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Biomass Power Generation Investment in China: A Real Options Evaluation

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Abstract: This paper proposes a real options model for evaluating the biomass power generation investment in China. The uncertainties in the market price of electricity, CO_2 price and straw price are considered. Meanwhile the dynamic relationship between installed capacity and fuel cost, as well as the long-term reduction of subsidy are described. Two scenarios, *i.e.*, with the carbon emission trading scheme existent and non-existent, respectively, is built to empirically analyze the investment of a 25-MW straw-based power generation project. The results show that investors should undertake the investment in 2030 under two scenarios. Investment values are 14,869,254.8 and 37,608,727 Chinese Yuan (RMB), respectively. The implementation of the carbon emission trading scheme theoretically helps improve investment value and advance the most likely optimal investment time. However, the current CO_2 price is not sufficient to advance the most likely optimal investment time. The impacts of several factors, including subsidy policy, CO_2 price, straw price, installed capacity, correlation structure and the validity period of investment, on the optimal investment strategy are also examined. It is suggested that governments take some measures, including increasing subsidy, setting the growth pattern of subsidy and establishing and perfecting a nationwide carbon trading market, to improve the investment environment and attract more investments.

Keywords: straw-based power generation; real options; uncertainty; optimal investment strategy

1. Introduction

As energy shortage and greenhouse gas emission problems become increasingly serious, the development of renewable energy becomes an inevitable choice for the future energy mix. As one of the renewable energy resources having the most potential, biomass has drawn wide attention across the world. China has made great efforts to promote the development of biomass energy. In its *Middle and Long Term Plan for Renewable Energy Development*, the Chinese government has proposed the target of increasing the installed capacity of biomass energy to 30 million kW by 2020 [1].

As a large agricultural country, China is abundant in straw resource, and annual output is about 700 million tons [2]. Straw-based power generation is the most effective way to utilize straw. There are many advantages to develop straw-based power generation [3]. First, since straw-based power generation does not require the type of straw, straw can be utilized more effectively. Second, straw-based power generation is carbon neutral and does not contribute to the greenhouse effect. Third, much straw is burned as waste *in situ*, which may result in serious environmental pollution and biomass resource waste. If straw is used to generate electricity, these adverse effects could be improved. Fourth, farmers can obtain more revenue from straw sale and collection.

The development of straw-based power generation in China is relatively late. The first straw-based and grid-connected power generation project was constructed in 2006 [4]. Afterwards, China's straw-based power generation industry endured a steady development. However, the widespread application of straw-based power still faces many difficulties, and the investors still hesitate to invest in straw-based power generation projects. On the one hand, the characteristics of straw being in season, territory, distribution and quality may increase the difficulties and cost in straw collection and transportation, which have adverse effects on the normal operation and investment of a straw-based power generation project. On the other hand, in order to promote straw-based power generation investment, the Chinese government has introduced many policies, such as feed-in tariff, finance-taxation policies and cost-sharing policies. However, the strength of incentive policies is not sufficient to attract investment. The changes of incentive policies in the future are full of uncertainties and investors cannot make sure whether government will maintain the strength of incentive policies. In addition, with the implementation of the nationwide carbon emission trading scheme in 2017, the uncertainty and complexity of the investment environment would be deepened. Given the above, whether and when to invest (concerns of investors), as well as how to design a reasonable and effective incentive policies system (concern of governments) become more difficult.

Recently, numerous studies have been undertaken to evaluate renewable energy investment, such as solar photovoltaic, wind and nuclear power [5–17]. However, there are not many studies focusing on biomass power generation, especially straw-based power generation. Table 1 provides a summary of previous studies. As shown, previous studies mainly analyzed the resource potential, cost structure, competitiveness and the development strategy of biomass power generation, and they mostly used a qualitative analysis method and a cost-profit analysis method. There are not many studies that evaluated the straw-based power generation investment by considering the uncertainties in the investment environment and the managerial flexibility in investment decision making. Wang *et al.* [18] have evaluated China's biomass power generation investment by considering the uncertainties in straw price and CO_2 price. Although great progress has been made by them, further research is necessary. First, further studies should consider more uncertain factors, especially the policy factors (e.g., the long-term change of supporting policies). Second, due to the introduction of multiple uncertain factors, the binomial tree method should be extended to the simulation method, which could handle more uncertain factors. Third, further studies are required not only to offer the optimal investment strategy to investors, but also to provide enough information about the influence of key factors on optimal investment strategy for governments to adjust relevant policies. Further studies, which are able to deal with these issues, have greater practical value.

Therefore, this paper aims to propose a real options model for evaluating the straw-based power generation investment in China. The uncertainties in the market price of electricity, CO_2 price and straw price are considered. Meanwhile, the dynamic relationship between installed capacity and fuel cost, as well as the long-term reduction of subsidy are described. Two scenarios, *i.e.*, the carbon emission trading scheme is non-existent and existent, is constructed to empirically evaluate the investment of a 25-MW straw-based power generation project. The results present not only the optimal investment strategy, *i.e.*, investment value and the most likely optimal investment time, but also the effects of some key factors on the optimal investment strategy. Thus, this study can provide some useful information for investors and the government at the same time. In contrast to the existing literature, this paper successfully addresses the following points: (1) considering more uncertain factors and the long-term reduction of subsidy; (2) explaining the dynamic relationship between installed capacity and fuel cost; (3) applying the simulation method to solve the model; and (4) providing not only the optimal investment strategy, but also the effects of some key factors on the optimal investment strategy.

Table 1. Summary of the studies on biomass power generation in China.

Study	Purposes of Study	Solution Methods	Uncertain Factors
Zhao and Yan [19]	Assessing the strengths, weaknesses, opportunities and threats (SWOT) of the biomass power generation industry of China.	SWOT analysis	—
Wu *et al.* [20]	Analyzing the economic characteristics regarding the associated costs for investment, electricity generation and waste treatment.	Net present value	—
Liu *et al.* [21]	Analyzing temporal and spatial patterns of crop stalk resources, the potential bio-energy of straw resources and the possible pathways of straw-based energy strategies.	Cost-profit analysis	—
Zhao and Feng [22]	Exploring the characteristics, opportunities and risks of the investment in biomass direct combustion power generation.	Cost-profit analysis	—
Zhao and Zuo [23]	Assessing the competitiveness of China's biomass power industry.	Five forces model	—
Zhang *et al.* [3]	Estimating the straw-fired power generation costs.	Cost-profit analysis	—
Sun *et al.* [24]	Identifying the appropriate developing areas of biomass energy at the regional level.	Spatial analysis technology, economic model and scenario analysis	—
Wang *et al.* [18]	Evaluating China's biomass power production investment based on a policy benefit model.	Real options method (binomial tree)	Straw price and CO_2 price

2. Model Formulation

2.1. System Boundary

In reference to the relevant literature (e.g., [25]), we divide the life cycle of straw-based power generation into four stages, *i.e.*, straw acquisition, transportation, power generation and grid connection. At the stage of straw acquisition, straw is bought from farmers and is pre-processed to facilitate transportation. At the stage of transportation, straw is transported to the storage area in the power plant. At the stage of power generation, straw is transformed to electricity by the power generation system. Finally, at the stage of grid connection, the electricity is input to the power grid. Note that the life cycle of straw-based power generation is accompanied by a value flow process (Figure 1). In this study, a 25-MW straw-based power plant will be empirically evaluated. In recent years, most of the straw-based power generation projects built in China have ranged from 20 MW to 50 MW. Thus, 25 MW is the scale representative for the straw-based power plant. At the same time, several earlier studies, e.g., Zhang *et al.* [3] and Wang *et al.* [18], also used 25 MW as the scale representative to carry out analyses. Thus, we choose 25 MW as the analysis object. In addition, it should be pointed out that the fuel consumed by this straw-based power plant is mainly crop straw, including corn stalk, cotton stalk and beanstalk, which are collected from the surrounding area.

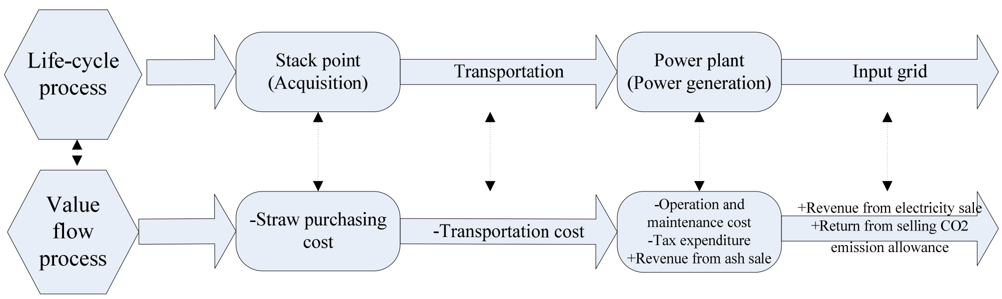

Figure 1. Life cycle and value flow process.

2.2. The Income Composition of Straw-Based Power Generation

2.2.1. Revenue from Electricity Sale

Electricity sale is the main source of revenue for a straw-based power generation project. The electricity generated by the straw-based power generation system is input to the power grid and sold with the feed-in tariff. The total revenue of electricity sale based on the annual running time and power generation efficiency can be calculated as follows [18,26,27]:

$$ESR_t = q_t^S \cdot IC \cdot Eue_t \cdot Fit_t \cdot (1 - r^{HSCR}) \quad (1)$$

where q_t^S denotes annual running time, IC is the installed capacity (MW), Eue_t represents power generation efficiency, r^{HSCR}stands for the house-service consumption rate (%) and Fit_t is the feed-in tariff (Chinese Yuan RMB/kWh).

The feed-in tariff is designed to ensure that the investors of renewable energy power generation project can obtain enough revenue. In China, the feed-in tariff of straw-based power generation is constituted by the market price of electricity and subsidy [14,28]. Thus, we can get:

$$Fit_t = P_t^d + EPS_t \quad (2)$$

where P_t^d denotes the market price of electricity (RMB/kWh) and EPS_t stands for unit subsidy (RMB/kWh).

Once the project is built in year t, the subsidy is determined and would be kept constant for 15 years [28]. For the entire industry, the Chinese government has announced that the subsidy should decrease by 2% per year. Thus, we assume that the subsidy follows an index movement with a constant change rate as follows:

$$EPS_t = EPS_{t-1} \cdot e^{\alpha^{EPS}} \quad (3)$$

where α^{EPS} represents the constant change rate of subsidy.

Recently, the Chinese government has attached great importance to the reform of the power sector. Nowadays, China's electricity pricing is transited from a government-led mechanism to a market-based one. As the reform of the power sector deepens, the electricity price would be completely determined by the market. Several previous studies (e.g., [5,29,30]) have used geometric Brownian motion to describe the changes of the market price of electricity. This study also assumes that the market price of electricity follows geometric Brownian motion:

$$dP_t^d = \alpha^d P_t^d dt + \sigma^d P_t^d dz_t^d \quad (4)$$

where P_t^ddenotes the market price of electricity, α^dstands for its drift rate and σ^d represents the instantaneous volatility rate. In addition, dz_t^d is the increment to a standard Wiener process,$dz_t^d = \varepsilon_t^d \sqrt{dt}$, and ε_t^d is a normally-distributed random variable with zero mean and unit standard deviation. It is shown that the expected value of electricity price is $E[P_t^d] = P_0^d \cdot e^{\alpha^d \cdot t}$.

2.2.2. Returns from Selling CO_2 Emission Allowance

Currently, coal accounts for 66% of China's energy mix in 2014. Oil and natural gas respectively occupy 17.5% and 5.6%. Then, renewable energy just accounts for 11.9%. In addition, electricity is an indispensable resource for the development of the social economy. China's electricity consumption accounts for a larger and larger proportion in energy end-use year by year. Due to the limitation of resource endowments, China's electricity power generation is mainly based on thermal power. In 2014, thermal power generation accounted for about 67.3% [31]. Since fossil fuel combustion is the main source of carbon dioxide, China's electricity production causes large amounts of carbon emissions. Therefore, due to the unique energy and electricity mix, China faces great pressure to reduce greenhouse gas emissions now.

In order to reduce carbon emission, recently, in the *U.S.-China Joint Statement on Climate Change*, China proposed the target of seeking a carbon emissions peak and increasing the share of non-fossil energy to 20% of the primary energy consumption by 2030 [32]. Furthermore, the *Climate Conference in Paris* put forward another stricter temperature reduction target of 1.5 °C [33]. Additionally, the huge pressure of emission reduction accelerates the formation of the carbon emission trading market in China. Seven provinces, e.g., Shenzhen, Guangzhou and Shanghai, have started their pilot carbon emission trading scheme. It is reported that a nationwide carbon trading market would be piloted in 2017, which means the carbon emission trading will get into the golden period of development in China [32]. The nationwide carbon emission trading market will bring great opportunities for the development of renewable energy.

Since straw-based power generation is carbon-central [18,19,34–37], the investors of the straw-based power generation project can get revenue from selling CO_2 emission allowance. This study assumes the carbon emission trading scheme is effective. The carbon emission reduction resulting from straw-based power generation can be calculated with the emission factors of local electric power production. Thus, the return from selling carbon emission allowance can be represented by:

$$CSR_t = q_t^S \cdot IC \cdot Eue_t \cdot CEF_t \cdot P_t^C \quad (5)$$

where CEF_t denotes the emission factor (kg/kWh) and P_t^C represents the CO_2 price (RMB/kg).

Since CO_2 price is completely determined by the market, stochastic processes can better reflect the motion process of the CO_2 price. Previous studies have assumed the CO_2 price follows geometric Brownian motion [29,30,38]. This study supports their assumptions and applies the geometric Brownian motion to describe the change of the CO_2 price as follows:

$$dP_t^C = \alpha^C p_t^C dt + \sigma^C p_t^C dz_t^C \quad (6)$$

where P_t^C denotes the CO_2 price, α^C stands for the drift rate of the CO_2 price and σ^C represents the instantaneous volatility rate of the CO_2 price. In addition, dz_t^C is the increment to a standard Wiener process, $dz_t^C = \varepsilon_t^C \sqrt{dt}$, and ε_t^C is a normally-distributed random variable with zero mean and unit standard deviation. It is shown that the expected value of the CO_2 price is $E[P_t^C] = P_0^C \cdot e^{\alpha^C \cdot t}$. This study considers the correlation between CO_2 price and the market price of electricity. ρ^{Cd} denotes the correlation coefficient between them with $dz_t^C dz_t^d = \rho^{Cd} dt$, which can reflect to what extent both stochastic variables influence each other beyond their development trends [30,39].

2.2.3. Revenue of Ash Sale

The ash produced by straw-based power generation, which contains potassium, calcium, phosphorus and other nutrients, is the high-quality raw materials of organic fertilizer. Thus, the ash has important commercial value. The revenues of selling ash could be represented by:

$$ASR_t = q_t^S \cdot IC \cdot Eue_t \cdot p_t^{AC} \quad (7)$$

where p_t^{AC} stands for the price of ash (RMB/kWh).

2.3. The Cost Structure of Straw-Based Power Generation

2.3.1. Investment Cost

Investment cost is an important factor that affects the rapid development of straw-based power generation. Nowadays, realizing the maturity of technology is a long and gradual process. In this study, given that investment cost may decrease with technological advance in the long run, we assume investment cost follows a constantly reduction trend. Thus, we can get:

$$TI_t = I_t \cdot IC \tag{8}$$

$$I_t = I_{t-1} \cdot e^{\alpha^{IDR}} \tag{9}$$

where TI_t represents the total investment cost (RMB), I_t denotes unit investment cost (RMB/kW) and α^{IDR} stands for the reduction rate.

2.3.2. Fuel Cost

Fuel cost refers to the costs in the process that straw is transported from the producing area to the storage area in the power plant. Thus, fuel cost mainly comprises straw-purchased cost, transportation cost and storage cost. Thus, we can get:

$$FTC_t^{SP} = C_t^{SPC} + C_t^{STC} + C_t^{SSC} \tag{10}$$

where C_t^{SPC} is the straw-purchased cost (RMB), C_t^{STC} denotes transportation cost (RMB) and C_t^{SSC} represents storage cost (RMB).

The straw-purchased cost of straw is mainly dependent on straw price and straw consumption. Mathematically, we can get:

$$C_t^{SPC} = q_t^S \cdot IC \cdot Eue_t \cdot P_t^{SP} \tag{11}$$

where P_t^{SP} denotes straw price (RMB/kWh).

Straw price is determined by the market. Wang *et al.* [18] thought that the straw price is full of uncertainty in the future because it may fluctuate with the prospect of the biomass power generation industry. They used geometric Brownian motion to describe straw price. In this study, we also use geometric Brownian motion to describe straw price:

$$dP_t^{SP} = \alpha^{SP} P_t^{SP} dt + \sigma^{SP} P_t^{SP} dz_t^{SP} \tag{12}$$

where P_t^{SP} denotes the straw price, α^{SP} stands for the drift rate of straw price and σ^{SP} represents the instantaneous volatility rate of straw price. In addition, dz_t^{SP} is the increment to a standard Wiener process, $dz_t^{SP} = \varepsilon_t^{SP}\sqrt{dt}$, and ε_t^{SP} is a normally-distributed random variable with zero mean and unit standard deviation. It is shown that the expected value of straw price is $E[P_t^{SP}] = P_0^{SP} \cdot e^{\alpha^{SP} \cdot t}$.

In generally, transportation cost contains transportation fuel cost, as well as loading and unloading cost. Transportation cost is directly related to the distance of collection. More straw consumption must lead to a bigger collection radius and a higher transportation cost. In order to reflect the process of determining transportation cost, we propose three assumptions: (1) The distribution of straw has the characteristics of universality and uniformity. Universality means that crop yield is able to meet the demand. Uniformity implies that the yield difference caused by crop varieties and differences in plant conditions do not exist and crops are distributed evenly. (2) There are enough transport vehicles and labor to complete the task of straw collection and transportation. (3) Some risk factors, e.g., weather factors, are not considered. On the basis of the above assumptions, the details of determining transportation cost could be described as follows.

First, it is necessary to determine the unit collection volume of straw (per ha). The unit straw yield in a certain area is represented bySuq_0. The collection coefficient that reflects the possibility and reliability of collecting straw is k_1. The planting coefficient isk_2, and the coefficient that reflects that straw is used as fuel is k_3. The unit collection volume of straw is calculated by:

$$Suq = Suq_0 \cdot k_1 \cdot k_2 \cdot k_3 \tag{13}$$

Second, it is essential to determine the collection radius. Based on the distance, we split the collection area into M areas, and the distance between two adjacent areas is 1 km (Figure 2). It is assumed that R_i represents the distance between area i and the power plant (considering that the roads in the countryside are usually winding, we use external diameter R_i to represent the distance between straw collection area i and power plant). For example, R_1 means the distance is 1 km, and R_{20} means the distance is 20 km. Thus, the acreage of area i is:

$$S_i = \pi \cdot (R_i^2 - R_{i-1}^2) \cdot 100 \tag{14}$$

On this basis, the collection radius is determined as follows:

$$R_{ML} = \inf \left\{ R_i \middle| q_t^S \cdot IC \cdot Eue_t \cdot Rts \geqslant \sum_{1}^{R_i} S_i \cdot Suq \right\} \tag{15}$$

where Rts is the unit straw consumption (t/kWh).

Third, the total transportation cost can be obtained:

$$C_t^{STC} = \sum_{i=1}^{R_{ML}-1} [S_i \cdot Suq \cdot (n \cdot C^{LUC} + UC^{SPC} \cdot R_i)] + [(q_t^S \cdot IC \cdot Eue_t \cdot Rts) - \sum_{1}^{R_{ML}-1} S_i \cdot Suq] \cdot (n \cdot C^{LUC} + UC^{SPC} \cdot R_{ML}) \tag{16}$$

where C^{LUC} represents the unit loading and unloading cost (RMB/t), n stands for the frequency of loading and unloading and UC^{SPC} denotes unit transportation fuel cost (RMB/t).

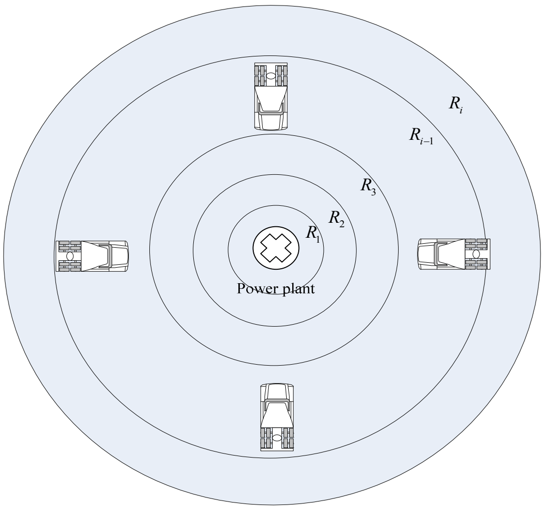

Figure 2. The collection radiuses of straw.

After straw is transported to the power plant, it is stored in stack up yard. This process would create the storage cost, including storage venue rental fees, office equipment, personnel salary and insurance premiums. Mathematically, we can get:

$$C_t^{SSC} = q_t^S \cdot IC \cdot Eue_t \cdot UC_t^{SSC} \tag{17}$$

where UC_t^{SSC} is unit storage cost (RMB/kWh).

2.3.3. Operation and Maintenance Cost

Operation and maintenance cost, which is used to ensure the normal operation of the power generation plant, mainly is comprised of repair cost, management fee, finance charge and material cost. Thus, we can get:

$$SOMC_t^S = q_t^S \cdot IC \cdot Eue_t \cdot SUOMC_t \tag{18}$$

$$SUOMC_t = SRC_t + SMC_t + SFC_t + SMAC_t \tag{19}$$

where SRC_t represents unit repair cost (RMB/kWh), SMC_t stands for unit management cost (RMB/kWh), SFC_t denotes unit finance cost (RMB/kWh) and $SMAC_t$ represents unit material cost (RMB/kWh).

2.3.4. Tax Expenditure

The tax expenditure mainly comprises value-added tax and corporate income tax. At present, the straw-based power generation project can enjoy two years of corporate income tax relief and three years half pay. Mathematically, the value-added tax and corporate income tax can be respectively represented by:

$$Tax_t = Vatax_t + CItax \tag{20}$$

$$Vatax_t = (ESR_t + CSR_t + ASR_t) \cdot r^{Va} \tag{21}$$

$$CITax_t = [(ESR_t + CSR_t + ASR_t) \cdot (1 - r^{Va}) - FTC_t^{SP} - SOMC_t^S] \cdot r^{CI} \tag{22}$$

where r^{Va} and r^{CI} respectively denote the rate of value-added tax and corporate income tax (%).

2.4. Net Present Value of the Straw-Based Power Generation Project

It is necessary to express the assumptions before describing the project value function. First, we assume the project can be constructed instantaneously. Second, after the completion of the project construction, the operating state of the power generation project is just the full load operation. Third, the investors may undertake the investment decision only once within the validity period.

The returns from selling electricity (ESR_t), gains through selling CO_2 emission allowances (CSR_t), gains through selling ash content (ASR_t), operation and maintenance cost ($SOMC_t^S$), fuel cost (FTC_t^{SP}) and tax expenditure (Tax_t) constitute the yearly cash flow. Thus, the yearly cash flow could be represented by:

$$YCF_t = ESR_t + CSR_t + ASR_t - FTC_t^{SP} - SOMC_t^S - Tax_t \tag{23}$$

Consider that a straw-based power generation project with lifetime L^{SL} could be built in year t ($1 \leqslant t \leqslant t_v$). Due to the impacts of several uncertain factors, the project value of a straw-based power generation project should be expressed with its expectation $E[\cdot]$. Thus, the project value of a straw-based power generation project is:

$$V_t = E[\sum_{i=t}^{t+L^{SL}} e^{-r\cdot(i-t)} \cdot YCF_t - TI_t] \tag{24}$$

where r is the discount rate.

2.5. Optimal Investment Rules

In the deterministic setting, *i.e.*, without the consideration of uncertainty and managerial flexibility, investors have limited investment decision options, *i.e.*, undertaking investment or abandoning investment. Nevertheless, in the stochastic setting, uncertainty and managerial flexibility endow investors with more decision options. They can delay investment and wait for the arrival of a better investment environment. That is, investors can choose the optimal time to undertake investment and get the highest value. Mathematically, we can get:

$$F = \max_{1 \leqslant t \leqslant t_v} [\max(V_t, 0)] \quad (25)$$

2.6. Model Solution

Given the introduction of three stochastic variables and the complexity of the project value function, we use the least squares Monte Carlo (LSM) method to solve the model [40]. The method and process resemble some previous studies [41–46]. The details of the solution process are as follows:

Step 1: Take W and N as the number of simulation paths and decision points per path, respectively, where $N = \frac{t_v}{\Delta t}$, and Δt is the step size. The stochastic variables are simulated by following the discrete versions of their stochastic motions. For each decision point per path, we should calculate the expected project value.

Step 2: For any path j, the model solution process starts from the last decision point and goes back to the beginning decision point. At the last decision point ($t = t_v$), conditional on not having invested before, we can get:

$$F_{t,j} = \max \{V_{t,j}, 0\} \quad (26)$$

$$\Pi_{t,j} = \begin{cases} 1, & V_{t,j} > 0 \\ 0, & Otherwise \end{cases} \quad (27)$$

where $\Pi_{t,j} = 1$ means immediate investment and $\Pi_{t,j} = 0$ means delaying investment.

In each decision point $1 \leqslant t < t_v$, the investors may evaluate whether it is better to invest immediately rather than delay the investment by comparing the expected project value from immediate investment and the expected investment opportunity value by delaying investment.

$$F_{t,j} = \max \{V_{t,j}, e^{-r} E_t[F_{t+1,j}]\} \quad (28)$$

$$\Pi_{t,j} = \begin{cases} 1, & V_{t,j} > e^{-r} E_t[F_{t+1,j}] \\ 0, & Otherwise \end{cases} \quad (29)$$

It should be pointed out that the expected investment opportunity value, *i.e.*, the continuation value, is estimated by least squares regression. The dependent variable is the investment value from year t + 1 to the end of the validity period under the optimal investment behavior. The independent variables are the uncertain factors in year t. The regression function is $e^{-r} E_t[F_{t+1,j}] = a_0 + a_1 P_t^C + a_2 (P_t^C)^2 + a_3 P_t^d + a_4 (P_t^d)^2 + a_5 P_t^{SP} + a_6 (P_t^{SP})^2$, which is the same as some previous studies [42,45]. Longstaff and Schwartz [40] have proved that the results are remarkably robust to the choice of basis functions, and the value of regression is unaffected by the correlation among the independent variables. However, we still test various polynomials to ensure the rationality of the results, which shows that the results may not be affected significantly in this study [43].

Step 3.The recursion is rolled back in time and repeated unit the optimal decision in each paths are determined. t_j is the optimal investment time in path j. The final most likely optimal investment time is the one with the highest frequency. Additionally, the final investment value is the average value over all of the paths.

$$t_j = \inf \{t \,|\Pi_{t,j} = 1\} \quad 1 \leqslant t \leqslant t_v \quad (30)$$

$$F = \frac{1}{W} \sum_{1}^{w} e^{-r \cdot t_j} F_{t,j} \quad j = 1, 2, 3......W \quad (31)$$

In addition, it should be noted that this studies applies the antithetic variable variance reduction technique to improve the accuracy of simulation and reduce the complexity [47].

3. Data

In this study, a 25-MW straw-based power plant will be evaluated with the model explained in Section 2. Table 2 shows the parameters used in this study. The base year is 2015 and the validity period is 15 years (2016–2030). The step size is one year. The desulfurization electricity price is used to represent the market price of electricity. Now the average desulfurization electricity price is 0.43 RMB/kWh. The data are collected from the *Notice of National Development and Reform Commission (NDRC) on Reducing the Price of Coal-fired Electricity and Electricity Prices for Industrial and Commercial Use in 2015* [48]. Under the free market mechanism, the market price of electricity varies with the power generation cost. The drift rate and volatility rate are taken from Zhou *et al.* [40]. In addition, we use the CO_2 prices from October 2014–June 2016 in the Shenzhen carbon trading market. The drift rate and volatility rate of the CO_2 price are estimated with the maximum-likelihood method [49]. The straw price is taken from the history data in the collection area. Additionally, its drift rate and volatility rate are estimated with the maximum-likelihood method [49]. The value-added tax rate and corporate-income tax rate are respectively collected from *The Provisional Regulations on Value Added Tax of China* [50] and *Corporate Income Tax Law of the People's Republic of China* [51].

Table 2. Parameters.

Variables	Descriptions	Values
q^S	Annual running time	5500
IC	Installed capacity	25MW
Eue_t	Power generation efficiency	0.85
r^{HSCR}	House-service consumption rate	15%
P_t^d	Market price of electricity	0.43 RMB/kWh
EPS_t	Unit subsidy level	0.32 RMB/kWh
α^d	Drift rate of electricity price	0.02
σ^d	Volatility rate of electricity price	0.02
α^{EPS}	The change rate of subsidy	−0.02
L^{SL}	Lifetime of straw-based power generation	20 year
r	Discount rate	0.06
CEF_t	Emission factor	0.997kg/kWh
P_t^C	CO_2 price	0.04 RMB/kg
α^C	Drift rate of CO_2 price	0.02
σ^C	Volatility rate of CO_2 price	0.03
ρ^{Cd}	The correlation coefficient	0.1
P_t^{AC}	The price of ash content	0.00628RMB/kWh
I_t	Unit investment cost	10,470 RMB/kW
α^{IDR}	Reduction rate of investment cost	−0.02
P_t^{SP}	Straw price	0.25RMB/kWh
α^{SP}	Drift rate of straw price	0.017
σ^{SP}	Volatility rate of straw price	0.03
Suq_0	The average yield of straw	15 t
k_1	Collection coefficient	0.8
k_2	Planting coefficient	0.7
Rts	Unit straw consumption	0.00105t/kWh
k_3	The coefficient of straw used as fuel	0.6
C^{LUC}	Unit loading and unloading cost	10 RMB/t
n	The frequency of loading and unloading	2
UC^{SPC}	Unit transportation fuel cost	2 RMB/t. km
UC_t^{SSC}	Unit storage cost	0.042RMB/kWh
SRC_t	Unit repair cost	0.04994 RMB/kWh
SMC_t	Unit management cost	0.01847 RMB/kWh
SFC_t	Unit finance cost	0.03748 RMB/kWh
$SMAC_t$	Unit material cost	0.02736 RMB/kWh

Table 2. *Cont.*

Variables	Descriptions	Values
r^{Va}	The rate of value-added tax	0.17
r^{CI}	The rate of corporate income tax	0.25
t_v	The validity period of investment	15 year (2016–2030)

4. Results and Discussions

4.1. Base Case Analysis

This study uses MATLAB software to solve the model [41,42]. The investment value and the most likely optimal investment time are employed to reflect the optimal investment strategy. Additionally, we differentiate two cases, *i.e.*, with the carbon emission trading scheme non-existent (Case 1) and existent (Case 2), respectively, to carry out analyses and examine the effects of the carbon emission trading scheme. At first, it is essential to check the stability of the results and then to determine an appropriate number of simulations. The robustness of the result is determined by calculating the investment value for a great number of simulated paths [44]. Figure 3a,b illustrate the statistical convergence of the investment value in both cases. It can be observed that the solutions are robust for a number of simulations greater than 7000 and 4000 in both cases. Thus, we perform 10,000 simulations.

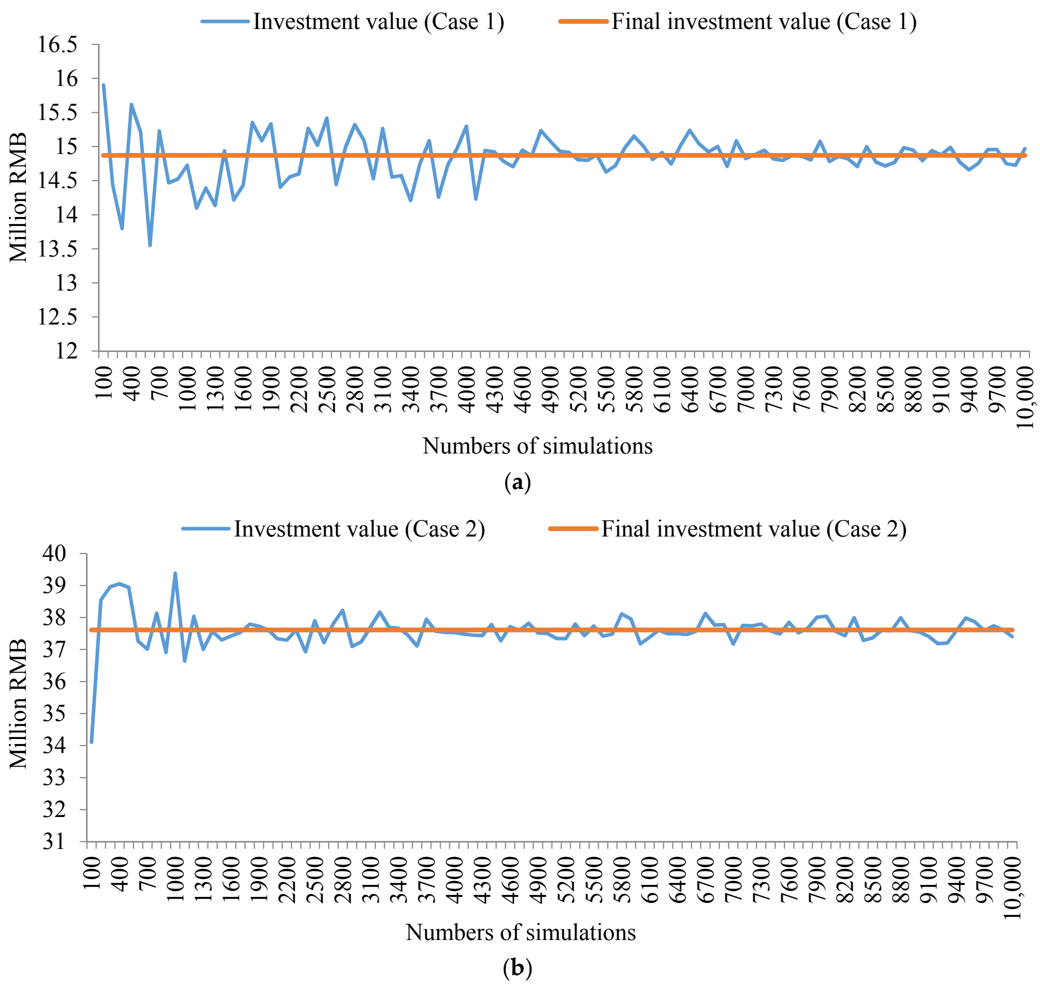

Figure 3. Investment value in Chinese Yuan (RMB) according to the simulation paths in Case 1 (**a**) and in Case 2 (**b**).

Table 3 shows the optimal investment strategy. As shown, it is not wise for investors to undertake an investment decision in 2016 under two cases. Investors should delay the investment decision. Figure 4 shows the probability distribution of the most likely optimal investment time. It can be seen that the investors should undertake the investment in 2030, *i.e.*, the last year of the validity period. Comparing two cases, the probability that the investment should be undertaken in 2030 in Case 2 is lower than that in Case 1. In other words, the implementation of the carbon emission trading scheme theoretically can advance the most likely optimal investment time. In Case 1, investors can obtain investment a value of 14,869,254.8 RMB. It is estimated that the payback period is 19 years. When the carbon emission trading scheme is considered, *i.e.*, in Case 2, the investment value reaches 37,608,727.6 RMB. It is estimated that the payback period is 17 years. Therefore, the implementation of the carbon emission trading scheme could improve the investment value. In short, although the current CO_2 price is not able to advance the most likely optimal investment time, the implementation of the carbon emission trading scheme is conductive to promote straw-based power generation investment.

Table 3. Results.

Cases	Case 1	Case 2
Investment value (RMB)	14,869,254.8	37,608,727.6
Most likely optimal investment time (Year)	2030	2030

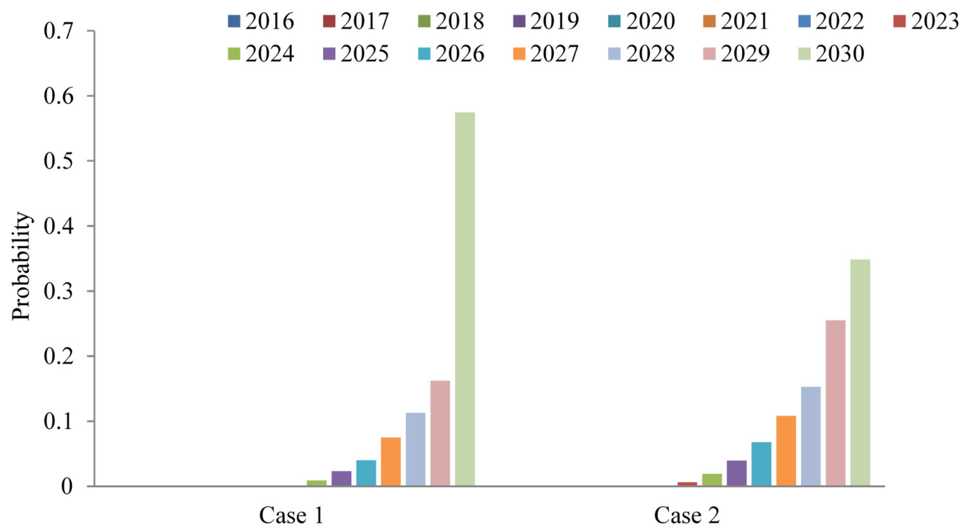

Figure 4. The probability distribution of investment time.

4.2. Discussions

The optimal investment strategy could be affected by many factors. It is meaningful to examine the extent of the optimal investment strategy's exposure to some key factors. In this section, we analyze the dynamics of the optimal investment strategy under different subsidy policies, CO_2 prices, straw prices, installed capacity, correlation structures and the validity period of investment.

4.2.1. Implications of Subsidy Policy

Under current conditions, it is essential to provide subsidy for investors to attract investment. The subsidy policy can affect the optimal investment strategy by two means, *i.e.*, subsidy level and change pattern. Figure 5a,b display the changes of the optimal investment strategy under different subsidy levels. The positive relationship between subsidy level and investment value can be clearly identified. At the same level of subsidy, the investment value in Case 2 is higher than the one in Case 1, which indicates the extra value brought by the carbon emission trading scheme. As a whole, the most likely optimal investment time is advanced by the increase of the subsidy level. The most likely optimal investment time could be advanced to the year 2016 when the unit subsidy is raised to 0.5 RMB/kWh under two cases. Furthermore, at the same level of subsidy, the most likely optimal investment time in Case 2 is equal to or earlier than the one in Case 1, which indicates the most likely optimal investment time is more easily advanced when the carbon emission trading scheme is implemented.

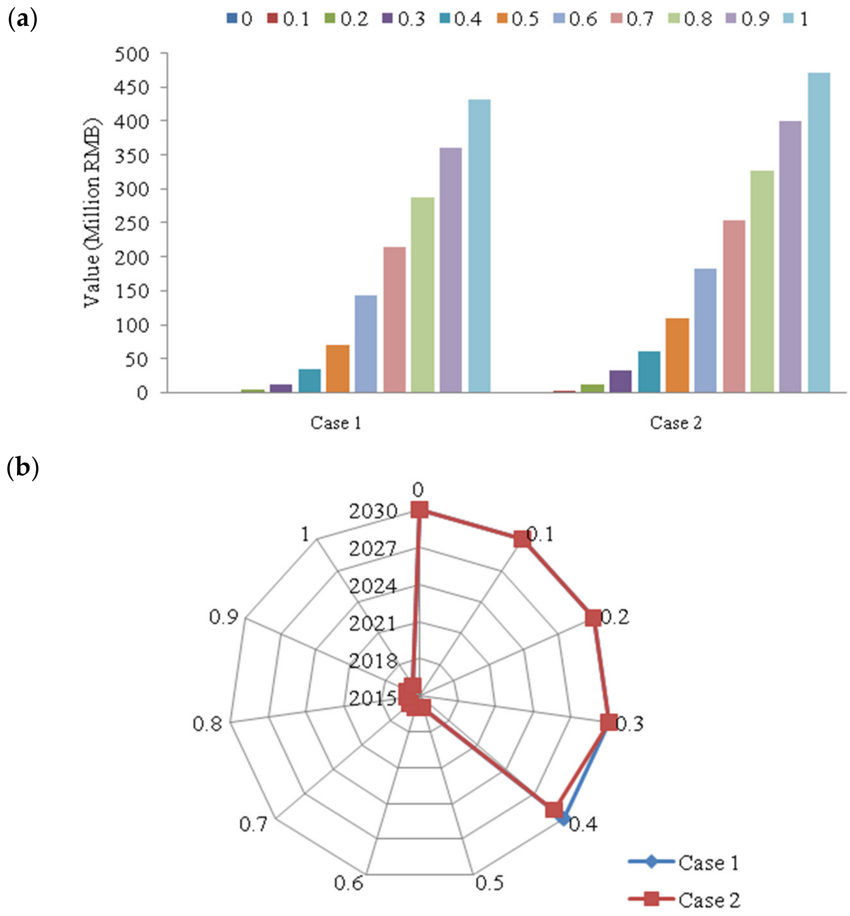

Figure 5. The impact of subsidy levels on investment value **(a)** and investment time **(b)**.

The National Development and Reform Commission (NDRC) has proposed that the subsidy should be reduced by 2% per year [52]. However, in the *Notice of Improving the Price Policy of Biomass Power Generation*, the NDRC further increased the feed-in tariff to 0.75 RMB/kWh, *i.e.*, the subsidy is raised to 0.32 RMB/kWh [53]. At the same time, many professionals also proposed that the subsidy should be further raised due to the increase of fuel cost. Therefore, the change pattern of subsidy has some effect on the investment of the straw-based power generation project.

In order to reveal the impact of different change patterns of subsidy, we set three values of α^{EPS} = {−0.02, 0, 0.02} to examine the corresponding changes of the optimal investment strategy. α^{EPS} = −0.02 is the base case. α^{EPS} =0 represents a constant-pattern, and α^{EPS} =0.02 indicates a growth pattern. Figure 6a,b display the results. It can be seen that the growth pattern of subsidy may lead to a higher investment value and the earliest investment time. These indicate that the government should continue raising the subsidy. In addition, the most likely optimal investment time in the constant pattern and the growth pattern is the same because the impact of the change pattern of the subsidy on the most likely optimal investment time is not even [14,18,39,41].

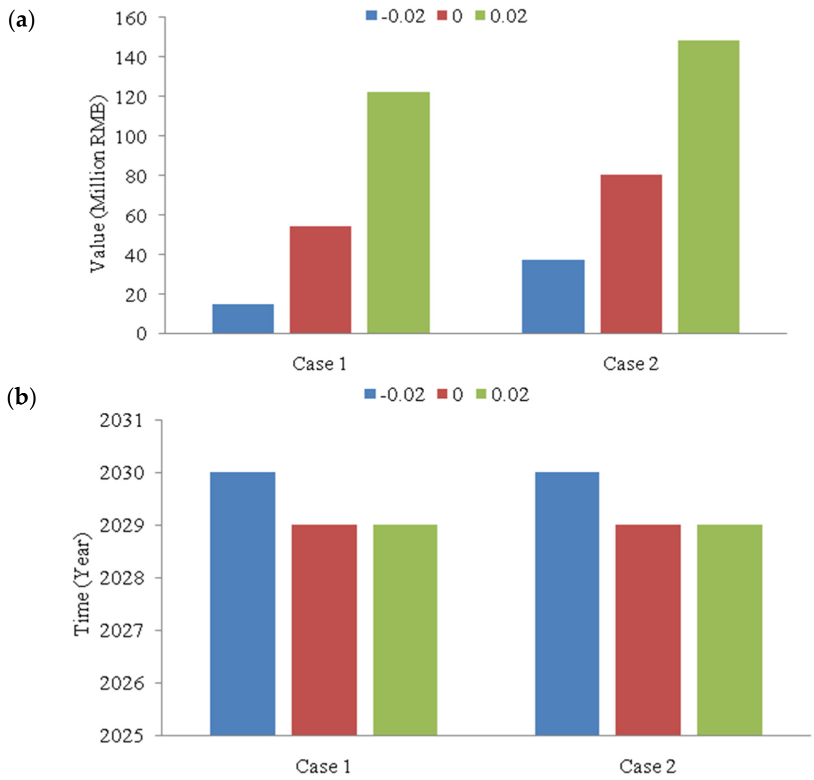

Figure 6. The impact of the subsidy's change pattern on investment value (**a**) and investment time (**b**).

4.2.2. Implications of the Carbon Emission Trading Scheme

The implementation of the carbon emission trading scheme has unavoidable effects on the straw-based power generation investment. In this subsection, we analyze the changes of the optimal investment strategy caused by the CO_2 price and its volatility. Figure 7 displays how the changes of the CO_2 price influence the optimal investment strategy. It can be observed that the increase of the CO_2 price corresponds to a growth of investment value. At the same time, the most likely optimal investment time is shifted to an earlier year. If CO_2 price is increased to 0.28 RMB/kWh, investors can undertake the investment in 2016. Thus, it can be concluded that the increase of the CO_2 price is completely conducive to attract straw-based power generation investment.

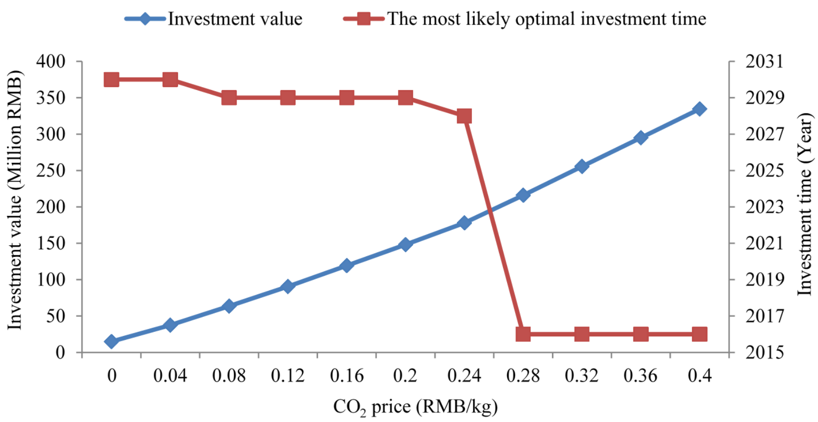

Figure 7. The impact of CO_2 price.

Figure 8 shows the dynamics of the optimal investment strategy under different CO_2 price volatilities. As shown, the increase of the CO_2 price volatility raises the investment value. Although the CO_2 price volatility can delay the most likely optimal investment time by following the real options theory, the most likely optimal investment time in this study is kept to the year 2030, *i.e.*, the last year within the validity period of investment, which indicates that we cannot advance the most likely optimal investment time just by reducing the volatility of CO_2 price. The volatility of the CO_2 price is caused by the carbon market fluctuation. Thus, maintaining the stability of the CO_2 price is an important measure to improve the investment environment and attract more recent investment.

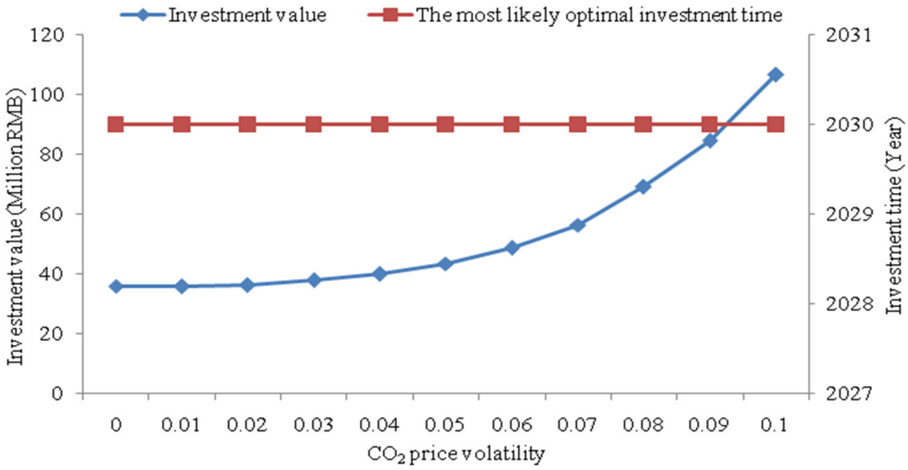

Figure 8. The impact of the CO_2 price volatility.

4.2.3. Influence of Straw Price

Straw price is an important factor influencing straw-based power generation investment. This subsection examines the impact of straw price and its volatility on the optimal investment strategy. Figure 9a,b show the impact of the straw price. It can be observed that the increase of the straw price may reduce investment value. Under the same straw price, the investment value in Case 1 is lower than that in Case 2, which indicates the extra revenue brought by the carbon emission trading scheme. Additionally, the most likely optimal investment time is delayed by the increase of the straw price. Under the same straw price, the most likely optimal investment time in Case 2 is equal to or earlier than the one in Case 1, which indicates that the most likely optimal investment time is more difficult to delay when the carbon emission trading scheme is implemented. The implementation of the carbon emission trading scheme mitigates the negative impact of straw price.

(**a**)

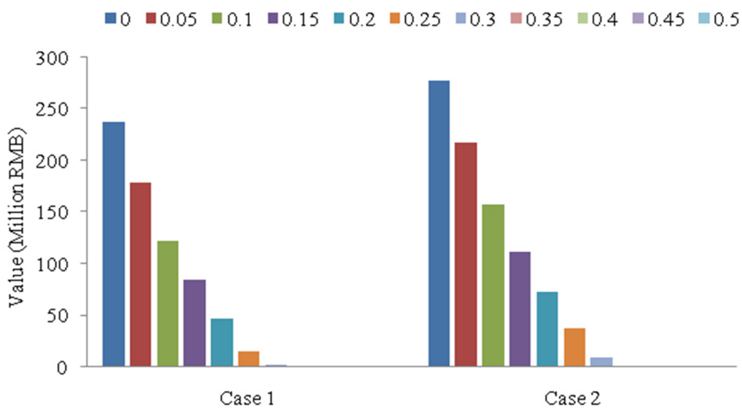

Figure 9. *Cont.*

(**b**)

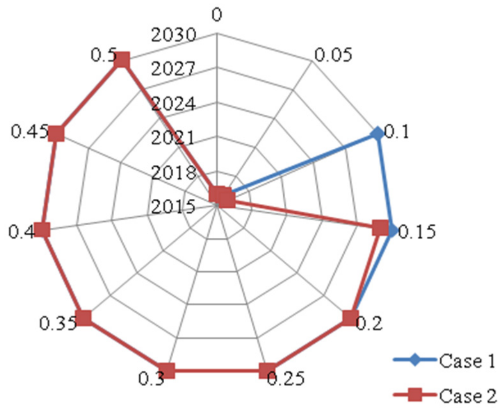

Figure 9. The impact of the straw price on investment value (**a**) and investment time (**b**).

Figure 10a,b display how straw price volatility affects the optimal investment strategy. Overall, the straw price volatility can lead to the reduction of the investment value. Under the same straw price volatility, the investment value in Case 2 is higher than that in Case 1. The most likely optimal investment time is kept in the year 2030 under two cases no matter how the straw price volatility changes. These indicate the small impact of straw price volatility on the most likely optimal investment time.

(**a**)

(**b**)

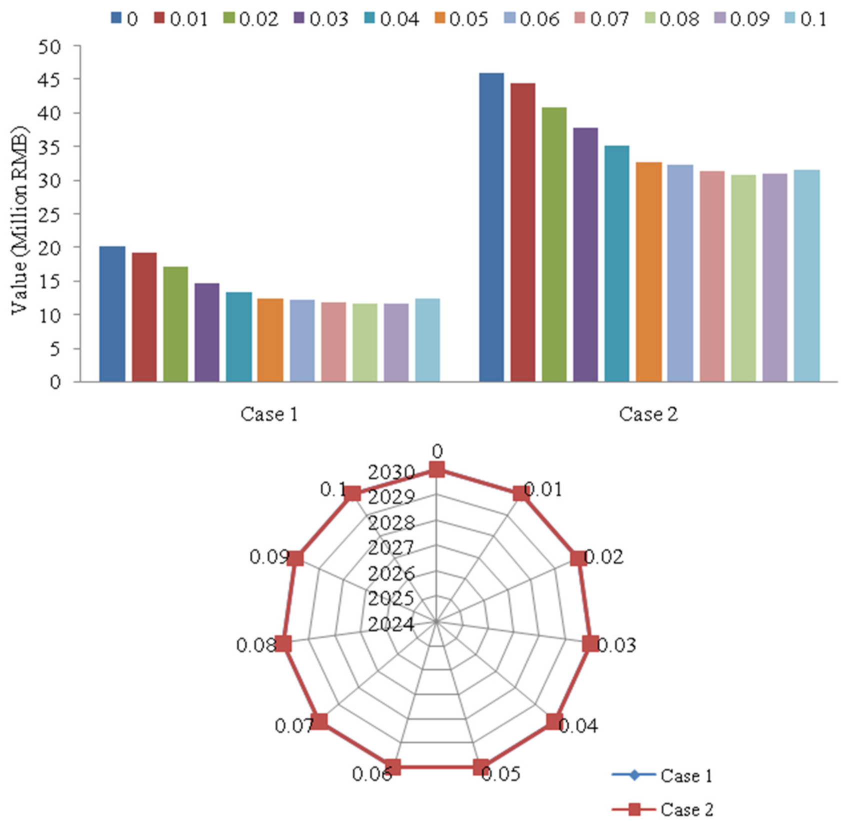

Figure 10. The impact of straw price volatility on investment value (**a**) and investment time (**b**).

4.2.4. Influence of Installed Capacity

Figure 11a,b show the changes of the optimal investment strategy under different installed capacity. Larger installed capacity is accompanied by more straw consumption, which may result in higher fuel cost. Thus, the changes of installed capacity may affect the optimal investment strategy. Recently, most of the straw-based power generation projects built in China range from 20MW–50MW. As shown, the investment value shows a growth trend with the increase of installed capacity. Under the same installed capacity, the investment value in Case 2 is higher than that in Case 1, which indicates the extra revenue brought by the carbon emission trading scheme. Additionally, the most likely optimal investment time in Case 1 remains at the year 2030. In Case 2, the most likely optimal investment time is shifted to the year 2029 when installed capacity is raised to at least 35 MW.

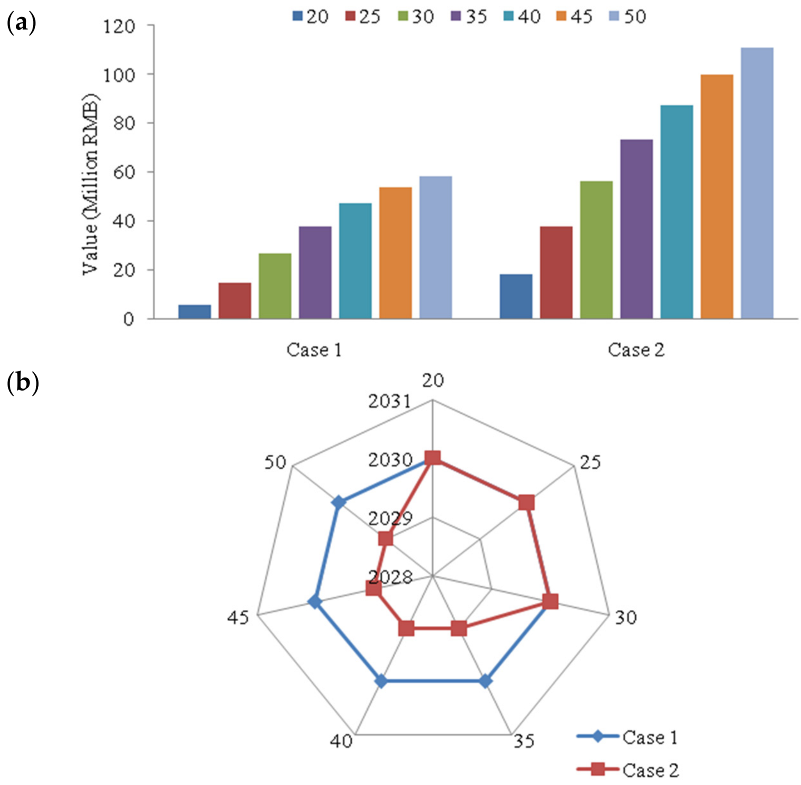

Figure 11. The impact of installed capacity on investment value (**a**) and investment time (**b**).

4.2.5. Impact of Correlation Structure

There may some interactive relationships among stochastic variables in the long run. This study considers the correlation between CO_2 price and the market price of electricity. This subsection examines the changes of the optimal investment strategy under different correlation coefficients between the CO_2 price and the market price of electricity. Figure 12 shows the results. This subsection only considers Case 2, because the carbon emission trading scheme is non-existent in Case 1. As shown, the investment value shows a growth trend. However, the most likely optimal investment time remains at the year 2030, *i.e.*, the last year of the validity period of investment.

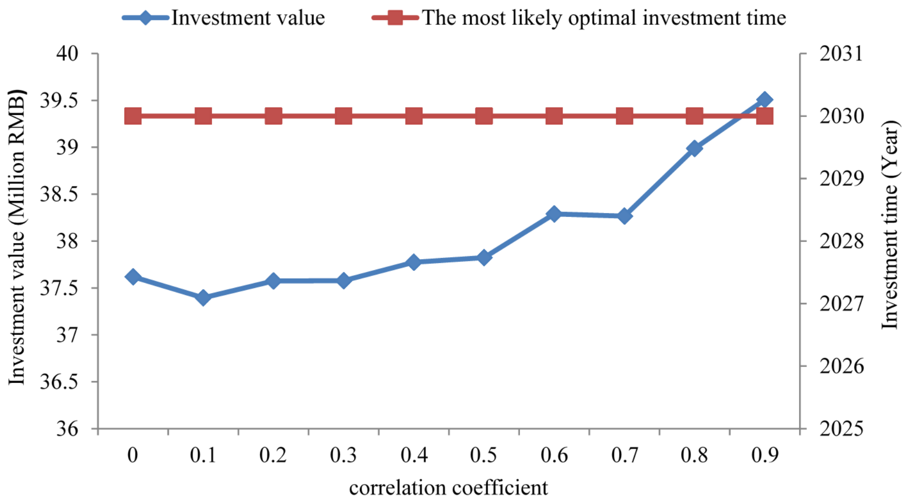

Figure 12. The impact of the correlation structure.

4.2.6. Impact of the Validity Period of Investment

As shown in the base case analysis, the most likely optimal investment time remains at the last year of the validity period, which indicates the choice of the validity period of investment may influence the optimal investment strategy. Figure 13a,b presents the optimal investment strategy under different validity periods of investment. It can be found that the extension of the validity period of investment may increase the investment value. However, the most likely optimal investment time is kept at the last year of the validity period, which further indicates the drawbacks of the current investment environment. In other words, the current investment environment may delay the straw-based power generation investment. Thus, the government should take great efforts to improve the investment environment.

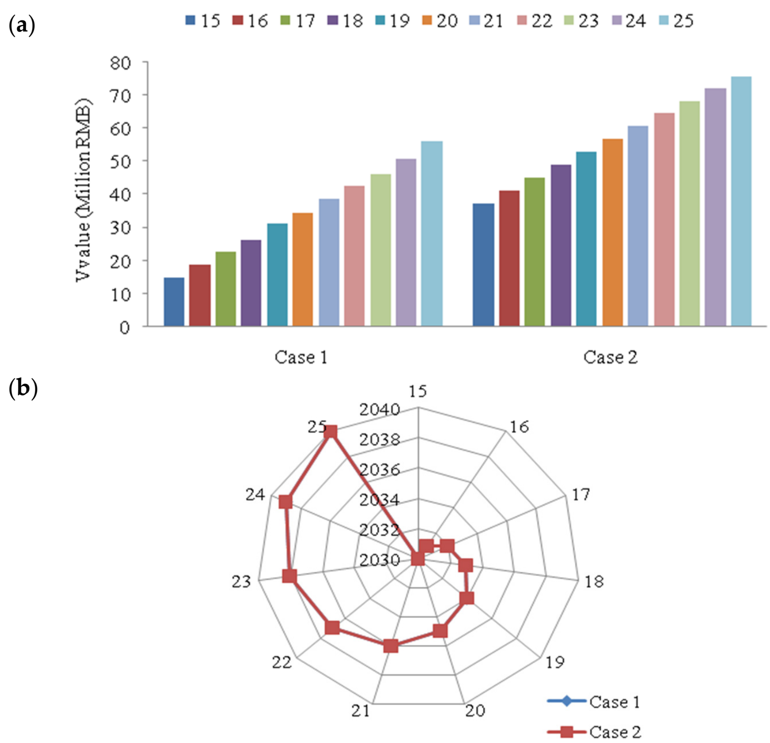

Figure 13. The impact of the validity period on investment value (**a**) and investment time (**b**).

5. Conclusions

As the energy shortage and greenhouse gas emissions problems become increasingly serious, biomass as an important renewable energy resource has drawn wide attention across the world. China is abundant with straw resource. Straw-based power generation is the most effective way to utilize straw. Given the uncertainty and complexity in the investment environment, it is hard to determine whether and when to invest (concerns of investors), as well as how to determine a reasonable and effective incentive policies system (concern of governments). This paper proposes a real options model for evaluating the straw-based power generation project investment in China. The uncertainties in the market price of electricity, CO_2 price and straw price are considered. Meanwhile the dynamic relationship between installed capacity and fuel cost, as well as the gradual reduction of subsidy are described. Two scenarios, *i.e.*, the carbon emission trading scheme is non-existent (Case 1) and existent (Case 2), is built to empirically evaluate the investment of a 25-MW straw-based power generation project. The results present not only the optimal investment strategy, *i.e.*, the investment value and the most likely optimal investment time, but also the impact of multiple key factors on the optimal investment strategy.

Several conclusions are derived from this study. First, the results suggest that investors should not undertake an investment decision in 2016 in both cases. Investors should undertake investment in 2030 based on which investors can obtain investment values of 14,869,254.8 RMB and 37,608,727.6 RMB, respectively. Second, the implementation of the carbon emission trading scheme theoretically could improve the investment value and the most likely optimal investment time. However, the current CO_2 price is not sufficient to advance the most likely optimal investment time. Third, the subsidy level and CO_2 price have a positive relationship with the investment value and may advance the most likely optimal investment time. The volatility of the CO_2 price could increase the investment value and does not change the most likely optimal investment time. The volatility of the straw price could reduce the investment value and does not change the most likely optimal investment time. Fourth, the growth pattern of subsidy helps attract investment, because it could increase the investment value and advance the most likely optimal investment time. Although the growth of installed capacity and the correlation coefficient can increase the investment value, it has less impact on the most likely optimal investment time. Due to the drawbacks of the current investment environment, the most likely optimal investment time remains at the last year of the validity period no matter how the validity period of investment is extended. Sixth, under the carbon emission trading scheme, the most likely optimal investment time is more easily advanced and difficult to delay by the relevant factors. Additionally, the project value is more difficult to change by the relevant factors.

Given the above, the investment environment that has the features of higher subsidy, higher CO_2 price, a growth pattern of subsidy and lower volatility of CO_2 price is conducive to attracting more investments of straw-based power generation projects. Thus, the government should take some measures, such as increasing the subsidy, setting the growth pattern of subsidy, establishing and perfecting a nationwide carbon trading market, as soon as possible. It should be stressed that the effectiveness of the incentive policies would be improved if the volatility of the CO_2 price were reduced to the lowest extent. In addition, strengthening technological progress and improving generating efficiency are also important.

In contrast to the existing literature, this paper successfully addresses the following points: (1) considering more uncertain factors and the long-term reduction of subsidy; (2) explaining the dynamic relationship between installed capacity and fuel cost; (3) applying a simulation method to solve the model; and (4) providing not only the optimal investment strategy, but also the impacts of several key factors on the optimal investment strategy. However, considering the complexity in evaluating the straw-based power generation investment, there are some limitations in this paper. First, the stability of straw supply is not considered. Second, the improvement of power generation efficiency resulting from technological progress is not considered. Future studies that can handle these issues would be of greater practical value.

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Conflicts of Interest: The authors declare no conflict of interest.

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