

Article

Strategic Decision-Making for Carbon Capture, Utilization, and Storage in Coal-Fired Power Plants: The Roles of Pollution Right Trading and Environmental Benefits

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Abstract

Promoting investment in Carbon Capture, Utilization, and Storage (CCUS) is essential for mitigating carbon emissions and combating climate change. This paper explores the uncertainties and environmental benefits associated with CCUS, integrating the frameworks of pollution right trading and carbon trading. A model for coal-fired power plant investment decisions on CCUS is developed and solved using the Least Squares Monte Carlo method, with results being robust beyond approximately 6000 simulation paths. Applied to a 600 MW ultra-supercritical coal-fired power plant in Shaanxi, China, our findings indicate that investment leads to a loss of CNY 1200.4 million in the absence of both environmental benefits and market trading mechanisms. A positive investment value of CNY 462 million with an optimal timing in the 10th year is achieved only when both environmental benefits and trading mechanisms are present. Furthermore, with only carbon trading, the option value is marginal (CNY 64.8 million), and investment remains unprofitable without government subsidies. Sensitivity analysis highlights that government subsidies significantly impact investment motivation. An initial carbon price of approximately CNY 95 per ton triggers immediate investment, while higher capture proportions and utilization levels positively affect decision-making. This study provides analytical tools for investment decisions in CCUS across multiple scenarios, serving as a reference for policymakers in designing emission reduction strategies.

Keywords: CCUS technology; Least Squares Monte Carlo method; carbon trading; pollution right trading; environmental benefits



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1. Introduction

Energy transformation and carbon emission reduction are crucial initiatives to address global climate change and achieve dual-carbon goals. Among these initiatives, the low-carbon transformation of the power industry represents a significant opportunity for reducing carbon emissions [1]. China, with the world's largest power consumption and installed capacity, relies predominantly on coal, leading to high carbon emissions [2]. This situation accentuates the critical need for reducing carbon emissions within its power industry [3] particularly in coal power sectors [4]. Therefore, proactive investments in carbon capture utilization and storage (CCUS) emerge as a pivotal strategy for facilitating large-scale decarbonization of fossil energy use in China.

CCUS involves capturing carbon dioxide from industrial, energy production, or air sources, and transporting it to a suitable site for utilization or sequestration, thereby reducing carbon emissions. It is a vital technology for achieving near-zero emissions from fossil fuels and ensuring energy security [5]. In China, CCUS still has substantial development potential and funding gaps. The Ministry of Science and Technology's technology development roadmap outlines that by 2050, widespread deployment of CCUS and the creation of new regional industries will be required, aiming for the utilization and storage of 800 million tons of CO₂ annually. By 2023, China had 87 CCUS demonstration projects either operational or under construction, collectively capturing a total of only 4 million tons of CO₂ annually. Goldman Sachs forecasts that achieving China's 2060 carbon neutrality goal could present cumulative investment opportunities in CCUS amounting to \$800 billion. The incremental investment opportunity amounts to USD 800 billion, and the annual investment size will increase over time. Whether or not to invest in CCUS is the result of a comprehensive assessment and selection of investment projects based on the investor's investment objectives, risk tolerance, and strategic preferences, taking into account the potential rewards and risks, industry and market prospects, environmental protection and social responsibility, etc., and guaranteeing that the investment optimally enhances both economic and social benefits. Considering the crucial role of CCUS technology in low-carbon emission reduction and environmental protection, as well as its investment potential, researching the retrofit of high-carbon-emission coal-fired power plants with CCUS holds significant strategic importance and long-term social value [6].

Government policies aimed at reducing emissions, such as carbon quotas, subsidies, taxes, and trading systems, offer significant economic incentives for advancing CCUS. Carbon trading and pollution right trading serve as cost-effective, market-based tools to meet emission reduction targets. By the end of 2024, China's carbon market had cumulatively traded 680 million t CO₂, establishing a national carbon-pricing framework anchored in the nationwide emissions trading scheme [7]. Pollution right trading allows enterprises, within the validated allowance and its valid term, to transfer permits through fixed-quota sales or public auction. In current pilots, sulfur dioxide, chemical oxygen demand, ammonia nitrogen and nitrogen oxides are routinely designated as mandatory tradable pollutants for aggregate control. Participation in both markets enables firms to monetize surplus carbon allowances, strengthening abatement incentives and fostering technological innovation and market development. Acting as effective complements to mandatory administrative tools such as pollution-discharge permits [8], these trading systems stimulate firms' green innovation and provide a financing channel for CCUS projects, facilitating deployment and technological advancement [9,10].

CCUS continues to face significant uncertainties, such as inadequate infrastructure, low technological maturity, and high costs. Moreover, investment is hindered by four major barriers within the regulatory framework: the absence of enforceable legal standards, limited operational data, weak market incentives, and insufficient financial subsidies [11]. The large-scale deployment of CCUS requires financial support, as public funding for upfront costs can help mitigate the uncertainties associated with emerging green technologies [12].

A comprehensive analysis of the uncertainties surrounding CCUS investments, combined with accurate predictions of their value, enables investors to make more timely and informed decisions. This also assists governments in evaluating and designing more effective incentive policies, thereby accelerating CCUS project investments and implementations. However, practical investment analyses often encounter challenges, including unpredictable fluctuations in carbon and electricity prices, insufficient evaluation of policies such as carbon trading and subsidies, and difficulties in assessing the direct or indirect

environmental benefits of projects [13]. These challenges complicate the determination of returns and the optimal timing for investments.

In order to cope with the above challenges, the real option can be introduced as an effective tool in the study of investment decision-making in uncertain investment environments. The real option method is a tool for evaluating large-scale assets, which are usually subject to great uncertainty, and it takes into account the dynamics of the real environment, simulates complex investment characteristics, and increases the flexibility and management flexibility of investment projects. Kim et al. [14] found that real options portrayed and evaluated the actual value of a project's investment in a much more comprehensive way compared to traditional investment decision-making methods. In this paper, we consider carbon trading and pollution right trading and use the real options method to develop an investment decision model that includes the environmental benefits of CCUS projects. This model serves as a guide for investing in CCUS at coal-fired power plants and provides empirical support for the government's initiative to promote the construction of technologies that reduce low-carbon emissions.

The contributions made by this paper in comparison to previous studies are (1) Unlike earlier studies on carbon capture and storage (CCS) technology adopted in low-carbon retrofit methods for coal-fired power plants, this paper studies the investment decision on CCUS retrofit, contributing to supporting the CO₂ industry to move from CCS to CCUS in an effort to achieve CO₂ emission reduction and resource utilization. (2) This study integrates uncertainties in electricity price, carbon price, carbon trading price, and unit investment cost into its model. It also addresses the overlooked environmental benefits, assesses the carbon trading mechanism's impact on investment, and examines the collaborative effect of the pollution right trading mechanism. The resulting model more accurately represents the investment decision scenarios faced by investors. (3) This paper adopts the method of solving the model through the inverse dynamic programming technique combined with Least Squares Monte Carlo simulation, which is more suitable for solving the investment decision under multi-dimensional uncertainty conditions. (4) Beyond analyzing the effects of government investment subsidies and the initial price of carbon trading on decision-making, this study also explores how the carbon capture rate and carbon utilization rate influence CCUS retrofit investment across varying levels of technological maturity. The paper provides investors with more precise estimates of returns and recommendations for optimal investment timing, while also offering support for the government in formulating more effective environmental policies. These policies are designed to promote the implementation of low-carbon emission reduction projects, particularly encouraging the retrofit of coal-fired power plants with CCUS to reduce carbon emissions and mitigate negative environmental impacts.

The organization of this paper is as follows: the first part presents the paper's background, the second part reviews the related literature and puts forward the research vacancies, the third part formulates the CCUS investment-decision model and details the solution procedure using the Least-Squares Monte Carlo method, the fourth part gives the analysis of the investment decision in different backgrounds and investigates the influence of different factors on the investment, the fifth part gives recommendations and conclusions.

2. Literature Review

2.1. Real Options in the Power Industry

The literature extensively explores the use of real options in assessing the value of project investments in the power industry [15–17]. Three primary methods are commonly applied: the partial differential approach, notably the Black-Scholes option pricing

model [18]; the dynamic programming approach, such as the Binomial Model [19]; and the simulation approach [20], with the Monte Carlo method being the most prominent.

However, this paper focuses on the flexibility of investment timing in CCUS, arguing that investors can make decisions on any trading day before the maturity date, rendering the partial differential approach less suitable [21]. In the power industry, the Binomial Tree Pricing Method is more commonly employed to address investment flexibility [22,23], and some scholars have expanded the Binomial Tree into a Trinomial Model [24,25] to investigate the incentives for CCS retrofits. Wang, Du [12] further incorporate uncertainties, such as carbon trading and electricity prices, by constructing a quadtree option model for CCS retrofits. Ref. [26] proposed conducting Strategic Environmental Assessments (SEA) for CCS infrastructure, including pipelines and storage sites, at an early strategic stage, integrating environmental assessments across various CCS phases. These studies deepen the application of real options in the power industry by addressing both investment uncertainties and the policy landscape. Although the Binomial Model and its extensions can represent a project's value under uncertainty and use NPV to track price changes, they fall short in capturing market price fluctuations in more complex scenarios [27].

Lin et al. [28] explored the use of captured CO₂ for enhanced oil recovery, employing the Monte Carlo method to simulate the fluctuation paths of oil and carbon prices. Unlike the binomial tree model, which is constrained by the number of underlying assets and option variables, Monte Carlo simulations are not significantly impacted by problem dimensionality. However, because the Monte Carlo method is forward-solving, it cannot compute ongoing holding returns or compare the benefits of immediate execution with those of future returns, limiting its ability to decide between immediate execution and continued holding [29].

To address these limitations, Schwartz [30] proposed the Least-Squares Monte Carlo (LSM) method. Zhu et al. [31] applied the LSM method to evaluate investments in retrofitting a supercritical pulverized coal (SCPC) unit with CCS, factoring in electricity prices, carbon prices, and additional O&M costs. Boomsma et al. [32] used the LSM method to study the influence of feed-in tariffs (FITs) and renewable energy certificates (RECs) on investment timing and project sizing for Nordic wind farms. Hu et al. [33] applied the LSM method to develop a real options model for flexible investment decisions in waste-to-energy projects within a carbon trading framework. The LSM method estimates the holding value by regressing the option's future value on its current state, approximating this value as a linear combination of basis functions, with the optimal coefficients determined through least squares regression [34]. This method is particularly suited for projects with flexible investment timing, overcoming the dimensionality limitations of the binomial tree model. A summary and comparison of the methodologies between this paper and representative studies are provided in Table 1.

Table 1. Comparison of related works.

Related Articles	CCUS	Carbon Trading	Pollution Right Trading	Environmental Benefits	Methods
Dusonchet et al. [35]		✓			NPV
Wang et al. [36]	✓	✓			system dynamics method
Masui et al. [37]		✓	✓		Computable General Equilibrium

Table 1. *Cont.*

Related Articles	CCUS	Carbon Trading	Pollution Right Trading	Environmental Benefits	Methods
Han et al. [38]		✓		✓	Comprehensive Evaluation
Fan et al. [24]		✓			Real option (Tree model)
M.M. et al. [39]		✓			Real option (LSMC)
Hu, Huanyue, Peng, Peng [33]		✓			Real option (LSMC)
This paper	✓	✓	✓	✓	Real option (LSMC)

2.2. Development of the CCUS

Retrofitting coal-fired power plants with CCUS has become a significant research focus in power sector investment. Yang et al. [40] developed a step function with random jumps at specific times to simulate carbon price shocks under climate policies, emphasizing the relative importance of CO₂ and fuel price uncertainties in electricity investment. Wang, Tang, Meng, Su [36] built a real options model for CCUS investment that incorporates carbon price uncertainty and declining investment costs based on CO₂ utilization rates, solving it through the Monte Carlo method. Zhang et al. [41] optimized source-sink matching models for onshore and offshore CCUS reservoirs by integrating a trinomial-tree real options model, which quantified the abatement potential of China's CCUS investments under various scenarios. This body of literature provides new perspectives on CCUS cost prediction by addressing both investment decisions and deployment challenges.

The development of CCUS is mainly driven by five factors: government and public financing, national incentives, carbon taxes, mandatory emission reduction policies, and carbon trading. Although most current CCUS projects remain in the R&D and demonstration phases, they are largely supported by government financial backing and national incentive policies [42]. At the firm level, the translation of penalties, taxes, and subsidies into actual investment is jointly determined by the interaction of regulatory instruments with financing frictions and political connections. Guo et al. [43] demonstrate that when financing constraints are weak, fines and taxes are more deterrent, whereas under tight constraints subsidies become more effective; political connections weaken the enforceability of fines but facilitate access to subsidy resources. At the industry level, climate-transition risk, green innovation, and carbon-market uncertainty alter expected returns and consequently shift the optimal timing of investment [44,45]. Sun et al. [46] suggest that as the industry transitions from demonstration to large-scale industrial deployment and commercial operations, mandatory emission reductions and carbon trading markets will become the primary drivers. Masui, Toshihiko, Dai, Hancheng, Wang, Peng, Cheng, Beibei, Zhao, Daiqing [37] further noted that while the carbon and pollutant emissions markets currently operate independently, their co-benefits should be considered in policy development. The pollution right trading system has contributed positively to promoting emission reductions and technological innovation [47]. However, most of the existing literature focuses on carbon trading as a factor in investment decisions, without considering the additional benefits of pollution right trading following CCUS retrofits or the synergistic effects of integrating emissions and carbon trading systems on investor decision-making.

In the decision-making process for CCS or CCUS investments, most studies primarily focus on economic factors, such as net present value [48] or investment option returns exceeding zero. However, the direct and indirect environmental benefits of low-carbon

emission reduction technologies should not be overlooked. Han, Li, Tang, Wang, Yang, Ge, Yuan [38] provided a comprehensive evaluation of CCUS projects from economic, ecological, and energy efficiency perspectives. Few studies, however, consider the environmental benefits of low-carbon power plant retrofits when evaluating CCUS investments. Additionally, decision-makers must navigate complex political and economic environments, making it difficult to fully capture all uncertainties. Many existing studies approximate real investment scenarios by estimating the uncertainties decision-makers face. For example, Zhang et al. [49] developed a real options model for carbon abatement investments in CCS, incorporating a carbon price floor and return conditions. Olfe-Kräutlein [50] further noted that the integration of carbon utilization significantly enhances CCUS's potential returns and environmental benefits. As more coal-fired power plants consider CCUS retrofits, the need for accurate assessment of investment decisions under multiple uncertainties—while factoring in environmental benefits—and understanding the influence of carbon trading and pollution right trading mechanisms on investments and operations has become urgent.

To address these challenges, this paper considers key uncertainties such as electricity price, carbon price, carbon trading price, and unit investment cost. An investment decision model is developed that integrates the environmental benefits of CCUS projects. The model simulates random fluctuations of these uncertainties and is solved using the least-squares Monte Carlo method. A numerical simulation is performed on a 600 MW coal-fired power plant to analyze investment decisions with and without the presence of carbon trading and pollution right trading mechanisms. The study further examines the effects of government subsidies, carbon trading prices, and variations in CO₂ capture and utilization on the optimal timing and value of investment decisions.

3. Model Establishment

3.1. Problem Description and Assumptions

This paper investigates the problem of making CCUS investment decisions by coal-fired power plants in the context of carbon trading. A coal-fired power plant making a CCUS investment is considered a discrete-time American option. Assuming the project activates at moment t due to the investment, it will operate at total load capacity for L years. The decision-maker of the project can determine the optimal investment time based on the project returns within an effective investment period T . During the effective investment period of a CCUS retrofit project for a coal-fired power plant, the decision-maker is faced with many uncertainties, such as changes in the cost of power generation and revenue from power sales of the plant due to market fluctuations, technological advances, and the policy environment. At the same time, the government's investment subsidies for low-carbon projects and the launch of carbon trading policies are also critical for investors' decision-making. Decision-makers can judge the value of investment more scientifically and maximize the return on investment by using the deferred investment decision-making method. The CCUS investment model constructed in this paper can help decision-makers evaluate the flexible value of investment projects in a complex and uncertain environment and help decision-makers make more flexible and accurate decisions. Policy instruments and their combinations directly raise the marginal revenue of low-carbon projects by channeling carbon price revenues, investment grants and concessional loans, thereby lowering capital costs and shortening pay-back periods. Moreover, decision-makers increasingly account for noneconomic benefits: CCUS deployment improves air quality, strengthens corporate green reputation and releases surplus emission allowances. Once these hidden gains are incorporated into the appraisal, the overall return of CCUS projects turns from negative to positive and the investment trigger falls. Policy incentives and non-

economic benefits thus reinforce each other, accelerating project implementation. Building on the above reasoning, we formulate the following hypotheses:

Hypothesis 1. *For any given exogenous price path, the real options approach yields a higher expected net present value than a fixed-date investment rule, i.e., the value of the waiting option is positive.*

Hypothesis 2. *The presence of both carbon trading and pollution right trading mechanisms increases project cash flows and significantly raises option value.*

Hypothesis 3. *When the environmental benefits of CCUS investment are taken into account, the investment threshold is lowered, the optimal stopping time is shortened, and the project enters the implementation phase earlier.*

3.2. Investment Modeling of CCUS

Considering the environmental uncertainty of low-carbon retrofit investment, this paper chooses four main uncertainties, namely, coal price, electricity price, carbon trading price, and unit investment cost, to simulate the complex and uncertain investment environment. Referring to [28,51,52] the stochastic fluctuation of carbon trading price, market electricity price, and coal price obeys Geometric Brownian motion, GBM. The selection of Geometric Brownian Motion (GBM) for modeling the key uncertainties in this study is motivated by both their long-term characteristics and the requirements of real options analysis. For long-term investment horizons like the one considered ($T = 10$ years), the carbon trading price and unit investment cost are primarily driven by unpredictable macroeconomic policies, technological breakthroughs, and market sentiments, which are better captured by the non-stationary and stochastic trend of GBM. While electricity and coal prices may exhibit short-term mean reversion, their long-term trajectories are dominated by fundamental structural shifts, making GBM a suitable and widely adopted approximation in generation investment models. Furthermore, the GBM assumption provides a mathematically consistent foundation for the subsequent Least Squares Monte Carlo simulation, ensuring the robustness of our option valuation. Therefore, the main four uncertainties selected in this paper conform to the GBM:

$$dP_s = a_s \cdot P_s \cdot dt + b_s \cdot P_s \cdot dz_s \quad (1)$$

$$dCu = a_u \cdot Cu \cdot dt + b_u \cdot Cu \cdot dz_u \quad (2)$$

$$dP_e = a_e \cdot P_e \cdot dt + b_e \cdot P_e \cdot dz_e \quad (3)$$

$$dP_c = a_c \cdot P_c \cdot dt + b_c \cdot P_c \cdot dz_c \quad (4)$$

where P_s is the carbon trading price, Cu is the unit investment cost, P_e is the market electricity price, and P_c is the coal price. a_s , a_u , a_e , and a_c are their drift parameters, b_s , b_u , b_e , and b_c are their volatility parameters. The random variables dz_s , dz_u , dz_e , and dz_c are standard Wiener process increments, $dz = \varepsilon\sqrt{t}$, $\varepsilon \sim N(0,1)$. The option term can be partitioned into N small intervals of length Δt to model the change paths of the four uncertainties. According to Ito's theorem, Equation (1) can be rewritten:

$$d \ln P_s = \left(a_s - \frac{b_s^2}{2} \right) \cdot P_s \cdot \Delta t + b_s \cdot dz_s \quad (5)$$

Equation (5) is approximated in discrete time:

$$\ln P_{s_{t+\Delta t}} - \ln P_{s_t} = \left(a_s - \frac{b_s^2}{2} \right) \cdot \Delta t + b_s \cdot dz_s \quad (6)$$

Therefore, the current carbon trading price P_{s_0} can be used to predict the carbon trading price P_{s_t} at moment t according to the above equation:

$$P_{s_t} = P_{s_0} \cdot \exp \left[t \left(\left(a_s - \frac{b_s^2}{2} \right) \cdot \Delta t + b_s \cdot dz_s \right) \right] \quad (7)$$

Similarly, unit investment costs, market electricity prices, and coal prices can be modeled in the same way to obtain Equations (8)–(10):

$$Cu_t = Cu_0 \exp \left[t \left(\left(a_u - \frac{b_u^2}{2} \right) \cdot \Delta t + b_u \cdot dz_u \right) \right] \quad (8)$$

$$P_{e_t} = P_{e_0} \exp \left[t \left(\left(a_e - \frac{b_e^2}{2} \right) \cdot \Delta t + b_e \cdot dz_e \right) \right] \quad (9)$$

$$P_{c_t} = P_{c_0} \exp \left[t \left(\left(a_c - \frac{b_c^2}{2} \right) \cdot \Delta t + b_c \cdot dz_c \right) \right] \quad (10)$$

Suppose that a specific value of uncertainty $\Phi_t = (P_{s_t}, Cu_t, P_{e_t}, P_{c_t})$ is observed at a certain point in time, and this value Φ represents the uncertainty scenarios during the CCUS investment time and operation periods. Set a set to represent all possible uncertainty scenarios, which contains a total of K different scenarios, denoted $S = \{\Phi^1, \Phi^2, \Phi^3 \dots \Phi^n\}$.

Each scenario S_i corresponds to a probability value p_i satisfying $\sum_i^k p_i = 1$. The decision-maker evaluates the value of the project at each moment t during the effective decision time T . If the decision-maker chooses to invest at moment t , then we further assume that the project will go into construction immediately after investment and start operation one year later, and the one-time investment cost that the investor needs to pay is F_t^k , and the project will continue to operate for L years after the cut. The cash flow of the project in the year i of operation is decomposed into four components: annual revenue (R_i^k), environmental benefits (E_i^k), government subsidy costs (G_i^k) and annual costs (Cy_i^k). Then, we can use the following Equation (11) to calculate the project value (PV_t) at moment t :

$$PV_t = \sum_{K=1}^K q^k \left[\sum_{l=t}^{t+L} e^{-\pi l} \left(R_l^k \left(P_{s_l}^k, P_{e_l}^k, P_{c_l}^k \right) + G_l^k \left(Cu_t^k \right) + \delta_1 \cdot I_{env}^k - Cy_l^k \left(P_{e_l}^k, P_{c_l}^k \right) \right) - F_t^k \left(Cu_t^k \right) \right] \quad (11)$$

$t = 0, 1, 2, \dots, T;$

where π is the discount rate of the CCUS. δ_1 is a binary variable to indicate whether the decision-maker considers the environmental benefits, and if $\delta_1 = 1$, signifies that the decision-maker internalizes the positive environmental externalities, reflecting the enterprise's environmental and social responsibility or its compliance with mandatory environmental assessment requirements; whereas $\delta_1 = 0$, represents a traditional, purely financially driven decision-making approach.

Equation (12) is the formula for calculating the annual revenue, which consists of the revenue from electricity sales Se , the income from carbon trading Ic , the income from pollution right trading Ie , and the income from carbon dioxide utilization Iu :

$$R_l^k \left(P_{s_l}^k, P_{e_l}^k, P_{c_l}^k \right) = Se_l^k + \delta_2 \cdot Ic_l^k + \delta_3 \cdot Ie + Iu \quad (12)$$

δ_2 and δ_3 are two binary variables, δ_2 is used to indicate whether the carbon trading mechanism is considered or not, and the carbon trading factor is considered if $\delta_2 = 1$. δ_3 is used to indicate whether the pollution right trading mechanism is considered or not, and the pollution right trading factor is considered if $\delta_3 = 1$.

Assuming that the remaining carbon allowances after carbon capture can be traded in the market, and the transaction cost is zero, Q_c is the fixed power generation, and u_c is the annual emission reduction. In the CCUS, the captured CO_2 will be sequestered and utilized, and the current use of CO_2 is mainly classified into three categories: industrial use, food use, and EOR to drive oil, in which, according to the existing literature, the conversion rate of EOR can be obtained as 1 [24].

$$Se_l^k = Q_c \cdot P_{e_l}^k \quad (13)$$

$$Ic_l^k = u_c \cdot P_{s_l}^k \quad (14)$$

$$Ie = (T_{SO} \cdot \min(Q_{SO}, Q_{SO_{allow}}) + T_{NO} \cdot \min(Q_{NO}, Q_{NO_{allow}})) \cdot \max(0, \min(1, (5 - t + 1))) \quad (15)$$

$$Iu = \beta \cdot u_c \cdot Pa \quad (16)$$

$$Pa = Pa_1 \cdot \gamma_1 + Pa_2 \cdot \gamma_2 + Pa_3 \cdot \gamma_3 \quad (17)$$

where $P_{e_l}^k$ is the market price of electricity, $P_{s_l}^k$ is the carbon trading price, u_c is the annual carbon dioxide capture, and β is a constant indicating the proportion of CO_2 captured to utilized. Q_{SO} , Q_{NO} are the amount of sulfur dioxide and nitrogen compounds purified. $Q_{SO_{allow}}$, $Q_{NO_{allow}}$ represent the permitted annual emissions of purified sulfur dioxide and nitrogen compounds. The tradable volume for each is calculated as the lesser of the actual emissions or the permitted amount. According to the existing pollution right trading policy, the validity period of the pollution right trading to obtain the emissions target is five years, and Equation (15) indicates the emissions benefit obtained in the five years after the project investment. In Equation (17), the selling price of industrial-grade CO_2 is Pa_1 , the selling price of food-grade CO_2 is Pa_2 [23], and the unit revenue of CO_2 driven oil is Pa_3 , γ_i denoting the proportion of CO_2 accounted. According to the Technical Specification for Accounting for Gross Ecosystem Product (GEP), the environmental benefit (I_{env}) pertains to the ecological impact achieved through the project's abilities in absorption, filtration, barrier creation, and decomposition, aimed at reducing atmospheric pollutants such as sulfur dioxide, nitrogen compounds, and dust, thereby improving the environment. The calculation of the environmental benefits of CCUS utilizes the substitution cost method, which estimates the cost of controlling atmospheric pollutants industrially, as demonstrated in Equation (18).

$$I_{env} = Q_{SO} \cdot P_{SO} + Q_{NO} \cdot P_{NO} + Q_{PM} \cdot P_{PM} \quad (18)$$

Herein, P_{SO} , P_{NO} , P_{PM} represent the purification values of sulfur dioxide, nitrogen compounds, and dust, respectively.

The government subsidy comprises two components: the government's cost subsidy for CCUS investment and the subsidy for cleaner power generation. Equation (19) is the formula for calculating the government subsidy:

$$G_t^k(Cu_t^k) = \alpha \cdot F_t^k(Cu_t^k) + Q_c \cdot P_g \quad (19)$$

where α is a constant, denoting the proportion of government subsidy on project investment $\alpha \in [0, 1]$, and P_g is the subsidized price for electricity sales.

The annual cost of CCUS $Cy_l^k(P_{e_l}^k, P_{c_l}^k)$ consists of operation and maintenance cost Ma , capture cost (1) Cp_l^k , CO₂ storage cost Cs , and transportation cost Ct . There are three main ways of transportation between the CO₂ source and the storage place: tanker truck transportation, new or renovated pipeline transportation, and ship transportation. At present, the primary mode of CO₂ transportation in China is tanker truck transportation [53]. Equation (20) is the cost calculation formula:

$$Cy_l^k(P_{e_l}^k, P_{c_l}^k) = Ma + Cp_l^k + Cs + Ct \quad (20)$$

$$Cp_l^k = u_c \cdot Pn + Lo_l^k \quad (21)$$

$$Lo_l^k = P_{c_l}^k \cdot Q_r \quad (22)$$

$$Cs = Ms \cdot COS \quad (23)$$

$$Ct = Mt \cdot COT \quad (24)$$

where P_n is the capture price per unit of CO₂, Lo_l^k is the increased cost due to carbon dioxide capture, Q_r is the increased coal usage due to carbon dioxide capture. Ms is the cost per unit of carbon dioxide storage, Mt is the cost per unit of carbon dioxide transportation, COS is the amount of carbon dioxide storage, COT is the amount of carbon dioxide transportation, and Equation (21) represents the cost of CO₂ capture and the increased fuel cost due to CCUS carbon capture.

Technological advances will reduce the investment cost of CCUS, F_l^k is the investment retrofit cost at time t . Equation (25) represents the investment cost of CCUS:

$$F_l^k = Cu_l^k \cdot tq \quad (25)$$

where Cu_l^k is the unit investment cost of the CCUS project, and tq is the installed capacity of a coal-fired power plant.

According to Equation (11), we can find out the project value PV_t for each decision-making period t in the investment period T . According to Equation (26), we get the optimal project value of CCUS investment and the optimal investment time:

$$PV_{t^*} = \max_{t=0,1,\dots,T} [\max(PV_t, 0)] \quad (26)$$

3.3. Calculation

After establishing the investment decision model of the CCUS, this paper uses the Least Squares Monte Carlo Simulation method to solve the model. The LSM method is particularly suited for this study as it efficiently handles the valuation of the American-style investment option under multiple sources of uncertainty (GBM processes) and accommodates the model's flexibility in decision-making. In this paper, the LSM first uses MATLAB R2018a to simulate multiple paths with changing uncertainties, calculates the most executable time and the optimal option return for each path, discounts the option returns for each sample path and averages them. The core of the problem here is how to estimate the conditional expected return from continued holding, which is solved by regressing the realized payments and state variables to obtain an estimated expression for the conditional expected return. The detailed solution process of the LSM method is as follows. First, this paper simulates the complex investment environment based on geometric Brownian motion. Because the Monte Carlo simulates the uncertainty paths to form K investment scenarios, according to the method of inverse dynamic programming, the option holder can easily derive the cash flow obtained after the immediate investment of the K th path at

the moment T according to Equation (11), i.e., the value of the immediate exercise of the option at the point of the moment PV_T^k . The least squares regression employs third-order power polynomials as basis functions, retaining the first three terms in each regression. The backward induction is performed over 6000 simulated paths, with the random seed uniformly set to 42.

Next, all paths with cash flow less than 0 are set as invalid paths. Discounting the cash flow obtained at the last moment T in the valid paths, we obtain the value of investing X_{T-1}^K and continuing to hold the asset Y_{T-1}^K at the moment $T - 1$.

$$Y_{T-1}^K = e^{-\pi} \cdot X_T^K \quad (27)$$

The project option price at $T - 1$ is then processed using a least squares regression, and the resulting regression expression is a valuation of the expected return on the option to continue to hold FV_{T-1}^K .

$$H_{T-1}^K = E[Y_{T-1}^K | X_{T-1}^K] \quad (28)$$

If PV_T^k is 0, the investment value of the project is less than or equal to 0, and the decision-maker chooses to give up the investment; if PV_T^k is greater than 0, and the project has the value of the investment, and then by comparing the investment return with the value of the return of the assets held, if at the moment t , the investment return is positive and is greater than the value of the return of the assets held, this time the decision is made to invest in the t moment.

Repeat the above steps, backward one node until the initial point $T = 0$, calculate the option value under the K path, as well as determine the optimal investment t_K^* and the optimal value of the investment $PV_{t_K^*}^k$ under the path. Then the optimal value of the project under all scenarios K is:

$$PV_{t^*} = \sum_{K=1}^K \frac{1}{K} \cdot PV_{t_K^*}^k \quad (29)$$

Through this series of detailed steps and calculations, the LSM method can more accurately assess the optimal investment timing and strategy under different scenarios, providing more detailed information to support decision-makers.

4. Discussion

In this paper, a coal-fired power plant undergoing CCUS transformation is taken as the background, and an investment decision model is established and solved using the LSM method above. To test the effectiveness of the model, a coal-fired power plant with an installed capacity of 600 MW of ultra-super criticality in Shaanxi Province, China, is selected for application analysis. In Shaanxi Province, the CCUS is essential for profound industrial emission reduction. The government strongly supports the low-carbon transformation of coal-fired power plants, and the government's investment subsidy is also known as an essential pillar of the project. In addition, the main advantage of ultra-supercritical coal-fired power plants over traditional plants is the improved energy conversion efficiency, with higher steam parameters helping to convert the thermal energy of the fuel into electricity more efficiently, thus reducing coal use and greenhouse gas emissions. The selection of this case is, therefore, representative.

4.1. Parameterization

Table 2 demonstrates the basic parameters of a coal-fired power plant in Shaanxi Province for low-carbon emission reduction CCUS investment.

Table 2. Basic parameters.

Description	Symbol	Values	Parameter Estimation Process
Operating life of CCUS	L	30	[46]
Investment period	T	10	Authors' setting
Annual energy output	Q_c	1.8×10^9 kWh	[41]
Investment cost	C_u	520 million CNY	Based on NZEC FEED, and authors made some adjustment
Price of electricity	P_e	0.35 CNY	[36]
Coal price	P_c	995 CNY/t	In late January 2024, the price of anthracite coal was 995 CNY/ton.
Carbon trading price	P_s	65 CNY/t	In January 2024, the average national carbon trading price was 65 CNY/ton
Drift rate of carbon trading price	a_s	0.03	Calculated by the authors based on historical data from 2015–2024, with reference to [54]
Drift rate of unit investment cost	a_u	−0.03	Calculated by the authors based on historical data from 2015–2024, with reference to [36]
Drift rate of electricity price	a_e	0.04	Calculated by the authors based on historical data from 2015–2024, with reference to [33]
Drift rate of coal price	a_c	0.04	Calculated by the authors based on historical data from 2015–2024, with reference to [12]
Volatility of carbon trading prices	b_s	0.04	Same as above, with reference to [54]
Volatility of unit investment cost	b_u	0.08	Same as above, with reference to [36]
Volatility of electricity price	b_e	0.01	Same as above, with reference to [33]
Volatility of coal price	b_c	0.04	Same as above, with reference to [12]
CO ₂ utilization	β	20%	According to the current CCUS level, set by this article
CO ₂ prices for industry	P_{a1}	250 CNY	[41]
CO ₂ price of food	P_{a2}	525 CNY	[41]
Benefits of the EOR	P_{a3}	564.5 CNY	[55]
Sulfur dioxide purification	Q_{SO}	5414 t	[38]
Nitrogen compound purification	Q_{NO}	2639 t	[38]
Amount of dust purification	Q_{PM}	7031.8 t	[38]
Purification value of sulfur dioxide	P_{SO}	450 CNY/t	Ecosystem assessment Guidelines for gross ecosystem product accounting
Purification value of Nitrogen compounds	P_{NO}	540 CNY/t	Ecosystem assessment Guidelines for gross ecosystem product accounting
Purification value of dust	P_{PM}	600 CNY/t	Ecosystem assessment Guidelines for gross ecosystem product accounting
Trading price of sulfur dioxide	T_{SO}	6000 CNY/t	[56]
Trading price of nitrogen compounds	T_{NO}	6000 CNY/t	[56]
O&M costs	Ma	3.745×10^7 CNY	Based on NZEC FEED, and authors made some adjustment
Discount rate	π	0.08	A general discount rate
CO ₂ capture cost	P_n	400 CNY/t	[57]

4.2. Results and Analysis

4.2.1. Optimal Investment Results

In this paper, MATLAB software computationally solves the CCUS investment model considering environmental benefits. When solving the model, the probability of occurrence

of different scenarios generated by uncertainties is set to the same value, i.e., it is assumed that the probability of occurrence of the simulated scenarios is all $1/k$. Figure 1 shows the variation in optimal investment value under different scenario settings. To draw more accurate conclusions, the optimal investment value for each scenario is calculated as the average value obtained from 100 simulations. It can be observed that when the number of simulated scenarios reaches approximately 6000, the results of the simulation become robust, and the calculated results stabilize. Figure 2 presents the histograms of the optimal investment value of the project and the distribution of the optimal stopping times for all paths when the scenario parameters are set to 6000. Due to the uncertainty path simulation stochasticity, the optimal value shows an overall stability of -1200.4 million CNY. This suggests that the current investment environment, which does not account for carbon trading, pollution right trading, and environmental benefits, may not immediately attract investment. Subsequent analysis will further explore investment strategies under altered conditions.

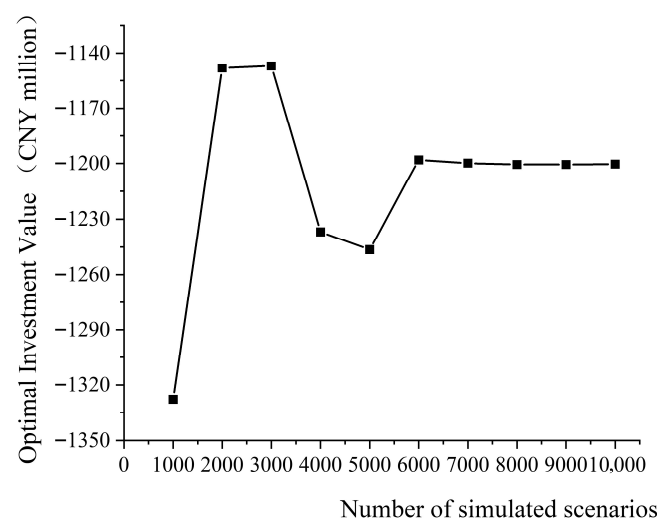


Figure 1. Optimal investment value with different number of simulations.

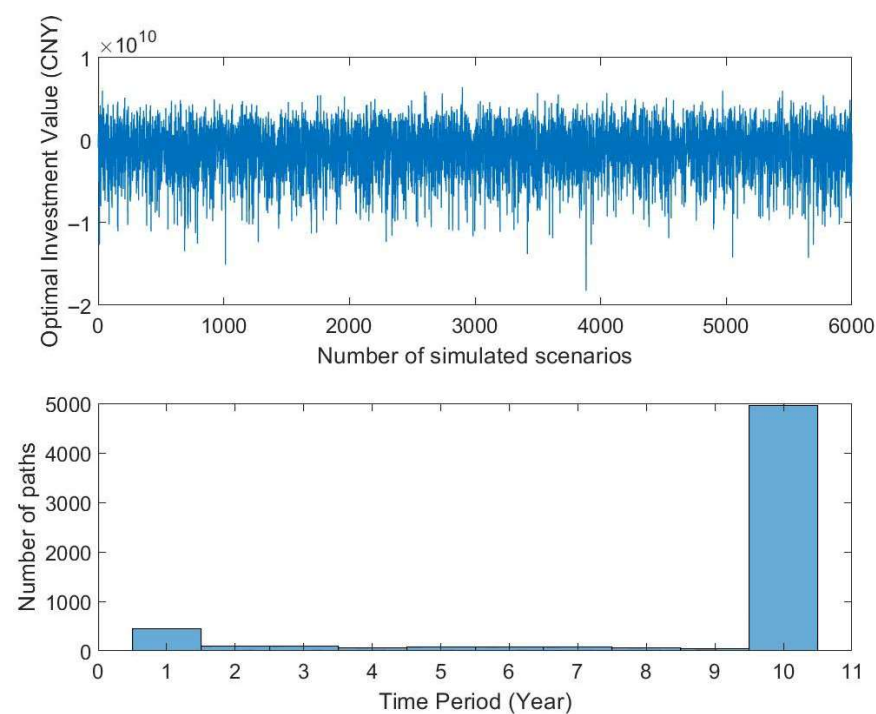


Figure 2. The optimal investment value and optimal stopping time under 6000 Monte Carlo simulations.

4.2.2. Monte Carlo Simulation Results

Figure 3 demonstrates the modeling of the four uncertainties of unit investment cost, electricity price, carbon trading price, and coal price through Equations (1)–(4), which reflects the 1000 paths of change in the four uncertainties under the parameters of volatility and drift rate that have been set.

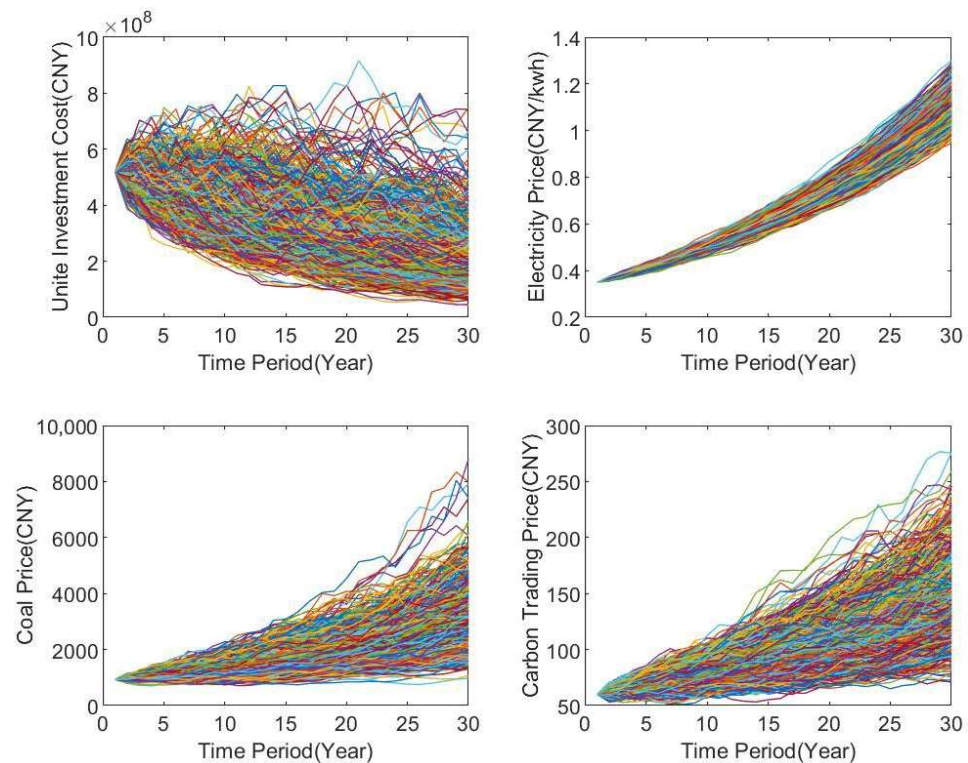


Figure 3. The unit cost, electricity price, coal price, and carbon trading price based on 1000 Monte Carlo simulations.

As can be seen from Figure 3, the unit investment cost of CCUS for coal-fired power plants has become a decreasing trend in general over time, and the development of related technologies and engineering practices has reduced the construction and operation costs of the projects, which has a positive impact on promoting the adoption of CCUS in more coal-fired power plants. On the other hand, electricity prices, carbon trading, and coal prices show a generally upward trend over time, and the volatility of electricity prices is small. Electricity prices are relatively stable, which is influenced by the regional electricity market structure, stable electricity supply chain, and reasonable pricing mechanisms. Carbon trading and coal prices are more affected by the market environment and therefore show greater volatility. This also shows that carbon trading and coal prices are more uncertain in the market, which brings more risks and opportunities for investment.

4.3. Comparative Analysis of Investment Decisions

In this subsection, the investment decision is analyzed for different scenarios: with and without carbon trading, with and without pollution right trading, considering environmental benefits, and without one-time cost subsidies from the government. As shown in Table 3, investing in CCUS during the effective investment period, without considering carbon trading and pollution right trading, leads to cost losses. In particular, the optimal investment value under the fixed investment decision is −1545 million CNY. In comparison, the optimal investment value considering the flexible investment decisions of the real options approach is −1200.4 million CNY. Flexible investment decisions are

more advantageous than fixed investment decisions. Uncertainty introduces both market risks and opportunities, and flexible investment decisions can better adapt to market and technological changes.

Table 3. Investment decisions under different strategies.

	Strategy Type	Optimal Investment Time (yr)	Best Investment Value (CNY Million)
No carbon and emissions trading	Invest immediately	Not recommended for investment	−1545
	Deferred Options	Not recommended for investment	−1200.4
Carbon trading exists	Invest immediately	Not recommended for investment	−199
	Deferred Options	10th year	64.8
Pollution right trading exists	Invest immediately	Not recommended for investment	−878
	Deferred Options	Not recommended for investment	−695
With carbon and emissions trading	Invest immediately	Invest immediately	321
	Deferred Options	10th year	462

When only considering the carbon trading mechanism or the pollution right trading mechanism, the optimal investment value of the project is −199 million CNY and −878 million CNY, respectively, both of which are lower than zero and therefore not recommended for investment. However, when considering both carbon trading and pollution right trading mechanisms, the project can profit 321 million CNY and is advised to be invested invest immediately. A deeper analysis of these results reveals two critical features of influence. First, we observe a powerful synergistic effect between the two market mechanisms; their combined impact is not merely additive but multiplicative. Carbon trading directly values the avoided cost of future carbon liabilities, while pollution right trading monetizes the co-benefit of reduced local air pollutants. This creates two parallel revenue streams, diversifying the project’s income and significantly de-risking it against the volatility of any single market. The model quantitatively demonstrates that this synergy is the key to unlocking positive economic value, transforming CCUS from a cost center into a potential profit center.

From the perspective of flexible investment, the optimal value of the project is increased in all cases. However, the project investment can generate profit only when the carbon trading mechanism or both carbon trading mechanism and pollution right trading mechanism are supported, which is 64.8 million CNY and 462 million CNY, respectively.

This leads to the second pivotal feature: the intrinsic value of managerial flexibility, as captured by the real options approach. The consistent superiority of the deferred option strategy underscores that the ability to “wait and see” is a valuable strategic asset in its own right. In unprofitable scenarios, this flexibility prevents certain losses. In marginally profitable scenarios, it represents the premium for bearing uncertainty and waiting for more favorable conditions. In the optimal scenario, it allows the investor to capture the most advantageous price paths over time. This fundamentally challenges the static decision-making of traditional NPV analysis.

The real options approach demonstrates high value in decision-making, highlighting the complexity of investment decisions under carbon trading and emission rights trading mechanisms. Carbon trading features a relatively more developed market mechanism and more objective capture metrics, offering greater investment value for CCUS. Under

carbon trading, CCUS gains increased attention. Emission rights trading can provide some economic value to projects; however, due to technical limitations, the total amount of captured pollutants is low, and monitoring emission and trading volumes accurately is challenging. Consequently, the direct effects of emission rights trading are limited. This insight offers guidance for policy formulation, emphasizing the need to robustly develop the carbon trading market, encourage technological breakthroughs related to emission rights trading, and promote the implementation of related policies to expand the emission rights trading market. Only with specific support mechanisms in place can projects benefit economically, providing new pathways for environmental protection. Hypotheses 1 and 2 are supported.

The results in Table 4 provide important implications for government management. If investors do not consider the environmental benefits of constructing CCUS, they are unlikely to choose to invest under the real options approach, even with a carbon trading mechanism in place. Investors' decisions are influenced not only by economic returns but also by the degree of attention given to environmental benefits. In the absence of one-time government subsidies, environmental policies introduced by the government or social awareness raised through public education can guide companies to voluntarily consider the environmental benefits of their projects. Non-economic policies can also promote the implementation of emission reduction technologies. Hypotheses 3 is supported.

Table 4. Optimal investment decisions with/without carbon trading in the absence of environmental benefits.

	With/Without Carbon Trading	Optimal Investment Time (yr)	Best Investment Value (CNY Million)
Disregard for environmental benefits	With carbon trading	Not recommended for investment	−63
	Without carbon trading	Not recommended for investment	−1283.7

4.4. Sensitivity Analysis

This subsection conducts a sensitivity analysis to examine the impact of different investment contexts on the optimal value and timing of investment decisions. The analysis considers changes in government investment subsidies, the price of carbon trading, and the extent of carbon dioxide capture and utilization of CCUS under pollution right trading. Sensitivity analysis of these factors provides a more comprehensive understanding of the extent to which particular variables affect investment decisions in different contexts. This analysis helps provide decision-makers with more precise information, enabling them to better understand the risks and opportunities of investment decisions, and thus make more informed strategic choices.

4.4.1. Impact of Carbon Trading Prices on Decision-Making

Figure 4 presents the recommended timing for investing in CCUS under different initial carbon trading prices. The carbon trading market plays a crucial role in investment timing decisions, and the level of carbon trading prices directly affects the final returns on investment. When companies do not participate in emission rights trading, a carbon trading price of 90 CNY can reduce the optimal investment time to 9 years. Under the combined influence of emission rights trading, the initial carbon trading price has a significant impact on investment decisions. When the initial carbon trading price is below 75 CNY, the investment returns are relatively slow, and it is recommended to invest in the 10th year. When the initial carbon trading price exceeds 75 CNY, the investment waiting time shortens

as the initial carbon trading price increases. Notably, when the carbon trading price reaches 95 CNY, immediate investment is recommended, as higher carbon trading prices lead to quicker returns and more sensitive investment timing.

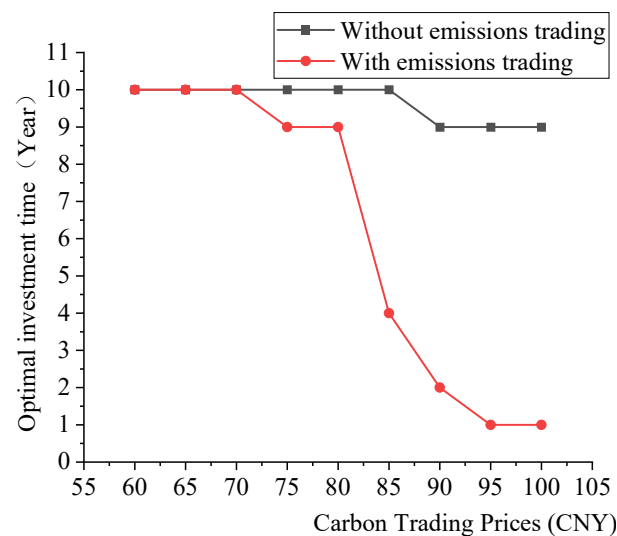


Figure 4. Optimal investment time under different carbon trading initial prices with/without pollution right trading.

This finding provides valuable references for decision-making and related industries regarding carbon reduction and climate change responses. With diversified market mechanisms, CCUS retrofitting becomes more attractive. When considering investing in CCUS low-carbon retrofitting technology, it is essential to pay attention to the dynamics of the carbon market and pollution right trading market to seize investment opportunities. For the government, the factors influencing carbon trading prices are multifaceted, primarily including market factors, environmental factors, and policy factors. The total carbon quota is determined by the carbon trading regulatory agency, which also sets the initial level of carbon trading prices. Establishing a scientifically reasonable carbon trading price requires clear direction and support from the government at the policy level, along with a deeper understanding of the essence and operational mechanisms of carbon finance by financial institutions. It is crucial to focus on the completeness and transparency of the system to ensure the healthy functioning of the market.

4.4.2. Impact of Government Subsidy Policy on Decision-Making

The conclusions drawn in Section 4.3 indicate that, without considering government subsidies for investment costs, projects employing carbon trading and real options approaches can achieve marginal profits in the last year of the effective investment period, suggesting investment renovations at that point. However, with only pollution right trading in place, projects remain unprofitable under both fixed investment and real options methods, advising against renovations within the investment period. When implementing carbon trading and pollution right trading simultaneously, the real options method recommends renovations in the ninth year of the investment period.

Analysis results, as depicted in Figure 5, reveal a critical insight. Without carbon trading and pollution right trading, the government's one-time cost subsidy fails to encourage decision-makers to invest early in the investment period. This reluctance is due to the high operational costs associated with CCUS. Only when the government fully subsidizes the project's cost can the project earn a meager profit during the operation period. In the case of carbon trading, when the government subsidy ratio reaches 70%, the optimal

investment return of the project reaches 1010 million CNY, and it is recommended to invest in the 8th year, while when the government subsidy ratio gradually increases to 100%, it is recommended that the investor invests immediately.

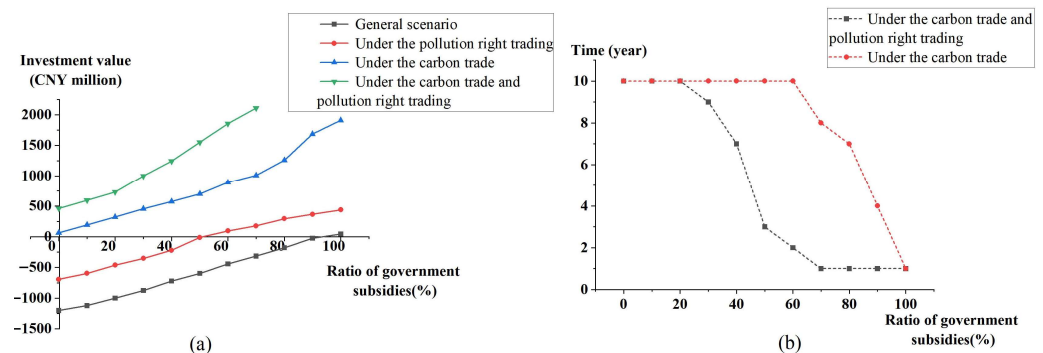


Figure 5. Impact of government subsidies on (a) optimal investment value and (b) investment timing under different scenarios.

In the scenario with only pollution right trading, when the government subsidy ratio reaches 60%, the optimal value of the investment reaches 95 million CNY, and it is recommended to invest in the 10th year. The expected optimal investment value of the project increases gradually as the government subsidy ratio increases, but in this scenario, the government subsidy is not enough to support the investor to invest in the project in advance of construction. However, when carbon trading and pollution right trading are conducted simultaneously, the government subsidy will significantly increase the optimal investment value of the project, attracting investment decision-makers to make investment decisions more quickly. When the proportion of government subsidies reaches 30%, it starts to push investors to invest in CCUS earlier, and as the government policy subsidies increase, the investment waiting time decreases significantly. When the proportion of government investment subsidies reaches 70%, it is recommended that investors invest immediately in the first year. The results of these analyses emphasize the importance of government subsidies provided in carbon capture projects for project investment decisions.

4.4.3. Carbon Capture and Utilization Ratio Impacts on Decision-Making

Figure 6 shows the impact of varying carbon capture and utilization ratios on the optimal investment value. When the carbon utilization rate is 20%, increasing the capture rate results in higher capture and operating costs. The growth rate of revenue from carbon utilization is slower than the cost increase, leading to a decline in the project's optimal value. However, as the utilization rate increases, the optimal investment value of the project gradually rises, particularly at high capture rates, where the increase in optimal investment value is more significant.

Capturing carbon dioxide for enhanced oil recovery can increase the revenue of CCUS investors [58]. However, higher carbon capture rates not only imply more significant emission reduction effects but also entail higher investment and operational costs. Current advanced solvent-based carbon capture technologies are designed for post-combustion flue gas and can theoretically achieve over 95% CO₂ capture efficiency. This means that most CO₂ emissions can be efficiently captured from combustion processes using this technology. However, coal-fired power plants, as sources of low-purity carbon emissions, incur capture costs that include increasing carbon concentration and reducing other component concentrations to meet pipeline standards. As a result, the actual capture rate is challenging to reach theoretical values, and capture costs are high. Consequently, increasing the capture rate leads to higher investment and operational costs.

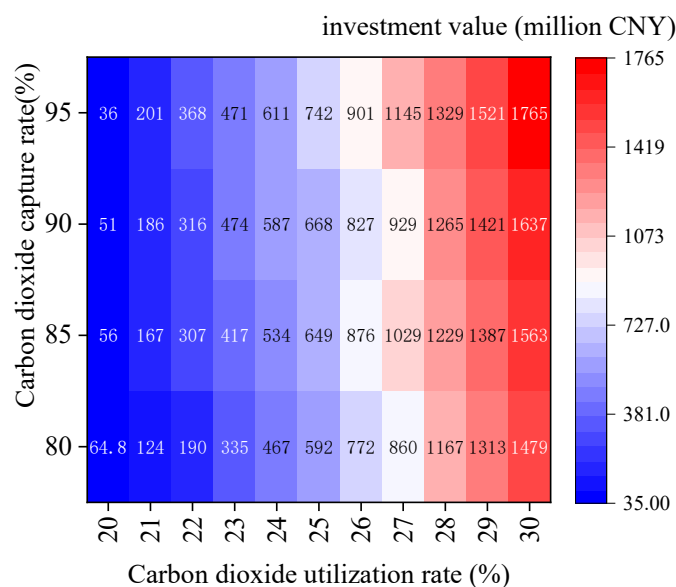


Figure 6. Effect of carbon capture rate and utilization ratio on optimal value.

Furthermore, the utilization rate of CO₂ significantly affects the project's economic benefits. In the model, the CO₂ utilization revenue is calculated based on a specified mix of applications: enhanced oil recovery (EOR, 60%), food-grade use (30%), and industrial-grade use (10%). Increasing the CO₂ utilization rate can enhance the revenue from CO₂ trading and utilization, thus improving the overall economic viability of the project. However, in practice, the utilization rate of CO₂ is often less than 30%, necessitating considerable storage costs for transporting and sequestering CO₂. As CCUS advances, improvements in carbon capture efficiency and reductions in costs will substantially alleviate the financial burden of CCUS. Exploring the potential for industrial CO₂ utilization is also one of the key directions for promoting the implementation of CCUS.

5. Conclusions

This paper investigates the investment decision-making for CCUS retrofits in coal-fired power plants in the context of fluctuations in market electricity prices, carbon trading prices, coal prices, and unit investment costs. The study provides a methodological contribution by demonstrating the efficacy of the LSM method in solving high-dimensional real options problems under complex policy uncertainties. Theoretically, it extends the real options framework by integrating and quantifying the synergistic value of multiple market-based mechanisms (carbon and pollution right trading) alongside non-market environmental benefits—a critical dimension often overlooked. These findings offer actionable insights for policymakers to design synergistic emission reduction strategies and for investors to navigate the evolving energy landscape. The research findings indicate that, in the absence of carbon trading and pollution right trading mechanisms, investing in CCUS within the effective period leads to significant cost losses, even when considering environmental benefits. Using the real options method to delay investments can mitigate these losses but still results in unprofitable outcomes. Therefore, under such conditions, investing in CCUS is not recommended. Moreover, without additional government financial subsidies, the real options method shows that investments in CCUS incur losses when only carbon trading or pollution right trading mechanisms are present. The absence of carbon trading support, with only pollution right trading, results in even greater losses. However, considering both mechanisms simultaneously and investing just before the end of the investment period yields the highest benefits. Sensitivity analysis revealed the critical role of government

subsidies in enhancing investment incentives for CCUS, which can shorten the waiting period for investments. Additionally, higher initial carbon trading prices are found to favor CCUS investments, and higher utilization rates significantly increase the optimal investment value.

In summary, this study delivers comprehensive theoretical and practical contributions. Theoretically, it provides a novel and quantifiable real options framework that captures the critical, non-linear synergies between multiple environmental policies—a significant advancement for the investment literature on low-carbon technologies. Practically, it offers clear guidance: for policymakers, our model underscores the necessity of implementing integrated carbon and pollution right markets and calibrating subsidies to trigger investment; for investors, it provides a decision-support tool to identify precise investment thresholds (e.g., the ~95 CNY/t carbon price) under uncertainty. These insights are crucial for de-risking CCUS investments, aligning financial incentives with China’s macro-level emission goals, and ultimately facilitating a sustainable energy transition.

This paper can be improved in the following aspects: (1) Refining the model formulation by incorporating more realistic stochastic processes (e.g., mean-reverting models), introducing empirical correlations among key variables, and enhancing statistical robustness through reporting confidence intervals and distributions of optimal stopping times; (2) Relaxing modeling assumptions by systematically evaluating the impact of simplifications—such as zero transaction costs and full-load operation—through the introduction of stochastic capacity factors and transaction cost functions; (3) Expanding decision behavior research by delving into the influence mechanisms of investor preferences and behavioral factors on CCUS investment decisions.

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