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# Impact of Carbon Tax and Carbon Emission Trading on Wind Power in China: Based on the Evolutionary Game Theory

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Global climate problems caused by the overuse of fossil energy need to be settled urgently. To solve global warming threatening human life and production, environmental control policies have been proposed as the mainstream ways to push renewable energy development worldwide, such as carbon tax, carbon trading, emissions trading, and fiscal subsidies. This study examines how carbon tax and carbon emission trading policies could be coupled with subsidy policies to better promote renewable energy development. The data come from seven carbon emission trading pilots from 2013 to 2017 in China. Based on the evolutionary game, the research simulates the onshore wind power investment to deeply explore the spontaneous evolution process. Considering carbon tax and carbon emission trading policies, the two evolutionary game models are constructed under the context of fiscal subsidy policy, respectively. The results show that, under the scenario of carbon trading and subsidy policy coordination, investors will vote for wind farms and under the scenario of the carbon tax and subsidies coordination, investors will pay the funds in coal-fired power generation. Besides, this is worth noting that excessive carbon tax may give rise to the shrinking of the power industry. Accordingly, it is suggested that the government should continue to implement the carbon emission trading policy and maintain the free quota below 80% and the carbon emission trading price above 120.02 yuan/ton.

**Keywords: carbon tax, carbon emissions trading, financial subsidy, evolutionary game, wind energy**

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## INTRODUCTION

Excessive use of fossil fuel emissions has begotten a series of climate problems seriously affecting human normal production and life, such as the greenhouse effect, global warming of 2°C, and rising sea levels. Therefore, carbon emission reduction has been a consensus all over the world in formulating environmental policies. As the world's largest carbon emitter, China accounted for 29.38% of global carbon emissions in 2019 (International Energy Agency, 2021). China's efforts to reduce emissions are pivotal to the world. President of the People's Republic of China Xi Jinping delivered an important speech at the general debate of the 75th UN General Assembly that China will achieve carbon neutrality by 2060.

The power sector is the largest source of carbon emissions in China, accounting for about half of China's total carbon emissions. Coal-fired power generation in China accounted for more than 69%

of total carbon emissions in 2019 (Wang P. et al., 2021). Implementing a carbon tax or carbon emission trading policy is beneficial to curbing coal-fired power generation, encouraging renewable energy generation, and reducing carbon emissions. China promotes the development of renewable energy using financial subsidies. As of June 2021, the central government has allocated more than 600 billion yuan in subsidies, leading to a large shortfall in renewable energy subsidies (Ministry of Finance of the People's Republic of China, 2021). Obviously, only relying on financial subsidies policy is not sustainable. Renewable energy development requires more carbon reduction policies to achieve carbon neutrality in 2030 and 2060.

China has made attempts on the path of carbon emissions trading; a nationwide carbon emission trading market in China was not operational before mid-2021, with only seven carbon trading pilots in place before then. The first pilot was built in 2013, Shenzhen. Currently, only 2,871 renewable energy power projects are qualified for carbon trading (China National Development and Reform Commission, 2021). However, with the launch of a nationwide carbon emission trading market, high-energy-consuming industries would enter the carbon emission trading market and increase the demand for carbon allowances, and the quota supply of renewable energy power generation enterprises should increase, leading the renewable energy power generators to achieve more carbon reduction benefits. The carbon emission trading policy still has a long way to go. Besides, the other effective emission policy, carbon tax, has not been implemented in China. Hence, when subsidies are gradually withdrawn, the comparative effects of carbon tax and carbon emission reduction policies are worth exploring.

From a theoretical point of view, under the conditions of a competitive market with completely symmetrical information, the policy effects of the carbon tax and carbon emission trading are the same, and both can achieve Pareto optimality (Wu et al., 2014). However, because the government and investors often do not have access to complete information, designing the best carbon tax level or the best tax exemption limit to meet the total emission standard becomes a problem. Therefore, this study explores how the carbon tax and carbon emission trading can promote the development of onshore wind power in China's power industry to achieve emission reduction targets as soon as possible.

This study adopts the trading data from all the carbon emission trading pilots in China, including Beijing, Shanghai, Tianjin, Chongqing, Guangdong, Shenzhen, and Hubei provinces. It focuses on free quotas at different levels and provides a basis for evaluating reasonable carbon prices. Moreover, the input-output information in the evolutionary model allows us to consider the repeated investment of investors, which is in line with the actual situation. Furthermore, this research explores the impact of different subsidies, carbon tax rates, and free allowances for carbon emission trading on wind power investment and provides the policy basis for the continued growth of wind power investment after the decline of subsidies. The rest of the article is as follows: *Literature Review* reviews previous studies; *Model* establishes the evolutionary game model of the investment willingness in coal-fired power plants or wind farms in China, which is motivated by the carbon tax or carbon emission trading policy; *Investment Simulations* presents the numerical analysis under subsidy, carbon tax, and carbon emission trading based on the data from seven carbon emission trading pilots; and *Conclusion* section concludes the study.

## LITERATURE REVIEW

Carbon taxes and carbon emission right trading are often used to promote the development of renewable energy. The general equilibrium model and econometric model are commonly used to compare the emission reduction effects of these two policies (Robinson, 2010; Aflaki and Netessine, 2017; Poelhekke, 2019; Kök et al., 2020; Chen et al., 2021). These studies analyzed the relationship between the economic, energy, and environmental sectors under the overall macroeconomic framework and analyzed energy consumption and environmental changes under subsidy, carbon tax, and emission trading policies. As summarized in **Table 1**, most studies analyzed the sector from a macro or meso perspective, but a few analyzed it from a micro perspective of enterprises selection (Li et al., 2021). Enterprises are the executors of the policy. The enterprise's perspective could reflect the effects of policy implementation in a bottom-up manner, making the policy effect more relevant to reality.

From the perspective of enterprises, optimization and game theory methods are usually used to study renewable energy investment under the carbon tax and carbon emission trading policies (Liu and Zhao., 2015; Bai and Xu, 2016; Chen et al., 2021). Bai and Xu (2016) studied the optimal production and emission reduction investment strategies for manufacturers under the limit of carbon emissions and carbon transactions. In addition to manufacturing, the power industry also vigorously promotes carbon emission reduction. Liu and Zhao (2015) analyzed the production decision-making problems of power companies under different energy consumptions affected by the renewable energy tariff subsidy policy, the technology research and development (R&D) investment subsidy policy, and the carbon emission price policy. Further research was based on carbon emissions trading, carbon tax, and subsidy to study the production decision of power enterprises. Zhang et al. (2017) demonstrated that carbon emission trading could help reduce subsidies. They used stochastic processes to describe electricity market prices, $CO_2$ prices, and investment costs to establish a real options model of optimal subsidies for renewable energy power generation projects. Goulder et al. (2022) analyzed the power generation and emissions of thermal power in a carbon trading pilot by matching analytically and numerically solved models, concluding that carbon trading gave positive incentives to power plants with lower emissions to expand their output. Although the previous studies discussed the decision-making behaviors of power companies under the low-carbon policy, these decisions often concentrated on the production decision-making and R&D decisions of enterprises. This study focuses on the investment decision-making problem of investing in new units.

**TABLE 1 |** Recent studies on carbon tax and carbon emission trading policies.

| Authors | Publication | Scope | Method | Research perspective | Carbon reduction policy |
|---|---|---|---|---|---|
| Barragán-Beaud et al. (2018) | Energy Policy | Mexico | Balmorel-MX model | The power sector | Carbon tax and carbon emission trading |
| Hu et al. (2020) | Journal of Cleaner Production | China | Game theory-Cournot model | Remanufacturing industry | Carbon tax and carbon emission trading |
| Jia and Lin (2020) | Technological Forecasting and Social Change | China | The CEEEA (China Environmental-Energy-Economy Analysis) model | National | Carbon tax and carbon emission trading |
| Zhao et al. (2019) | Renewable Energy | China | Mathematical modeling | National | Carbon tax and carbon emission trading |
| Fu et al. (2021) | Science of the Total Environment | China | FCGE model | National | Carbon tax |
| Zhang et al. (2020) | Journal of Environmental Management | China | CGE model | National | Carbon tax |
| Li et al. (2021) | Journal of Cleaner Production | Low-carbon community | Game theory-Nash bargaining | P2P | Carbon tax |
| Domon et al. (2022) | Regional Science and Urban Economics | Urban | Mathematical modeling | Residents | Carbon tax |
| Taghizadeh-Hesary et al. (2021) | Journal of Economic Policy Reform | Japan | ARDL model | Household | Carbon tax |
| Gugler et al. (2021) | Journal of Environmental Economics and Management | Germany and Britain | Mathematical modeling | National | Carbon tax |
| Zhang et al. (2022) | Resources, Conservation and Recycling | China | Robust optimization-based dynamic generation expansion planning model | Power system | Carbon tax |
| Cao et al. (2019) | Energy Economics | China | Dynamic CGE model | National | Carbon emissions trading |
| Luo et al. (2022) | Journal of Cleaner Production | Guangdong-Hong Kong-Macao Greater Bay Area in China | The AIM/Enduse model | Power system | Carbon emissions trading |

Low-carbon policies would promote renewable energy generation in the power industry, ultimately reducing carbon emissions. According to the statistics of the International Energy Agency (2021), The sum of carbon dioxide emissions in China's electricity and heat sectors account for 9.58% of total carbon dioxide emissions of all sectors. Reducing emissions in the power industry by encouraging renewable energy generation can help achieve China's carbon neutrality.

Game theory is a relatively suitable method in power investment decision-making (Lu et al., 2014). The Cournot competition model, the Bertrand competition model, the SFE model, and the evolutionary game model are common ways to simulate the investment decision in the power industry (Gao and Sheng, 2003; Shafie-Khah, 2013; Lu et al., 2014; Liu et al., 2015; Wang et al., 2021a; Wang et al., 2021b). Among the four, the evolutionary game model does not require participants to be completely rational and emphasize a dynamic equilibrium. In the real game between the investors, information is generally incomplete and imperfect, and participants are not completely rational, so they need to achieve equilibrium through the continuous game, trial, error, and learning. These models considered the choice of investors when implementing policies but ignored the repeated trial and error game process between investors and the imitating attempts between participants. The evolutionary game theory considers bounded rationality, learning mechanism, and decision-making process, which is more in line with reality (Vincent and Newsom-Davis, 1985). This article uses the evolutionary game theory to build a model to analyze the impact of the carbon tax and carbon emission trading policies on wind power and thermal power investment.

However, there are further improvements in the above studies. 1) Most research studied the power sector from a macro or meso perspective (Barragán-Beaud et al., 2018; Hu et al., 2020; Fu et al., 2021), but few studies analyzed it from a micro perspective of enterprises selection. With the establishment of China's carbon emission trading market, more enterprises will be included in the market access scope in the future. At that time, as the beneficiaries (investment in renewable energy power) and purchasers (investment in coal-fired power), the correct investment decisions towards enterprise will increase its right in the carbon market. 2) However, most existing studies use static analysis (Taghizadeh-Hesary et al., 2021; Fu et al., 2021). Such analysis is difficult to describe the repeatability and dynamics of enterprise investment and hard to reflect changes in firms' investment behavior over time. This leads to inaccurate long-term forecasts, allowing policy effects to deviate from the original design. 3) Besides, in terms of exploring enterprises' investment decisions, the decision model and assumptions need more

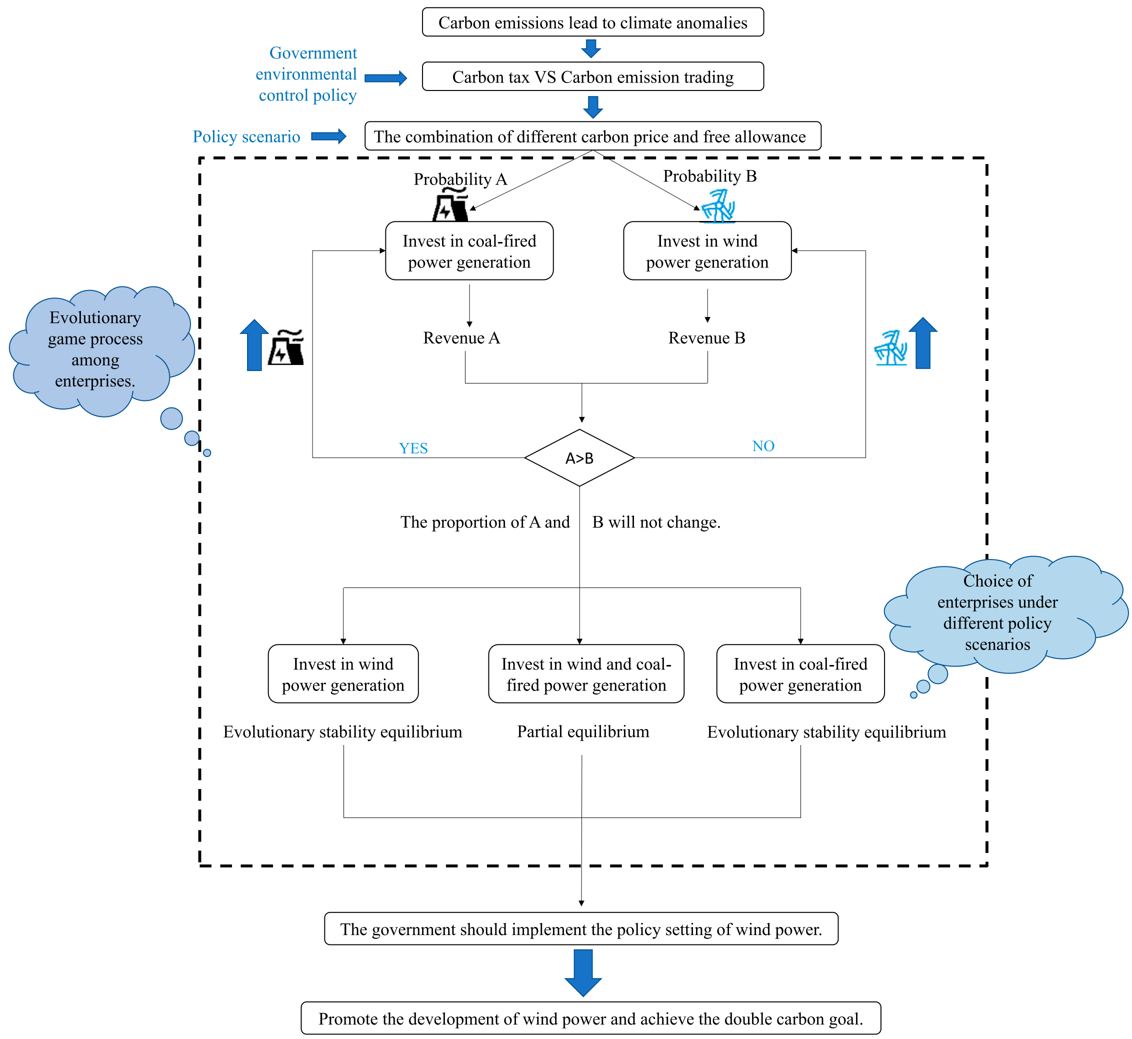


**FIGURE 1 |** The framework of evolutionary game theory for an investment decision.

discussion. Few studies analyzed the effects of the carbon tax and carbon emission trading under the same model, and the conclusions between different studies could not be compared. The CGE model and its extension rely heavily on hypothetical parameters when simulating the effect of carbon tax or carbon emission trading policy, while the values of parameters may still be different when different articles study the same country and the same department (Cao et al., 2019; Zhang et al., 2020). Therefore, the conclusions drawn using CGE are not suitable for direct comparison.

The marginal contribution of this study to the current literature could be summarized as follows: 1) the impact of carbon emission reduction policies on investment in renewable energy generation is analyzed under the carbon tax and carbon trading policies from the perspective of enterprises investment, respectively, which enriches the study of enterprise perspective; 2) the dynamic model of the evolutionary game theory was used in this research to reflect the evolution of enterprises investment; and 3) analyzing carbon tax and carbon trading policies under the unified method makes the results more comparable.

## MODEL

Carbon taxes and carbon emission right trading are often used to promote the development of renewable energy. The government needs to consider the appropriate policies and their combination to promote investment in renewable energy. China's carbon emission trading pilot has been successfully operated for many years, and China has a complete tax system. Thus, this article only studies the carbon tax policy and carbon emission trading policy. Under the exogenous low-carbon policy, we considered the price of carbon emission trading to be relatively stable in a certain period because the impact of carbon emissions from new units is also small on the entire electricity market and the balance of the existing carbon emission trading market. Besides, given that the proportion of new power generation to total power generation is very low, in 2019 and 2020, the ratio is 2.04% and 2.56%, respectively (China National Energy Administration, 2020; China National Energy Administration, 2021), it is assumed that the power generation of new power plants will not affect the overall on-grid price; that is, the on-grid price $P$ will not be affected by the amount of power generation $Q$.

The conceptual framework of the research is shown in **Figure 1**. The evolutionary game is employed to investigate the investment of wind power under carbon tax or carbon emissions trading. Under different low-carbon policies, thermal and wind units possess different costs and benefits. When the profit of thermal turbines is greater than that of wind turbines, more investors will invest in thermal turbines, and when the profit of thermal turbines is less than that of wind turbines, more entrepreneurs will inaugurate in wind turbines until the game results in an evolutionary stable equilibrium or a partial equilibrium. The government implements a policy of corporate investment in wind power according to the results of the corporate game to promote corporate investment in wind power and achieve China's carbon peaking and carbon neutrality goals.

## Evolutionary Game Matrix for Investors

The basic idea of the evolutionary game is that participants have different strategic choices, in which they choose their strategy while obeying a certain probability distribution. According to the income of the previous game, the participants will reduce the probability of selecting a low-yield strategy and increase the probability of selecting a high-yield strategy in the next game. The evolutionary game assumes that the game object is randomly selected from a large population, and the extracted samples are played according to the established rules. The results will be fed back to the large population, and the distribution of the random extraction will be changed. The above process will be repeated until the evolution is stable.

Following Stanford Encyclopedia of Philosophy (2021), consider a $2 \times 2$ bimatrix game, the two pure strategies of investors in population A (investor A) are investing in wind power units ($A_1$) and investing in thermal power units ($A_2$), and two pure strategies of investors in population B (investor B) are investing in wind power units ($B_1$) and investing in thermal power units ($B_2$). Let $a_{ij}$ denote the payoff to investor A using strategy $A_i$ when it meets investor B using strategy $B_j$, and denote the payoff to investor B in this interaction by $b_{ij}$ so that we have the payoff matrix:

$$\begin{array}{ccc} & & Inverster\ B \\ & & B_1\,(wind)\ B_2\,(thermal) \\ Inverster\ A & \begin{array}{c} A_1\,(wind) \\ A_1\,(thermal) \end{array} & \begin{pmatrix} a_{11}, b_{11} & a_{12}, b_{12} \\ a_{21}, b_{21} & a_{22}, b_{22} \end{pmatrix}, \end{array} \quad (1)$$

## Investor Strategy Choice for Investing in Thermal Power and Wind Power

### Profit Function for Investing in Thermal Power

Following Yao (2015), the payoff function of thermal power investors is given by **Eq. 2**. The function contains the revenue of electricity sales, the cost of coal, and carbon dioxide emission cost:

$$\pi_{thermal} = PQ_{thermal} - C_{thermal} - C_{CO_2}, \quad (2)$$

where$P$ represents the power price, $Q_{thermal}$ represents the power generation of the thermal units, $C_{thermal}$ represents the cost of thermal power generation, and $C_{CO_2}$ represents the carbon dioxide emission cost which differs in government policies. When the low-carbon policy is a carbon emission trading policy, the cost of the carbon dioxide emission equals $P_{CO_2}(1-\beta)eQ_{thermal}$. While the policy is carbon tax policy, the cost of the carbon dioxide emission equals $tQ_{thermal}$, where $P_{CO_2}$ represents the carbon emission trading price, $\beta$ represents the free emission allowances for thermal power units, $e$ represents the carbon emission factor, and $t$ represents the value of the carbon tax.

### Profit Function for Investing in the Wind Power

Following Yao (2015), Gartman et al. (2016a), and Gartman et al. (2016b), the payoff function of wind power investors is given by **Eq. 3**. The function contains the revenue in the electricity sale, the subsidies given by the government, the cost of building the wind power unit, and the revenue $\pi_{wind}$ in carbon dioxide emission trading:

$$\pi_{wind} = (P+S)Q_{wind} - C_{wind} + R_{CO_2} \quad (3)$$

$S$ represents subsidies, $Q_{wind}$ represents the power generation of the wind power units, $C_{wind}$ represents wind power units' generation cost, $R_{CO_2}$ represents the carbon revenue of wind power units. When the low-carbon policy is a carbon emission trading policy, the revenue equals $P_{CO_2}Q_{CO_2}$, and while the policy is a carbon tax, it equals 0, where $Q_{CO_2}$ represents the reduction of $CO_2$ approved by the government.

## Replicator Dynamics for Investors

If the probability of investor A investing in the wind power units is $x$, then the probability of investor A investing in the thermal power units is *1-x*. If $y$ is the probability of investor B investing in the wind power units, *1-y* is the probability of investor B investing in the thermal power units. Following Friedman (1991) and Stanford Encyclopedia of Philosophy (2021), the replicator dynamics for the bimatrix game 1) is given as follows:

$$\begin{aligned} \frac{dx}{dt} &= x\left(E\left(A_1\right) - \mathrm{E}\left(A\right)\right) \\ &= x\left(1-x\right)\left(\left(a_{12}-a_{22}\right)\left(1-y\right) + \left(a_{11}-a_{21}\right)y\right)\frac{dy}{dt} \\ &= y\left(E\left(B_1\right) - \mathrm{E}\left(B\right)\right) \\ &= y\left(1-y\right)\left(\left(b_{21}-b_{22}\right)\left(1-x\right) + \left(b_{11}-b_{12}\right)x\right) \end{aligned} \quad (4)$$

where $E(A_1)$ and $E(B_1)$ are the profits of strategies $A_1$ and $B_1$, respectively, and $E(A)$ and $E(B)$ are the average profits of investors A and B, respectively.

Let $f(x) = (b_{21}-b_{22})(1-x) + (b_{11}-b_{12})x$. There are three kinds of cases.

If $f(x) = 0$, then $y^{*}\epsilon[0,1]$. In other words, when $x = \frac{b_{22}-b_{21}}{b_{11}+b_{22}-b_{21}-b_{12}}$, the strategy of investor A will not change, where $y^{*}$ means the probability of the situation, in which investor B builds wind power units after a rescaling of time. If $f(x) < 0$, then $y^{*} = 0$, which means investor B will eventually invest in the thermal power unit. If $f(x) > 0$, then $y^{*} = 1$, which means investor B will eventually invest in the wind power unit.

Let $f(y) = (a_{12}-a_{22})(1-y) + (a_{11}-a_{21})y$, there also are three kinds of cases:

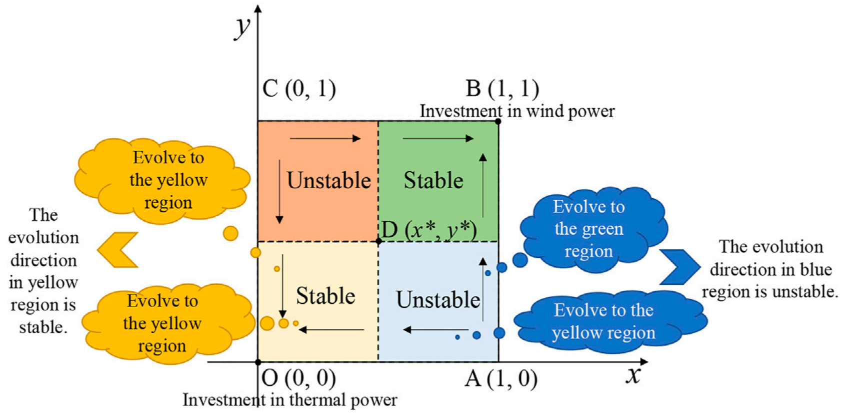


**FIGURE 2 |** Phase diagram of investors evolution game.

If $f(x) = 0$, then $x^* \epsilon [0, 1]$. In other words, when $y = \frac{a_{22}-a_{12}}{a_{11}+a_{22}-a_{21}-a_{12}}$, the strategy of investor B will not change, where $x^*$ means the probability of the situation, in which investor A builds wind power units after a rescaling of time. If $f(y) < 0$, then $x^* = 0$, which means investor A will eventually invest in the thermal power unit. If $f(y) > 0$, then $x^* = 1$, which means investor A will eventually invest in the wind power unit.

Following Li et al. (2015), the evolutionary game has four boundary equilibria [(0, 0), (1, 0), (0, 1), (1, 1)] and one interior equilibrium $(\frac{b_{22}-b_{21}}{b_{11}+b_{22}-b_{21}-b_{12}}, \frac{a_{22}-a_{12}}{a_{11}+a_{22}-a_{21}-a_{12}})$. Two states, (0, 0) and (1, 1), are locally asymptotically stable. They correspond to the two strict Nash equilibria $(A_2, B_2)$ and $(A_1, B_1)$. The final result is determined by the revenue of the wind power units and the thermal power units. The mixed equilibrium $(\frac{b_{22}-b_{21}}{b_{11}+b_{22}-b_{21}-b_{12}}, \frac{a_{22}-a_{12}}{a_{11}+a_{22}-a_{21}-a_{12}})$ is a saddle point. The evolution game phase diagram is shown in **Figure 2**.

In **Figure 2**, the evolution process and the steady population state are affected by the initial state of the system and the relative position of the saddle point D. When the initial state falls in the OD region (i.e., the yellow region), the evolutionary game system converges to *O (0,0)*. At this time, investors all decide to build thermal power units. When the initial state falls in the BD region (i.e., the green region), the evolutionary game system converges to *B (1,1)*. At this time, investors all decide to build wind power units. However, investors will not reach equilibrium in other regions. If $S_{BD} > S_{OD}$ (i.e., the green area is larger than the yellow one), the system will evolve along the green path with a higher probability of building wind power units. If $S_{BD} < S_{OD}$, the system will evolve along the yellow path with greater probability of building thermal power units. If $S_{BD} = S_{OD}$, the probability of building wind power units is equal to building thermal power units, and the evolutionary direction of the system is not clear.

## INVESTMENT SIMULATIONS

### Parameter Initialization Settings

This study counts all the approved wind farm projects from 2013 to 2017 in China Certified Emission Reduction Exchange Info-Platform (China National Development and Reform Commission, 2021) and selects the average value of the on-grid energy and the carbon dioxide emission reduction from 393 wind farm projects with an installed capacity of 49.5 MW. The 49.5 MW wind farm was chosen because most of the newly built wind farms in China have an installed capacity of it as wind farms whose installed capacity above 50 MW requires approval of the National Energy Administration. Meanwhile, other wind farms only require local government' approval. In the numerical example, the $CO_2$ emission of the wind turbine is $Q_{CO_2}$, which is 90,157.91 tons. We set the installed wind power unit's capacity $R_{wind}$ as 49.5 MW and the installed thermal power unit's capacity $R_{thermal}$ is 49.5 MW too. According to the IEA data, the carbon dioxide emission of the standard coal is 2.46 kg $CO_2$/kg, and the consumption of standard coal is 309 g per kilowatt-hour power generation. Then, we calculated the carbon dioxide emission factor $e$ as 760.14 g $CO_2$/KWh. The coal price is taken from the average price of the January–December 2017 coal price index issued by the National Development and Reform Commission Price Testing Center. For the subsidy for wind power, the calculation principle is the on-grid price of wind power minus the on-grid price of coal-fired power generation. The current on-grid price of onshore wind power is calculated according to the four types of resource zones in China, and the on-grid price of coal-fired power generation is calculated by province. The above calculation results show that, by December 2017, the maximum subsidy in China is 0.233 yuan/kWh in Qinghai province, and the minimum subsidy is 0.0586 yuan/kWh in Hebei South Network, thus obtaining the subsidy range, that is, 0.0586–0.233 yuan/kWh.

The other parameters in our simulation are shown in **Table 2**.

## The Result of Simulation

### Baseline Scenario

Basically, China only implements the fiscal subsidy policy for wind power units, such as the carbon revenue of wind power units $R_{CO_2} = 0$ and the cost of carbon dioxide emission $C_{CO_2} = 0$. The cost of thermal power generation $C_{thermal}$ contains the variable cost $C^V_{thermal}$ and the fixed cost $C^F_{thermal}$. The variable cost of power generation per MV capacity unit of a thermal power plant comprises the coal cost and other costs from labor, maintenances, management, and taxes. According to Yao (2015), the fuel cost of thermal power generation accounts for about 70% of the variable

**TABLE 2 |** Parameter and the value in our model.

| Symbol | Meaning | Value | Data source |
|---|---|---|---|
| $P$ | On-grid price | 0.3894 yuan/kWh | Notice of the National Development and Reform Commission on Reducing the On-Grid Electricity Price of Coal-Fired Power Generation and the Price of General Industrial and Commercial Electricity (2015) |
| $C^F_{thermal}$ | Fixed thermal power engineering unit cost | 4105.5 yuan/kW | China Power Industry Annual Development Report (2018) |
| $C^F_{wind}$ | Fixed wind power engineering unit cost | 7,719 yuan/kW | China Power Industry Annual Development Report (2018) |
| $C^V_{wind}$ | Variable wind power engineering unit cost | 5,400 yuan/kW | Yao (2015) |
| $h_{themal}$ | Thermal power utilization hours | 4209 h | National Electric Power Industry Statistics Express (2017) |
| $h_{wind}$ | Wind power utilization hours | 1948 h | National Electric Power Industry Statistics Express (2017) |
| $P_{coal}$ | Coal price | 515.99 yuan/ton | National Development and Reform Commission Price Monitoring Center (2017) |

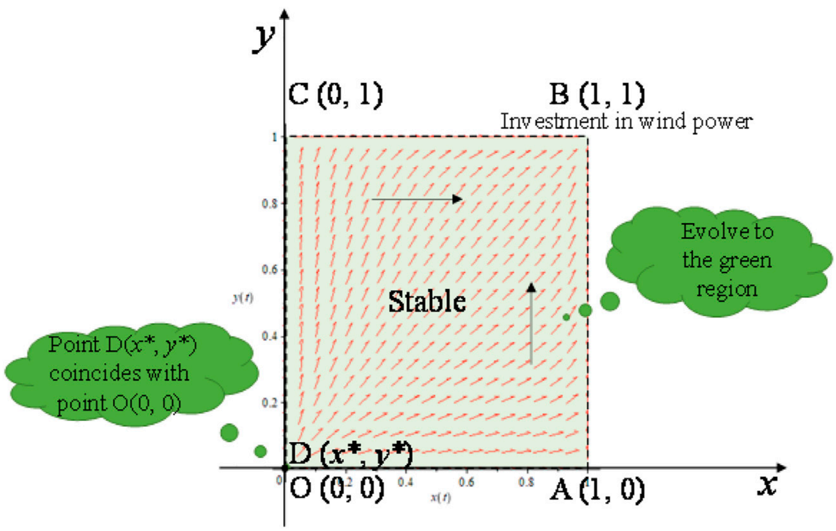


**FIGURE 3 |** Simulation results in the basic scenario.

cost. Therefore, the power generation cost per MV coal-fired power unit can be described as follows:

$$C^V_{thermal} = C_{coal}/0.7 = P_{coal}\,(h_{thermal}e700/05500)/0.7, \qquad (5)$$

where $C^V_{thermal}$ is the thermal power variable cost of generating 1 MW energy, $C_{coal}$ is the cost of coal during the power generation, $P_{coal}$ is the coal price. Fixed cost $C^F_{thermal}$ is the cost of annualized construction units, the thermal power unit running time is usually 30 years, and the wind power unit can normally run for 25 years. Now, the cost of thermal power generation is about 0.24 yuan/kWh, and wind power generation is about 0.44 yuan/kWh.

When the financial subsidy is less than 0.047 yuan/kWh, investors will choose to invest in the thermal power units. When the subsidy is more than 0.047 yuan/kWh, investors will choose to invest in the wind power units, as shown in **Figure 3**. In **Figure 3**, point D ($x^*$, $y^*$) coincides with point O (0, 0). No matter where the initial situation is, all evolutionary directions eventually point to point B (1, 1), and the evolution result is (1,1), which means investors A and B all choose wind power generation. It is suited for the actual situation and proves that our model is reasonable. At the end of 2017, China's renewable energy subsidy gap has reached 100 billion yuan, unsustainable for the wind power industry (Polaris solar photovoltaic network, 2018). Therefore, it is necessary to reduce subsidies and promote renewable energy development through a policy combination.

## The Carbon Emissions Trading and Subsidy Scenario

In China's carbon emission trading pilot areas, the average carbon emission trading price during 2017 was 27.85 yuan/ton in Shenzhen, 50.48 yuan/ton in Beijing, 23.35 yuan/ton in Shanghai, 14.28 yuan/ton in Guangdong, 13.70 yuan/ton in Tianjin, 18.52 yuan/ton in Hubei, and 4.01 yuan/ton in Chongqing. Therefore, this section discusses the impact of free quotas on the game when the carbon trading prices are 5, 10, 15, 20, 30, and 50 yuan/ton. The different carbon emission trading prices and financial subsidies are brought into the evolutionary

**TABLE 3 |** Simulation results in the carbon emission trading policy.

| | Subsidy (yuan/kWh) | | | |
|---|---|---|---|---|
| Carbon trading price (yuan/ton) | 0 | 0.047 | 0.056 | 0.1372 |
| $\beta$ = 95% | | | | |
| 5 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 10 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 15 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 20 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 30 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 50 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| If the investor invests in wind power units when the subsidy is canceled, the carbon trading price needs to be greater than 187.85 yuan/ton | | | | |
| $\beta$ = 80% | | | | |
| 5 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 10 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 15 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 20 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 30 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 50 | (0,0) | (0,0) | (0,0) | (1,1) |
| If the investor invests in wind power units when the subsidy is canceled, the carbon trading price needs to be greater than 151.22 yuan/ton | | | | |
| $\beta$ = 60% | | | | |
| 5 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 10 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 15 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 20 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 30 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 50 | (0,0) | (0,0) | (0,0) | (1,1) |
| If the investor invests in wind power units when the subsidy is canceled, the carbon trading price needs to be greater than 120.02 yuan/ton | | | | |

game matrix, and the results under different conditions are obtained in **Table 3**. In the results, (0,0) represents the evolutionary game reaching the evolutionary stability equilibrium (ESS), where all investors invest in the thermal power units. (1,1) represents the evolutionary game reaching the evolutionary stability equilibrium (ESS), where all investors invest in the wind power units. (0,1) and (1,0) represent the evolutionary game reaching partial equilibrium, in which investor A invests in thermal power units and investor B invests in wind power units, and investor A invests in wind power units and investor B invests in thermal power units, respectively. **Figure 4** shows some typical simulation results of different carbon trading prices under different subsidies in the carbon emission trading policy. **Figure 4A** implies that investors arrive at the evolutionary stability equilibrium for wind power. **Figure 4B** means the evolutionary game of investors reaches partial equilibrium, and the investment evolution direction of investors in green and yellow regions is random. Investors in these two regions may eventually invest along the red region or the blue region. Both red area and blue area mean that the investment is in an evolutionary unstable equilibrium state, with both investors investing in wind power and thermal power. At this point, investors are likely to invest in both wind power and thermal power. In **Figure 4C**, all investors prefer thermal power to reach evolutionary stability equilibrium.

**Table 3** shows that when the current financial subsidies are implemented, some investors invest in thermal power units, and others invest in wind turbines, which is the same as the real world. This finding is consistent with Luo et al. (2022), stating that the carbon trading policy does not play a role in carbon emission reduction under a 95% free quota. Besides, for comprehensive consideration, this study also analyzes more possible scenarios compared to the previous studies, the free quota at 80% and 60%. Under these two kinds of quotas, the lowest carbon emission trading price corresponding to enterprises' investment in wind power is different, and enterprises can optimize their investment decisions according to our guidance price. The results of both papers conclude that the carbon trading mechanism can play a better role when the carbon trading price reaches 120 yuan/ton.

Additionally, we can reduce government financial pressure by increasing the price of carbon emission trading and reducing the free emission allowances of thermal power units. According to our simulation, if the free emission allowance of thermal power units is cut from 95% to 60% and the carbon trading price is greater than 120.02 yuan/ton, then the government can save at least 4020 million yuan per year (China National Energy Bureau 2017). The government could adapt to local conditions and change the access conditions in different regions, indirectly guiding the carbon emission trading price and changing the

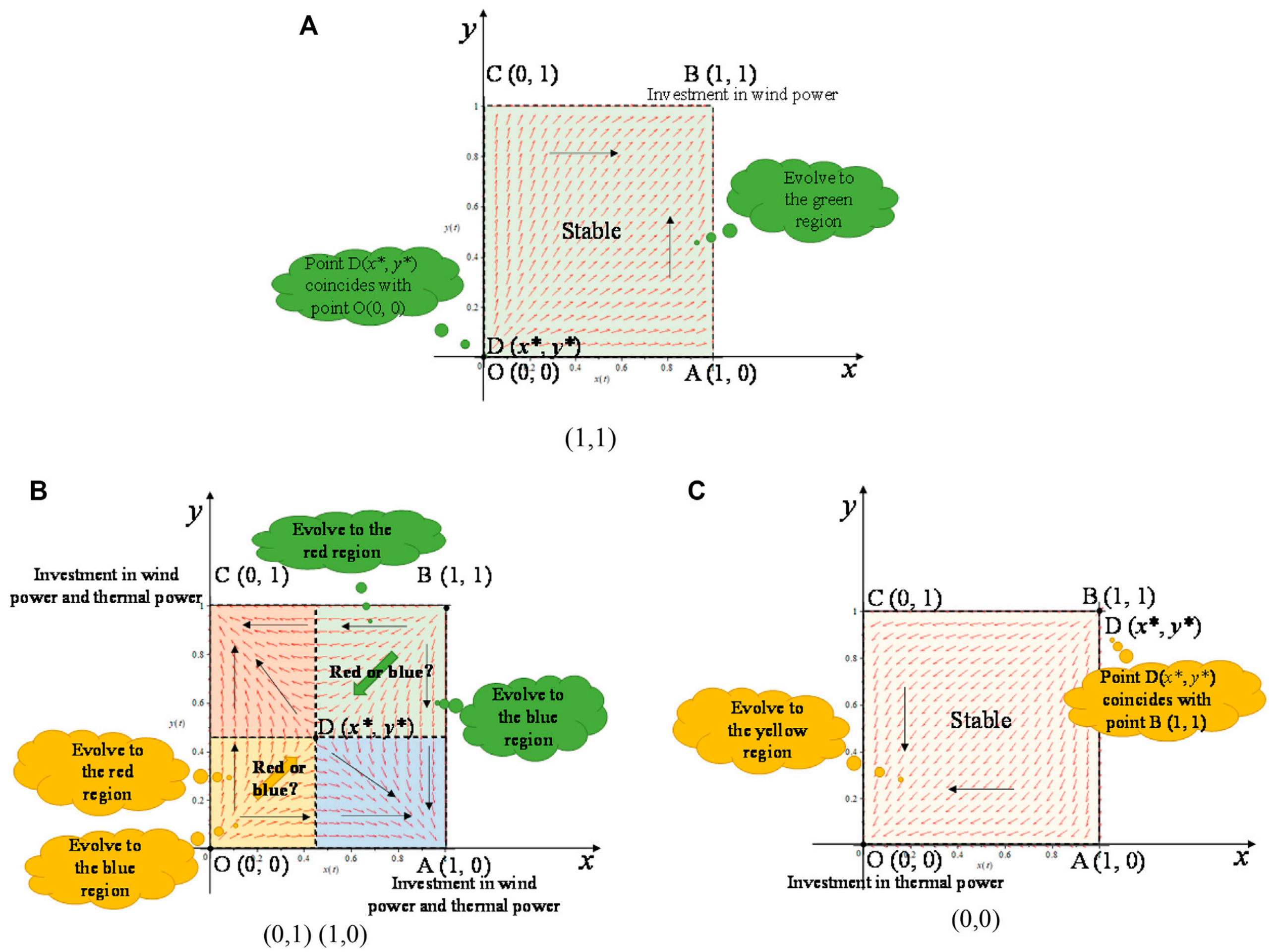


**FIGURE 4 |** Typical simulation results in the scenario **(A)** evolutionary to (1, 1) which means investor invest in wind power. **(B)** evolutionary to (0,1) (1,0) which means investor invest in wind power and thermal power. **(C)** evolutionary to (0,0) which means investor invest in thermal power.

free emission quotas of thermal power units. By the above methods, the government can choose not to subsidize wind power units to alleviate the fiscal pressure.

## The Carbon Tax and Subsidy Scenario

Studies on China's optimal carbon tax never implemented in China are extremely different. This section separately solves the evolutionary game under different carbon tax levels. In China, the study shows the carbon tax should include 17.18, 36.49, 40, 81.08, and 132 yuan/ton (Yao and Liu 2010; Zhang 2011; Wang et al., 2012). China Carbon Forum (CCF) and ICF International Consulting Co., Ltd. jointly released the "China Carbon Price Survey" in August 2015. The result shows that the expected carbon tax in 2020 is 40 yuan/ton. According to the Carbon Pricing Watch 2017 report released by the World Bank, Mexico, Poland, and Ukraine have a carbon tax of less than 1 $/ton. The carbon tax is 84 $/ton in Switzerland, 52 $/ton in Norway, 33 $/ton in France, 25 $/ton in Denmark, and 126 $/ton in Sweden. In summary, we set the carbon tax in this section as 20, 40, 80, and 130 yuan/ton. The carbon emission cost of coal-fired units is determined by the carbon tax, and the tax rate of the carbon tax is set by the Chinese government.

**TABLE 4 |** Simulation results in the carbon tax policy.

| | Subsidy (yuan/kWh) | | | |
|---|---|---|---|---|
| Carbon tax (yuan/ton) | 0 | 0.047 | 0.056 | 0.1372 |
| 20 | (0,0) | (0,0) | (0,0) | (0,1), (1,0) |
| 40 | (0,0) | (0,0) | (0,0) | (1,1) |
| 80 | (0,0) | (0,1), (1,0) | (0,1), (1,0) | (1,1) |
| 130 | No investment | (1,1) | (1,1) | (1,1) |

**Table 4** shows the results of the carbon tax policy; that is, when the subsidy is 0.1372 yuan/kWh, enterprises with carbon prices higher than 40 yuan/ton will invest in wind power. Otherwise, they would invest in thermal power is in accordance with recent studies Zhao et al. (2019) and Gugler et al. (2021). Based on the previous study, the study also analyzed the situation of the investment without subsidy to imitate the investment behavior of enterprises after subsidy declining. The future of China's carbon reduction policy will be subsidy-free. The study could

provide the basis for the government to predict the behavior of enterprises and promote the policy formulation to encourage enterprises to invest in wind power, so as to ensure the achievement of China's double carbon target. We can see from the table that carbon taxes can replace subsidies, but there is a possibility to lead to a power industry shrinking when subsidies are too low or carbon taxes are too high.

## DISCUSSION

In this article, the evolutionary game is employed to study the investment of wind power under subsidy, carbon tax, and carbon emissions trading. By simulation analysis of the evolutionary game process, the impacts of free allowances, subsidy, the price of carbon emissions trading, and carbon tax are discussed. Then, under the two low-carbon policies, we conduct an in-depth scenario analysis to investigate the influences of those variables on the strategic evolution of participants. The results can be summarized as follows:

(1) The evolutionary game of investors has five partial equilibrium points, representing the following five cases: a) all investors invest in wind power units; b) investor A invests in wind power units and investor B invests in thermal power units; c) investor A invests in the thermal power unit and investor B invests in wind power units; d) all investors invest in thermal power units; and e) investors invest in thermal power units and wind turbines in a certain proportion. a and c are evolutionarily stable strategies.

(2) In the carbon emission trading policy, the government can change the price of carbon trading and the free emission quota of thermal power units and effectively reduce subsidies by means of multiple measures. In contrast, the government will turn to nothing but tax reduction to reduce subsidies on the carbon tax policy.

(3) In the two policies of the carbon tax and carbon emissions trading, the stability of the evolutionary game is more sensitive to the carbon tax policy, which means that the government's choice of carbon tax policy is more conducive to guiding investors' investment behavior, while carbon tax policies could lead to policy failures, so carbon emission trading policy is more suitable for China.

(4) There are some other partial equilibrium points in carbon emissions trading, in which investors will invest in wind power units and thermal power units. This will make the process of energy transition more gradual in China.

## CONCLUSION

This research analyzes the impact of subsidies, carbon tax policies, and carbon emission trading policies on the investment in wind power units and thermal power units to promote carbon emission reduction. Based on a simulation of the model with the carbon emission trading in Beijing, Shanghai, Tianjin, Chongqing, Guangdong, Shenzhen, and Hubei provinces, the result shows that when the free quota is below 80%, free quotas can make up for the negative impact of reduced subsidies on wind power investment. Moreover, by simulating the impact of investment under a carbon tax, this article finds it is difficult to determine a reasonable carbon price, and fluctuations in carbon prices are likely to cause investment to switch from wind power to thermal power. Excessive carbon prices will even reduce investment in the power industry and gradually shrink.

Based on the above research results, to promote the development of wind power, this study proposes the following policy recommendations. 1) From the perspective of promoting renewable energy development, carbon emission trading is more effective than carbon tax policy in China. This study suggests that the government implements the carbon emission trading policy cause without the subsidy, and investors would prefer to invest in wind power under the carbon emission policy rather than carbon tax policy. In the absence of subsidies, only the implementation of carbon emission trading policy could increase the proportion of investment in wind power and achieve China's double carbon target. 2) The reduction in wind power investment caused by the reduction of subsidies should be offset by the free allowance for carbon emission reduction trading. By this means, the wind power development plan could be reached without increasing the government subsidy gap. After the calculation, the government could reduce the total subsidy about 4020 million yuan per year by reducing the free quote from 95% to 60%. The establishment of appropriate quotas and trading prices of carbon emission rights could maintain the enterprises to continue to invest in wind power during the non-subsidy transition period and prevent the wind power investment from cooling down. 3) The future carbon emission trading market should be designed according to the price and free quota proposed in this research. The scenario analysis in the research is detailed and comprehensive, and the resulting free allowance and carbon trading prices are credible and could provide anchor prices for future carbon trading. The free allowances' proportion in the carbon emission trading policy should not be higher than 80%. Once the subsidies are canceled, the carbon emission trading price should be 151.22 yuan/ton. When the free quota is 60%, the removal of subsidies will lower the carbon emissions trading price to 120.02 yuan/ton. Only by establishing a carbon emission trading market with such free quotas and carbon prices range, could enterprises be encouraged to invest in wind power and realize the wind power development plan of China's "Economic and Social Development during the 14th Five-Year Plan Period".

Nevertheless, this article still has some limitations which can be addressed in future research. Above all, the uncertainty faced by wind power, for instance, the change in the cost of power generation of coal-fired units caused by changes in coal-fired power prices and changes in the price of a carbon-emission trading investment, can be discussed in future research. Next, this article only analyzes the two scenarios of carbon tax, subsidy and carbon emissions trading, which can partially describe the situation that may occur in reality, but there are far more scenarios in reality. The impact of low-carbon policies such as green power certificates on wind power could be simulated. Ultimately, this article does not consider the preferences of different types of investors. Therefore, the environmental preferences of investors should be investigated in the future to refine the impact of low-carbon policies on investment in wind power.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

Conceptualization: XZ and CS. Data curation: CS. Funding acquisition: XZ. Methodology: CS. Software: CS. Supervision: XZ and JW. Writing—original draft preparation: CS and XZ. Writing—reviewing and editing: JW and FY. All authors have read and agreed to the published version of the manuscript.

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