the NPV and RO methods reveal that the investment value of distributed wind power projects in Shanghai is positive, and thus the investment is profitable. Considering carbon revenue, the investment value of wind power projects as measured by the NPV method rises from 1885.20 yuan/kW in 2022 to a maximum value of 1949.99 yuan/kW in 2028, after which it starts to decline. Based on this trend, investors should delay their investments until 2028. This delay will enhance the economic benefits of their enterprises and increase future profits. However, because the NPV method ignores the value of future uncertainty, it underestimates the investment value of distributed wind power projects. When we use the RO method, the investment value of distributed wind power projects in Shanghai in 2022 is 2133.87 yuan/kW. The investment value shows an increasing trend from 2022 to 2031, reaching a maximum value of 2329.09 yuan/kW in 2031, before beginning to decrease. Moreover, the options values of distributed wind power projects based on the RO method are all positive and show an upward trend over time (see Fig. 6). Based on the decision rules presented in Table 1, investors should choose to delay their investment until 2031. A positive options value means that future changes in uncertainty will bring increased economic benefits, and investors who choose to delay their investment will obtain more opportunity value, and thus maximize their return on investment. The conclusions based on the NPV and RO methods are consistent in that both

Table 2
Parameters related to the wind power project in Shanghai.

Parameter Name	Parameter Symbol	Parameter Value
Wind power feed-in tariff	P_t^e	0.4155yuan/kW·h
Expected drift rate of wind power feed-in tariff	μ_e	0.4 %
Volatility rate of wind power feed-in tariff	σ_e	2.7 %
Wind turbine generation hours	q_t^e	2274 h
Total installed capacity	IC	10 MW
Value added tax rate	r_v	8.5 %
Enterprise income tax rate	r_i	15 %
Unit operation and maintenance cost	θ_{om}	0.1yuan/kW·h
Unit investment cost	θ_i	6000yuan/kW
Learning curve coefficient	τ	1 %/year
Risk-free interest rate	r	5 %
Life cycle of wind power project	T	20yuan
Investment valid period	t_e	10yuan
Step length	Δt	1yuan

Table 3
Parameters related to the carbon trading market.

Parameter Name	Parameter Symbol	Parameter Value
Carbon trading price	P_t^c	0.0340yuan/kW·h
Expected drift rate of carbon trading price	μ_c	4.91 %
Volatility rate of carbon trading price	σ_c	5.39 %
Carbon emission reduction coefficient	ξ	0.8615 kg/kW·h

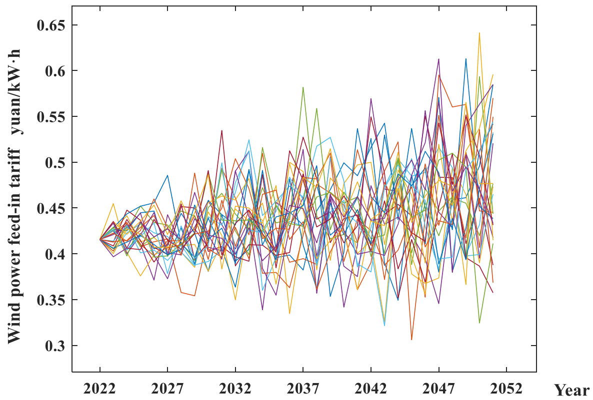

Fig. 3. Monte Carlo simulation results for the wind power feed-in tariff.

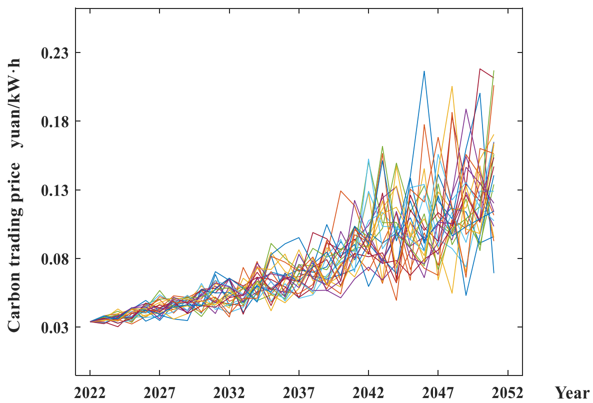

Fig. 4. Monte Carlo simulation results for the carbon trading price.

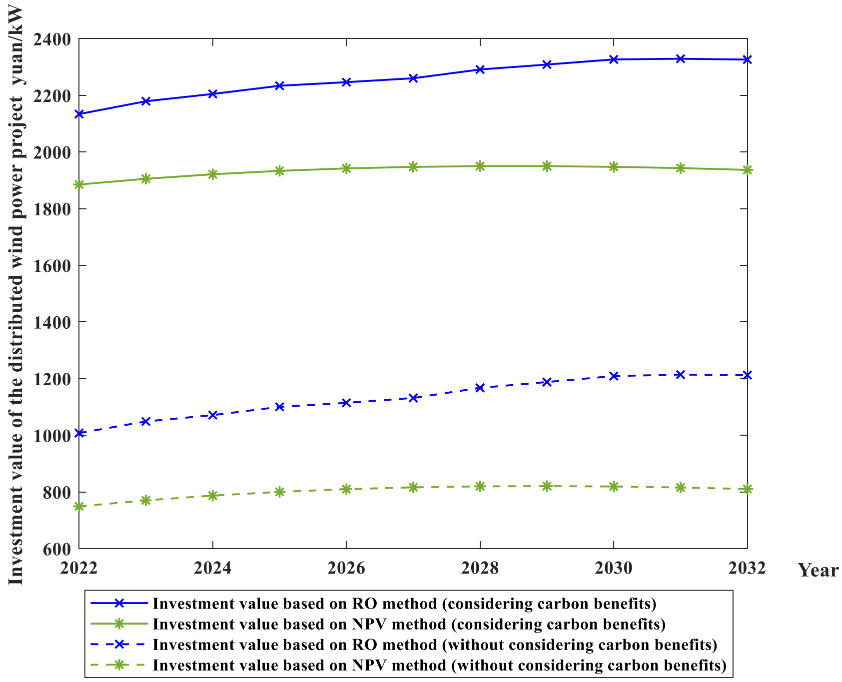

Fig. 5. Effect of carbon revenue on the investment value of distributed wind power projects in Shanghai.

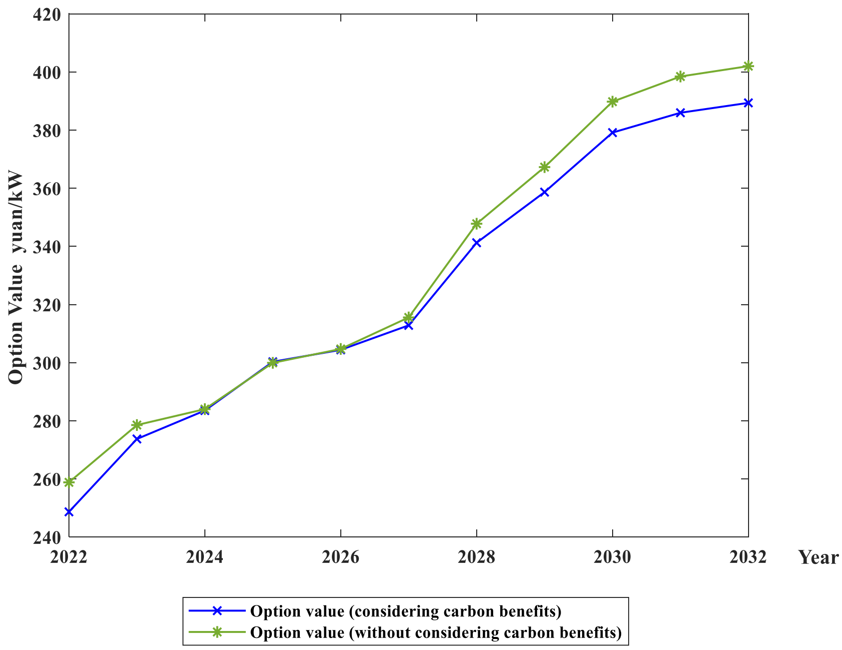

Fig. 6. Effect of carbon revenue on the options value of distributed wind power projects in Shanghai.

indicate that the optimal investment strategy is to delay investment in distributed wind power. However, unlike the NPV method, the RO method, which yields a higher investment value, considers the effect of changes in the wind power feed-in tariff and carbon trading price. Thus, it yields a more realistic and reliable investment value for distributed wind power projects than that measured using the NPV method.

In response to the elimination of wind power subsidies and the implementation of grid parity, the economic benefits of distributed wind power enterprises have declined, and operational pressures have risen. However, distributed wind power enterprises can partially recoup their economic benefits through carbon reduction revenue, as China's carbon trading market has been gradually

improving. Fig. 5 shows that when carbon revenue is not considered the investment value of distributed wind power projects in 2022 is 1007.92 yuan/kW (RO method) or 749.09 yuan/kW (NPV method). The inclusion of carbon reduction revenue will increase the investment value of distributed wind power projects in Shanghai by about 1125 yuan/kW, an amount exceeding the RO and NPV estimates of current value, over the valid investment period. Thus, the carbon trading market plays an essential role in supporting the development of the wind power industry in the absence of wind power subsidies.

Although relying on market-based measures, such as trading, can partially compensate for the reduced economic benefits of distributed wind power enterprises in the absence of wind power subsidies, the optimal investment strategy for wind power investment agents is still to defer investment. This is because the carbon reduction revenue obtained is insufficient to compensate for the economic losses experienced by the enterprises as a result of the complete removal of wind power subsidies. Thus, the trading market and carbon reduction revenue are not sufficient to stimulate investment in the absence of these subsidies. The average carbon trading price in China's trading markets was 50–60 yuan/ton in 2022; in the Shanghai trading market in particular, it was only 39.46 yuan/ton. This indicates that the current carbon market trading price in Shanghai is relatively low. This observation aligns with Tu et al.'s conclusion [22], which stated that carbon emission prices from wind power in China are insufficient and need to be increased to compensate for revenue loss. Zhang et al. [33] estimated that the carbon trading price in China will reach 68 yuan/ton during the period of the 14th Five-Year Plan (2021–2025), and will be even higher in the future [33]. We predict a slightly lower carbon trading price of 46 yuan/ton in 2025 based on the expected drift rate μ_e of the carbon trading price as measured by historical data. The carbon price in Shanghai is below the average Chinese carbon price, as reported by Zhang et al. [33]'s study. The current rate of increase in the Chinese carbon trading price is also slower than Zhang et al. [33]'s estimations. Regardless, it is evident that even though carbon reduction revenue has a positive effect on investment in distributed wind power projects, it does not sufficiently stimulate investment in wind power projects owing to the low carbon price.

4.3.2. Effect of carbon revenue on the dynamic investment payback period of distributed wind power projects

The dynamic investment payback period is the time required for the present value of the future net cash flow to equal the present value of the initial investment, considering the time value of money. The specific calculation is as follows: the dynamic investment payback period = (the year in which the present value of the cumulative net cash flow is first positive – 1) + (the absolute value of the present value of the cumulative net cash flow in the previous year/the present value of the net cash flow in the year in which it is first positive). Using this formula, we calculate the dynamic investment payback periods for distributed wind power projects with and without carbon reduction revenue, as shown in Fig. 7.

As the figure shows, the dynamic investment payback period for distributed wind power projects shows a declining trend over time, regardless of whether the NPV or RO method is adopted, which indicates that delayed investment shortens the dynamic investment payback period of wind power projects. This is verified by our finding that the optimal investment strategy for distributed wind power investors is delayed investment. Assuming no wind power subsidies but ignoring carbon revenue, we calculate that the dynamic investment payback period for distributed wind power projects will extend to 14–17 years during 2022–2027. With the gradual improvement of the carbon trading market, the carbon reduction revenue obtained by distributed wind power enterprises will reduce the dynamic investment payback period by 2–3 years. Li et al. [34] calculated a dynamic investment payback period of 8–10 years for

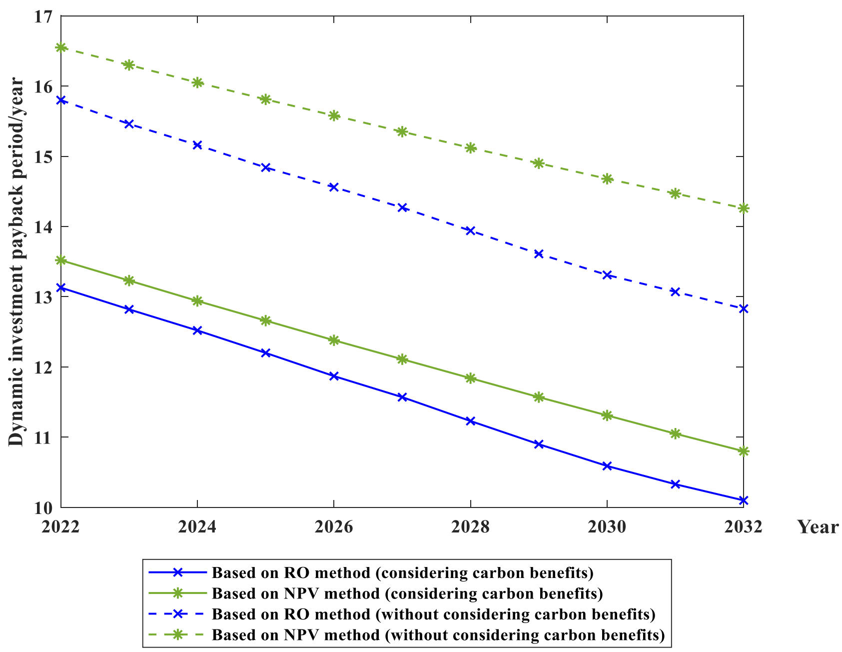

Fig. 7. Effect of carbon revenue on the dynamic investment payback period of distributed wind power projects in Shanghai.

wind power projects in the presence of wind power subsidies. Therefore, carbon reduction revenue does not allow the dynamic investment payback period for distributed wind power projects to reach the levels experienced under wind power subsidies.

5. Conclusions, policy implications and limitations

5.1. Conclusions

The conclusions drawn in this paper are mainly for the typical areas of distributed energy development such as the Yangtze River Delta represented by Shanghai, and in the future, with the large-scale development of distributed wind power, the object of the study can be expanded to other provinces and even the whole country. The development of China's carbon market is relatively mature, thus this paper mainly explores the impact of carbon emission reduction revenue on the investment benefits of distributed wind power, and the scale of China's green certificate market is comparatively small, with the development of the green certificate market, the next step needs to comprehensively consider the impact of the carbon price and the price of the green certificate on the investment benefits of distributed wind power.

In the context of the complete elimination of wind power subsidies and the official launch of China's carbon trading market, this paper constructs an investment value model for distributed wind power projects, drawing on the whole life-cycle cost and real options (RO) theories. Moreover, we examine a 10 MW distributed wind power project in Shanghai as a case study to analyze the influence of carbon revenue on the investment value and dynamic payback period of distributed wind power projects. The main conclusions are as follows:

(1) Investment in distributed wind power projects is feasible, as indicated by both the Net Present Value (NPV) and RO methods. However, the optimal investment strategy is to delay investing. Unlike the NPV method, the RO method considers the options value induced by future changes in uncertain factors, particularly the wind power feed-in tariff and the carbon trading price. Therefore, the RO method assesses the investment value of distributed wind power projects more accurately. Based on the RO method, we estimate the optimal time for investing in distributed wind power projects to be 2031.

(2) With the elimination of wind power subsidies and the official launch of China's carbon trading market, carbon reduction revenue enhances the return on investment of distributed wind power projects. Without carbon revenue, the investment value of distributed wind power projects would be about 1125 yuan/kW lower during the investment's life cycle. However, the current carbon trading price in the Yangtze Delta, exemplified by the Shanghai wind power project, is low, and its rate of increase is slow. This negatively affects decisions to invest in wind power, as the carbon reduction revenue received by distributed wind power enterprises is insufficient to compensate for the economic loss caused by the abolition of wind power subsidies. Carbon reduction revenue does not fully reflect the positive environmental externalities of wind power enterprises, and its reflection of these externalities is insufficient to motivate investors.

(3) The carbon reduction revenue earned by distributed wind power enterprises through the carbon trading market partially compensates for the economic loss resulting from the complete elimination of wind power subsidies, and shortens the dynamic investment payback period for wind power projects. However, compared to the effect of wind power subsidies, the contribution of carbon reduction revenue is limited. Our empirical analysis of the wind power project in Shanghai reveals that carbon reduction revenue is only sufficient to shorten the dynamic investment payback period by 2–3 years, and does not restore the payback period to levels experienced under the subsidy policy. Thus, the carbon reduction revenue provides only limited incentive to invest in distributed wind power projects.

5.2. Policy implications

Based on the conclusions mentioned earlier, we offer several countermeasures to promote investment in and utilization of distributed wind power:

1. Cost Reduction and Value Improvement: In the short term, distributed wind power enterprises could partner with energy storage companies to increase the efficiency of wind energy use, thereby enhancing its consumption and absorption capacity and boosting project investment value. For the long term, these enterprises should ramp up R&D investments to drive innovation in key components like wind turbines. The emphasis should be on technological advancements that bolster core technologies and realize economies of scale, consequently lowering the cost of power generation.
2. Incentivizing Immediate Investment: Our findings indicate that current carbon reduction revenue is insufficient to significantly encourage investment in distributed wind power projects in Shanghai. Local governments should thus focus on increasing carbon trading prices by fine-tuning the carbon tax mechanism and adjusting tax rates. Where carbon reduction revenue falls short, subsidies could be applied to encourage immediate rather than deferred investments. Furthermore, efforts should be made to stabilize the reserve mechanism of the carbon market, diversify the investor base, and broaden the scope of market trading. New carbon trading products should be introduced, and demand for carbon trading should be expanded. Pricing should be rationalized based on the 'cap and trade' principle to improve the investment value of distributed wind power enterprises.
3. Innovative Financial Products and Risk Control: The government should facilitate the development of innovative carbon-related financial products like futures and options while enhancing the risk control systems of carbon markets. A long-term objective should be the integration of a mortgage registration and credit system for environmental rights, such as carbon emission rights, into

the national unified movable property financing registration system. These measures would mitigate risks and increase the attractiveness of investing in distributed wind power projects, paving the way for their large-scale development.

5.3. Limitations and future studies

The investment decision-making for distributed wind power projects occurs within complex contexts. While the investment model constructed in this paper offers practical insights, it does have some limitations:

1. The limited duration of available data for distributed wind power projects hampers in-depth empirical analysis. Because of data availability issues, this paper focuses solely on an arithmetic study of Shanghai, a city with advanced distributed energy development. As distributed wind power projects continue to scale and more data becomes available, future research can extend to a broader analysis covering the entire country.
2. This paper considers only two uncertainty factors—wind power feed-in tariff and carbon trading price—that are highly correlated with the investment value of distributed wind power projects. In reality, market-based instruments like carbon taxes, carbon emission rights mechanisms, and green credit certificates also influence project investment value. Given the ongoing development of China's carbon trading market and the expanding scale of carbon trading, further in-depth discussions on this topic are warranted. These considerations will offer additional policy insights and serve as valuable references for future investment in distributed wind power projects both in China and globally.

CRediT authorship contribution statement

Fengyun Wang: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft. **Jingjing Ma:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. **Milin Lu:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Yanqi Sun:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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