Investment Decisions of CCUS Projects in China Considering the Supply–Demand Relationship of CO₂ from the Industry Symbiosis Perspective

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Abstract: Carbon capture, utilization, and storage (CCUS) technology is vital for China to achieve its carbon neutrality goal. However, the high cost of CCUS projects, multiple processes, and insufficient policy support make it difficult for firms to invest independently. As an innovative way to achieve waste resource utilization, industrial symbiosis can effectively break through this dilemma. Based on the real options theory, this study establishes decision models for independent investment in a carbon capture and storage project by a coal-fired power plant (CFPP) and independent investment in an enhanced oil recovery project by an oil company. Then, from the perspective of industrial symbiosis, the decision models of cooperative investment in a CCUS project by a CFPP and an oil company are constructed. The models consider the supply–demand relationship of CO₂, the correlation between carbon and oil prices, and technological uncertainty. The differential equation method is used to solve the models to obtain the investment thresholds and option values. Finally, all models are applied to a CCUS project in Guangdong Province, China, for simulation analyses. Based on the simulation results of the CCUS project in Guangdong Province, our major findings are as follows: (1) Industrial symbiosis can effectively promote the development of CCUS projects. Compared with the independent investment mode, industrial symbiosis reduces the investment threshold of the project by at least 25.42% and increases the option value by at least 12.94%. (2) It is more likely to trigger the project’s investment when CO₂ supply and demand are balanced. The CCUS project’s investment threshold increases with the imbalance between CO₂ supply and demand. (3) Stable carbon and oil prices can promote the project’s investment, and increasing the positive correlation coefficient of the prices will increase the project’s investment threshold.

Keywords: industrial symbiosis; CCUS; real options; investment decisions; coal-fired power plants

1. Introduction

China is the largest emitter of carbon emissions globally and has committed to achieving carbon peak by 2030 and carbon neutrality by 2060 [1]. The power sector in China emits more than 40% of the country’s total carbon emissions, which primarily come from coal-fired power plants (CFPPs) [2]. Therefore, it is crucial to promote the low carbon transition of CFPPs for achieving carbon neutrality. China’s energy structure determines that CFPPs cannot be replaced in the short term. Thus, it is necessary to develop the carbon capture, utilization, and storage (CCUS) technologies [3]. CCUS refers to the capture and separation of CO₂ from energy use, industrial production, and other sources for transport to a suitable site for utilization or storage to reduce CO₂ emissions [4]. The technology is essential for CFPPs to advance decarbonization operations. According to the China CCUS Annual Report 2023, CFPPs are expected to reduce 1 billion tons of CO₂ emissions using CCUS by 2060 [5].

China’s CCUS projects have developed rapidly in recent years, with significant increases in number and scale, but are mainly concentrated in the power and oil sectors [6].
For instance, CFPPs independently invest in carbon capture and storage (CCS) retrofit projects, and oil companies independently invest in enhanced oil recovery (EOR) projects. There is a lack of cross-industry cooperative investment in CCUS projects [7]. Therefore, CCUS development in China is slow, and a large gap exists in contrast to some developed countries. Specifically, the emissions reduction capacity of CCUS in China is only one-tenth that of the United States [6]. However, by establishing industrial symbiosis with oil companies, CFPPs can advance the high-value use of CO$_2$ and lower the investment thresholds for CCUS projects to increase investment value [8]. Considering the multiple uncertainties of policy, market, and technology that CCUS projects incur in investment and construction processes [9], this study investigates the CCUS project investment decisions from the industrial symbiosis perspective under multiple uncertainties. The findings provide insights to facilitate the overall efficient development of CCUS projects, promote the low-carbon transformation of CFPPs, and advance China’s dual-carbon goals.

Industrial symbiosis promotes cross-industry use of waste, energy conservation, and synergistic control of multiple pollutant emissions, which is an essential breakthrough in industrial energy conservation and emissions reduction [10]. An example of industrial symbiosis is the collaboration between CFPPs and cement companies. During production, CFPPs produce large amounts of solid waste, such as fly ash and desulphurization gypsum. These wastes are then used as raw materials in cement production to replace cement clinker. Thus, it would reduce high levels of carbon emissions [11]. Industrial symbiosis has proven to produce significant environmental and economic benefits. The internal rationale for forming industrial symbiosis is to promote continuity in the industrial chain, and the external rationale is that the industrial chain can promote value appreciation [12]. CFPPs are the primary source of CO$_2$ capture, and oil companies are responsible for the most advanced CO$_2$ utilization technology in oil recovery. The two can collaborate to ensure industrial chain continuity, advance CO$_2$ reuse, realize the geological storage of CO$_2$, and enhance the economic and environmental value of CCUS projects. Therefore, CFPPs and oil companies can establish symbiotic industrial relationships to cooperate and invest in CCUS projects for effective CO$_2$ utilization and reduced environmental pollution.

However, most existing studies focus on CFPPs as the main body to study the problems related to the investment decision of CCUS projects. There is a lack of studies on the cooperative investment of CCUS projects by CFPPs and oil companies from the industrial symbiosis perspective. Therefore, this study explores the CCUS project investment decision-making process under multiple uncertainties, such as carbon price, oil price, and technological advancement, from the industrial symbiosis perspective. Firstly, independent investment decision models are constructed for a CFPP’s CCS project and an oil company’s EOR project. Then, this study develops investment decision models for a CCUS project considering the supply–demand relationship of CO$_2$ from the perspective of industrial symbiosis, by solving the models to obtain the investment thresholds and option values. Finally, these models are applied to an active CCUS project in Guangdong Province, China, to validate our approach.

The main contributions of this study can be summarized as follows. Firstly, this study constructs an investment decision model for CCUS projects from the perspective of industrial symbiosis between a CFPP and an oil company. The study then compares the results of investment decisions under independent and cooperative investment modes to quantify the value that industrial symbiosis brings to the project. Secondly, this study incorporates the supply–demand relationship of CO$_2$ into the investment decision models of the CCUS project to study the impacts of industrial symbiosis on the project’s investment decision. Finally, this study provides a scientific framework for evaluating the investment thresholds and option values in the CCUS project investment process, considering market, technology, policy, and other uncertainties. Therefore, this study helps to encourage enterprises to realize cost savings and low-carbon transition through industrial symbiosis and promote the development of CCUS projects.
2. Literature Review

As an innovative approach to waste resourcing, industrial symbiosis can promote green economic growth and resource efficiency. Industrial symbiosis practices have been found to create good economic, environmental, and social benefits. It is an essential way to promote sustainable development. Therefore, it is crucial to analyze the potential benefits of industrial symbiosis. Jacobsen quantified and analyzed the environmental and economic benefits generated by industrial symbiosis in the Kalundborg industrial ecosystem [13]. Chertow and Miyata used industrial symbiosis in the Guayama region of Puerto Rico as a case study, quantifying reductions in \( \text{SO}_2 \), \( \text{NO}_x \), \( \text{PM}_{10} \), and other pollutants, and lowering enterprises’ operating costs [14]. Sokka et al. evaluated the potential environmental benefits of industrial symbiosis in a forest industrial complex in Finland [15]. Investigating an industrial park, Fan et al. found that industrial symbiosis increased the park’s sustainable development capacity by 33%, saving non-renewable resource inputs, imported resource inputs, and related services at rates of 99.71%, 26.54%, and 9.82%, respectively [16]. Based on the industrial symbiosis perspective, Su examined the impact of manufacturing and logistics symbiosis on manufacturing enterprises’ productivity, revealing that the degree of coupling coordination between the two has a significant positive impact [17]. Cao and Xiao explored manufacturing companies’ investment decisions under the carbon trading mechanism from the perspective of industrial symbiosis, demonstrating that industrial symbiosis is beneficial to companies’ long-term development [18]. These studies show that establishing industrial symbiosis in different industries can improve economic, environmental, and social benefits. However, limited research has examined the industrial symbiosis between CFPPs and oil companies and the economic benefit of industrial symbiosis in cooperative CCUS projects. The methodologies used in previous research efforts provide a reference for examining CCUS projects’ investment values from the industrial symbiosis perspective.

Numerous uncertainties are associated with current CCUS development, and relevant investors are still hesitant to invest in CCUS projects. Therefore, an empirical project value assessment can help guide investors to make sound investment decisions. Li and Xu constructed a complete cost–benefit estimation model to evaluate the CCS project economy, establishing a foundation for project investment evaluation [19]. Wu et al. employed the net present value method to determine the critical carbon price of Chinese CFPPs’ investing in CCUS projects of 72 USD/ton [20]. Renner compared the economic feasibility of CCS project investment in the EU and China using levelized electricity costs, determining that the critical carbon prices for CCUS investment in the EU and China are 25 EUR/ton and 35 EUR/ton, respectively [21]. Liu et al. established a balanced power cost model to evaluate the economic benefits of retrofitted CFPPs’ CCS projects, comparing the economic competitiveness of retrofitted CFPPs with other types of power plants [6]. Based on the whole life cycle theory, Han et al. analyzed investment costs and economic benefits at each stage of CFPPs’ CCUS projects [22]. Notably, the investment analysis methodologies used in previous studies failed to capture the impact of various uncertainties on CCUS project investment decisions.

CCUS project investment includes market, policy, technology, and other uncertainties. Zhou et al. established a real options (RO) model to consider uncertain stochastic carbon price. The model was built to determine the optimal investment strategy for a CCS project and analyze the impact of climate policy on the decision-making process [23]. Zhu and Fan established an RO model considering uncertainties of thermal power generation cost, carbon price, technology investment costs, and other factors to evaluate CCS projects’ investment benefits and environmental impact [24]. Elias et al. also used the RO model, revealing a critical carbon price for investments in post-combustion carbon capture technology and oxygen-rich combustion carbon capture technology in CFPPs at 140 USD/ton and 185 USD/ton, respectively [25]. Yao et al. established an investment decision model including energy price, carbon price, and policy fluctuation uncertainties based on the RO theory, revealing that investment can only be economically feasible by increasing carbon prices under current market and policy conditions [26]. Yang et al. constructed a trinomial tree
RO model to evaluate Chinese CFPPs’ investment decisions regarding CCUS projects under different coal prices and subsidies [27]. Based on the RO theory, Wang and Du constructed a CCUS project investment decision model considering carbon trading price uncertainty and decreasing CCUS investment cost and determined CFPPs’ investment option value and optimal investment opportunity based on a numerical simulation of different CO₂ usage rates [28]. The above studies analyzed CCUS project investment decisions employing the RO theory, which considers various uncertainties that arise in the CCUS project investment process, considering the value flexibility of investments. However, the previous studies are all based on the perspective of independent investment by enterprises. There is a lack of studies on the potential cooperation between different industries from industrial symbiotic perspective when investing in CCUS projects.

The remainder of this study is organized as follows. Section 2 analyzes the costs and benefits of projects under the independent and cooperative investment modes, constructs the value functions considering the supply–demand relationship of CO₂, and solves for the project’s investment thresholds and option values. Section 3 examines how industrial symbiosis can contribute to the CCUS project’s development using the data from a CCUS project in Guangdong Province, China. Section 4 presents some conclusions and recommendations based on the findings of this study.

3. Methodology

This study first constructs investment decision models for a CFPP’s independent investment in a CCS project and an oil company’s independent investment in an EOR project, and develops investment decision models for a cooperative CCUS project from the perspective of industrial symbiosis.

Figure 1 presents the activity flow of the projects and CO₂ transfer pathways under different investment modes [22]. Under the independent investment mode, CCS projects include CO₂ capture, transportation, and storage; EOR projects include CO₂ purchase and utilization. Under the cooperative investment mode, CCUS projects include the whole process from CO₂ capture to utilization.

![Figure 1. The activity flow and the CO₂ transfer path of projects.](image)

3.1. Independent Investment Mode

Under the independent investment mode, the CFPP independently invests in the CCS project, captures the CO₂ produced during power generation through a CCS, and is responsible for transporting the CO₂ for storage. The oil company independently invests in the EOR project to improve oil recovery by injecting CO₂ into oil wells to drive oil.
3.1.1. CFPP

This section analyzes the investment cost and benefits of the CCS project and determines the investment threshold and option value of the project.

1. Investment cost

The investment costs of the CCS project include the initial investment cost, the transportation cost for CO$_2$, and the storage cost for CO$_2$.

Considering the impact of technological progress, the initial investment cost for the CCS project will decrease over time, based on the learning curve effect [23,24,29]. The initial investment cost for CCS considering the technological progress rate can be calculated by the following formula:

$$ I_{CCS}^t = I_{CCS}^0 \cdot e^{-\alpha t} $$

(1)

where $I_{CCS}^0$ denotes the initial investment of the CCS project, $\alpha$ is the CCS technological progress rate.

The amount of CO$_2$ captured from the CFPP is related to the CFPP’s characteristics [30,31]. And it can be expressed as follows:

$$ Q_{CCS}^t = \phi \cdot IC \cdot RT_t \cdot EF \cdot CR $$

(2)

where $Q_{CCS}^t$ is the amount of CO$_2$ captured from the CFPP, ton; $\phi$ is the coal-fired unit’s efficiency; $IC$ denotes the coal-fired unit’s installed capacity, MW; $RT_t$ denotes the CFPP’s annual operating time in year $t$; $EF$ denotes the CFPP’s carbon emissions factor, g/kWh; and $CR$ denotes carbon capture efficiency [32,33].

The transportation cost for CO$_2$ of the CCS project in year $t$ can be calculated by the following formula:

$$ C_{CCS}^{tra}_t = UC_{tra} \cdot Q_{CCS}^t $$

(3)

where $UC_{tra}$ is the unit transportation cost for CO$_2$, USD/ton.

The CO$_2$ storage cost for CO$_2$ of the CCS project in year $t$ can be calculated by the following formula:

$$ C_{CCS}^{sto}_t = UC_{sto} \cdot Q_{CCS}^t $$

(4)

where $UC_{sto}$ is the unit storage cost for CO$_2$, USD/ton.

2. Investment benefit

CCS project investment benefits include carbon trading benefits and investment subsidies. Carbon trading benefits refer to the reduced carbon emissions fees paid by the CFPP from capturing the CO$_2$ produced during production processes through the CCS. This benefit is obtained through the carbon price, which is influenced by the carbon market. Carbon trading price dynamics can be determined using geometric Brownian motion (GBM) [24,34,35], as follows:

$$ dP_t^c = \mu_c P_t^c dt + \sigma_c P_t^c dz_t \quad (P_0^c \equiv P_c) $$

(5)

where $P_t^c$ is the carbon trading price in year $t$, USD/ton; $\mu_c$ and $\sigma_c$, respectively, denote carbon trading price drift and volatility rates, $dz_t$ is the increment of a standard Wiener process, and $P_0^c$ is the initial carbon trading price [36].

The carbon trading benefits of the CCS project in year $t$ can be expressed as follows:

$$ \pi_{t}^{CCS,CO2} = Q_{t}^{CCS} \cdot P_c $$

(6)

Because the initial investment cost for the CCS project is extremely high, government support is the primary funding source to encourage the CFPP’s investment [37,38]. The investment subsidy for the CCS project can be expressed as:

$$ S_t^{CCS} = K_1 \cdot I_{t}^{CCS} $$

(7)
where $K_1$ is the investment subsidy ratio for the CCS project.

3. Investment option value

After carefully considering the costs and benefits outlined above, and disregarding the construction timeline, we calculated the expected value of the CFPP’s investment in the CCS project, assuming an operation time of $T_1$ years after CCS project implementation. The expected value of the CCS project is represented by $\phi_{CCS}$, as indicated by the following equation.

$$
\phi_{CCS} = E\left[\int_{t}^{t+T_1} (\pi_{t}^{CCS, co2} - C_{t}^{CCS, tra} - C_{t}^{CCS, sto}) e^{-r(f-t)} df - (1 - K_1)I^{CCS}_t \right]
$$

The CFPP’s CCS project investment is similar to a time-continuous call option in the US. The CFPP can determine the best time to invest by maximizing the value of the investment option [39]. The CCS project’s investment option value is represented by $F_{CCS}(P_c)$, which is considered the value of the underlying asset. Referencing Dixit’s analysis and the process of determining the option value, we construct the following second-order chi-squared linear differential equation [40]:

$$
\frac{1}{2} \sigma^2_c (P_c)^2 F''_{CCS} + \mu_c P_c F'_{CCS} - r F_{CCS} = 0
$$

According to the basic theory of differential equations, its generalized form is expressed as a linear combination of two roots to the power as follows:

$$
F_{CCS}(P_c) = A_1 (P_c)^{\omega_1} + A_2 (P_c)^{\omega_2}
$$

where $A_1$ and $A_2$ are constants determined by the boundary conditions. $\omega_1$ and $\omega_2$ are the positive and negative roots of the standard quadratic equation, respectively, the formula for which is as follows:

$$
\begin{cases}
\omega_1 = \frac{1}{2} - \frac{\mu_c}{\sigma_c^2} + \sqrt{\left(\frac{\mu_c}{\sigma_c^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma_c^2}} \\
\omega_2 = \frac{1}{2} - \frac{\mu_c}{\sigma_c^2} - \sqrt{\left(\frac{\mu_c}{\sigma_c^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma_c^2}}
\end{cases}
$$

where $P_c^*$ denotes the CCS project’s investment threshold, and the boundary condition constraint is as follows:

$$
\begin{cases}
F_{CCS}(0) = 0 \\
F_{CCS}(P_c^*) = \phi_{CCS}(P_c^*) \\
F'_{CCS}(P_c^*) = \phi'_{CCS}(P_c^*)
\end{cases}
$$

where $F_{CCS}(0) = 0$ indicates that, when the carbon trading price is 0, the CCS project’s investment option for the CFPP will signal a non-execution, meaning that the option value is 0. The value matching condition, $F_{CCS}(P_c^*) = \phi_{CCS}(P_c^*)$, derived from the continuity in the dynamic planning problem, indicates that the investment option value and expected value of the CCS project are equal at the investment threshold. The smooth pasting condition $F'_{CCS}(P_c^*) = \phi'_{CCS}(P_c^*)$ requires that the derivatives of the two functions, the investment option value of the CCS project and the expected value of the project investment, are also equal at the investment threshold.

Based on Equation (11), if $\omega_2 < 0$ and $P_c$ approaches 0, then the value of the CCS project investment option will tend to be 0, meaning that the value should be equal to 0.

Therefore, we can conclude the following:

$$
F_{CCS}(P_c) = A_1 (P_c)^{\omega_1}
$$
where $P^*_c$ and $A_1$ are obtained by solving for the boundary constraints as follows:

$$
P^*_c = \frac{\omega_1}{\omega_1 - 1} \cdot \frac{r - \mu_c}{Q_t^{CCS} (1 - e^{-rT_1})} \cdot \left( 1 - K_1 \right) \cdot \frac{r_f^{CCS} + C^{CCS,tra}_t + C^{CCS,sto}_t}{r} \cdot (1 - e^{-rT_1})$$

(14)

$$
A_1 = \frac{\left( P^*_c \right)^{\omega_1 - 1}}{\omega_1} \cdot Q_t^{CCS}
$$

(15)

Therefore, $F_{CCS}(P_c)$ is as follows:

$$
F_{CCS}(P_c) = \begin{cases} 
A_1(P_c)^{\omega_1} & P_c < P^*_c \\
\frac{\pi_t^{CCS,co}}{r - \mu_c} \cdot (1 - e^{-rT_1}) + (1 - K_1) I_t^{CCS} - \frac{C^{CCS,tra}_t + C^{CCS,sto}_t}{r} \cdot (1 - e^{-rT_1}) & P_c \geq P^*_c 
\end{cases}
$$

(16)

### 3.1.2. Oil Company

This section analyzes the cost and benefits of the oil company’s EOR project and calculates the investment threshold and option value.

1. Investment cost

The investment costs of the EOR project include the initial investment cost, the purchase cost for CO$_2$, and the transportation cost for CO$_2$ [41,42].

The initial investment cost for EOR considering the technological progress rate can be calculated by the following formula [43–45]:

$$
I_t^{EOR} = I_0^{EOR} \cdot e^{-\beta t}
$$

(17)

where $I_0^{EOR}$ denotes the initial investment cost, and $\beta$ is the EOR technological progress rate [41].

After the oil company invests in the EOR project, the oil company must purchase the amount of CO$_2$ needed to support the company every year. The purchase cost for CO$_2$ in year $t$ is calculated as follows:

$$
C_t^{EOR,pur} = U_{C_pur} \cdot Q_t^{EOR}
$$

(18)

where $U_{C_pur}$ is the unit purchase cost for CO$_2$, USD/ton; $Q_t^{EOR}$ is the amount of CO$_2$ purchased in year $t$, ton.

The transportation cost for CO$_2$ in year $t$ is calculated as follows:

$$
C_t^{EOR,tra} = U_{C_{tra}} \cdot Q_t^{EOR}
$$

(19)

2. Investment benefit

The investment benefits of the EOR project include the oil trading benefits and the investment subsidies.

Oil trading benefits refer to the revenue generated by the oil company through the improved oil recovery rate that is achieved by injecting CO$_2$. This benefit is calculated based on oil price, which is affected by the oil market. Previous research has shown that oil price dynamics can be described using GBM [30,38,41], as shown in the following formula:

$$
dP_t^o = \mu_o P_o dt + \sigma_o P_o dz_o \quad (P_0^o \equiv P_0)
$$

(20)

where $P_t^o$ is the oil price in year $t$, $\mu_o$ and $\sigma_o$, respectively, denote oil price drift and volatility rates of oil, $dz_o$ denotes the increment of the standard Wiener process, and $P_0^o$ is the initial oil price.

The oil trading benefits of the EOR project in year $t$ can be expressed as follows:

$$
\pi_t^{EOR,oil} = H \cdot Q_t^{EOR} \cdot P_o
$$

(21)
where $H$ is the incremental proportion of the oil drive [46,47].

Due to the high initial investment cost for the oil drive system, the oil company relies heavily on government support to encourage EOR project investment. The investment subsidy provided by the government in year $t$ is calculated as follows:

$$S_{t}^{EOR} = K_{2} \cdot I_{t}^{EOR}$$  \hspace{1cm} (22)

where $K_{2}$ represents the EOR project’s investment subsidy ratio.

3. Investment option value

The operation time of the EOR project is $T_{2}$ years. And the expected value of the EOR project is represented by $\phi_{EOR}$, which can be determined as follows:

$$\phi_{EOR} = E\left[\int_{t}^{t+T_{2}} \left(\pi_{t}^{EOR,oil} - C_{t}^{EOR,pur} - C_{t}^{EOR,tra} \right) e^{-r(f-t)} df - (1 - K_{2})I_{t}^{EOR}\right]$$  \hspace{1cm} (23)

The EOR project’s investment option value is represented by $F_{EOR}(P_{o})$ and $P_{o}^{*}$ denotes the EOR project’s investment threshold. Similar to the steps used to determine the investment option value for the CCS project in Section 3.1.1, the results of the solution are as follows:

$$P_{o}^{*} = \frac{\psi_{1}}{\psi_{1} - 1} \cdot \frac{r - \mu_{o}}{H \cdot Q_{i}^{EOR}(1 - e^{-rT_{2}})} \cdot \left(1 - K_{2}\right) \frac{I_{t}^{EOR} + C_{t}^{EOR,tra} + C_{t}^{EOR,pur}}{r} \cdot \left(1 - e^{-rT_{2}}\right)$$  \hspace{1cm} (24)

$$F_{EOR}(P_{o}) = \begin{cases} B(P_{o})^{\frac{1}{\psi_{1}}} P_{o} < P_{o}^{*} \frac{n^{EOR,oil}}{r - \mu_{o}} \cdot \left(1 - e^{-rT_{2}}\right) + (1 - K_{2})I_{t}^{EOR} - \frac{C_{t}^{EOR,tra} + C_{t}^{EOR,pur}}{r} \cdot \left(1 - e^{-rT_{2}}\right) P_{o} < P_{o}^{*} \\ B \cdot \frac{(P^{*})^{\frac{1}{\psi_{1}}} - 1}{\psi_{1}} \cdot H \cdot Q_{i}^{EOR}(1 - e^{-rT_{2}}) \end{cases}$$  \hspace{1cm} (25)

where $B = \left(\frac{(P^{*})^{\frac{1}{\psi_{1}}} - 1}{\psi_{1}} \cdot H \cdot Q_{i}^{EOR}(1 - e^{-rT_{2}}) \right)$.

3.2. Cooperative Investment Mode

The CFPP and the oil company form an industrial symbiosis and collaborate to invest in the CCUS project, where the former is responsible for capturing the CO$_{2}$ generated by its production activities, and the latter uses the CO$_{2}$ captured by the former to enhance oil recovery, reusing the captured CO$_{2}$.

Compared with the independent investment mode, two differences occur in the cooperative investment mode under the industrial symbiosis perspective. First, the cooperative investment mode reduces CO$_{2}$ storage and purchase cost, which lowers the project’s total investment cost [48]. Second, the investment return of the cooperative investment mode is determined using carbon trading and oil prices; therefore, CCUS project investment is subjected to the simultaneous influence of the carbon trading and the oil markets, with a positive correlation. According to the portfolio theory, the correlation of the influencing factors can reduce investment risks [8].

Under the cooperative investment mode, when the supply and demand of CO$_{2}$ are balanced, the amount of CO$_{2}$ captured by the CFPP matches the oil company’s requirements. The investment cost for the CCUS project includes the initial investment cost and the cost of transporting captured CO$_{2}$. The investment benefits include profits from carbon trading, oil sales, and subsidies provided by the government. Notably, an imbalance can occur between the supply and demand of CO$_{2}$ because the scale of the CFPP and the oil company are fixed. As a result, the amount of CO$_{2}$ captured may not meet or could exceed the oil company’s requirements, which can increase the CCUS project’s investment costs compared with the case in which CO$_{2}$ supply and demand are balanced. Therefore, this study examines the CCUS project investment decisions from an industrial symbiosis perspective based on the supply–demand relationship of CO$_{2}$.
3.2.1. Supply Equals Demand

The balanced supply and demand of CO\(_2\) is an ideal condition for saving the cost of CO\(_2\) storage and purchase, reducing investment expenses, and conducting complete CO\(_2\) reuse.

1. Investment cost

When the supply and demand of CO\(_2\) are equal, the CCUS project’s investment costs include the initial investment cost and the transportation cost for CO\(_2\). The initial investment cost of the CCUS project can be calculated by the following formula:

\[
I_t = I_{t}^{CCS} + I_{t}^{EOR}
\]  

(26)

If \(Q_t^{CCS} = Q_t^{EOR}\), the transportation cost for CO\(_2\) in year \(t\) can be expressed as:

\[
C_{tra}^t = UC_{tra} \cdot Q_t^{EOR}
\]  

(27)

2. Investment benefit

The investment benefits of the CCUS project include carbon trading benefits, oil trading benefits, and investment subsidies.

The CCUS project’s investment benefits face simultaneous uncertainties in the carbon trading and oil markets, and a positive correlation between carbon trading price and oil price exists, i.e., \(E[\Delta z_c \Delta z_o] = \rho dt\) \([8]\), and \(\rho\) denotes the correlation coefficient between carbon trading price and oil price.

The carbon trading benefits of the CCUS project in year \(t\) is calculated as follows:

\[
\pi_{t}^{co} = Q_t^{CCS} \cdot P_c
\]  

(28)

The oil trading benefits in year \(t\) is calculated as follows:

\[
\pi_{t}^{oil} = H \cdot Q_t^{EOR} \cdot P_o
\]  

(29)

The investment subsidies provided by the government can be expressed as:

\[
S_t = K \cdot I_t
\]  

(30)

where \(K\) is the investment subsidy ratio for the CCUS project.

3. Investment option value

Assuming that the operation of the CCUS project after completion is \(T\) years, the expected value of investing in the CCUS project when the supply and demand of CO\(_2\) are equal is represented by \(\phi^{(1)}\), as indicated by the following formula:

\[
\phi^{(1)} = E\left[\int_0^{T} \left(\pi_{t}^{co} + \pi_{t}^{oil} - C_{tra}^t\right) e^{-r(t-1)} dt - (1 - K) I_t\right]
\]  

(31)

The investment option value of the CCUS project when CO\(_2\) supply and demand are equal is represented by \(F^{(1)}(P_c, P_o)\), which is a function of \(P_c\) and \(P_o\), representing the expected net present value of the project at the optimal investment timing. We assume that the investor is risk-neutral because the underlying stochastic process is a Markov \([39]\); therefore, \(F^{(1)}(P_c, P_o)\) satisfies the Bellman equation as follows:

\[
F^{(1)}(P_c, P_o) = \max \left\{ \phi^{(1)}, \frac{1}{1 + dt} E\left[ F(P_c + dP_c, P_o + dP_o) \right] \right\}
\]  

(32)

Extending the above expectation by applying Ito’s lemma yields the following second-order chi-squared partial differential equation, where the investment option value must be a solution to the following differential equation:
We use the analytical approach by Boomsma and Linnerud to solve the second-order real-options problem. For the equation to hold in its generalized form and satisfy the following equation, both variables must be greater than 0 [49].

\[
\frac{1}{2} \left[ \sigma^2_r (P_c)^2 (F(1))'' + \sigma^2_o (P_o)^2 (F(1))'' + 2 \rho \sigma_r \sigma_o P_c P_o (F(1))' + \mu_c P_c (F(1))' + \mu_o P_o (F(1))' - r (F(1)) = 0 \right]
\]

To ensure that the value of the investment option is maximized, the boundary conditions are obtained as follows:

\[
\frac{\partial F(1)(P_c, P_o)}{\partial P_c} = \frac{H \cdot Q_i^{\text{EOR}}}{r - \mu_c} \cdot (1 - e^{-rT}) = r_o H \cdot Q_i^{\text{EOR}}
\]

\[
\frac{\partial F(1)(P_c, P_o)}{\partial P_c} = \frac{Q_i^{\text{CCS}}}{r - \mu_c} \cdot (1 - e^{-rT}) = r_c Q_i^{\text{CCS}}
\]

\[
F(1)(P_c, P_o) = \phi(1)
\]

where \(P_o^{(1)*}(P_c^{(1)})\) denotes the CCUS project’s investment threshold when the supply and demand of CO\(_2\) are equal, which is obtained as follows:

\[
p_c^{(1)} = \frac{\alpha_c}{\alpha_c + \alpha_o - 1} \cdot \frac{r(1 - K) I_t + C_{\text{tra}}}{r_c \cdot r}
\]

\[
p_o^{(1)*}(P_c^{(1)}) = \frac{\alpha_o}{\alpha_c + \alpha_o - 1} \cdot \frac{r(1 - K) I_t + C_{\text{tra}}}{r_o \cdot r \cdot H}
\]

Therefore, \(F(1)(P_c, P_o)\) is as follows:

\[
F(1)(P_c, P_o) = \begin{cases} 
\eta_1 (P_c)^{\alpha_c} (P_o)^{\alpha_o} & P_o < P_o^{(1)*}(P_c^{(1)}) \\
\eta_2 (P_c)^{\alpha_c} (P_o)^{\alpha_o} + r_o \pi_{i}^{\text{EOR}} (1 - K) I_t - C_{\text{tra}} & P_o \geq P_o^{(1)*}(P_c^{(1)})
\end{cases}
\]

where \(\eta_1 = \frac{1}{(P_c^{(1)})^{\alpha_c} (P_o^{(1)})^{\alpha_o}} \cdot \frac{r(1 - K) I_t + C_{\text{tra}}}{(\alpha_c + \alpha_o - 1)}\)

### 3.2.2. Supply Exceeds Demand

If \(Q_i^{\text{CCS}} > Q_i^{\text{EOR}}\), the investment cost rises compared with equal supply and demand. \(C_t\) denotes the increased cost for the transportation and storage cost of CO\(_2\) and the calculation equation as follows:

\[
C_t = (U C_{\text{tra}} + U C_{\text{sto}}) \cdot (Q_i^{\text{CCS}} - Q_i^{\text{EOR}})
\]

Investment benefits include carbon trading benefits, oil trading benefits, and investment subsidies, which are similar when CO\(_2\) supply and demand are equal.

The expected value of the CCUS project when CO\(_2\) supply exceeds the demand is represented by \(\phi(2)\), as indicated by the following formula:

\[
\phi(2) = E \left[ \int_0^{T} (\pi^{\text{Q2}}_t + \pi^{\text{Q3}}_t - C_{\text{tra}} - C_t) e^{-r(t-t)} df - (1 - K) I_t \right]
\]

The investment threshold for the CCUS project is represented by \(P_c^{(2)*}(P_o^{(2)})\), which is determined in accordance with the steps outlined in Section 3.2.1 as follows:

\[
p_c^{(2)} = \frac{\alpha_c}{\alpha_c + \alpha_o - 1} \cdot \frac{r(1 - K) I_t + C_{\text{tra}} + C_t}{r_c \cdot r}
\]
\[
P_{c}^{(2)}(P_{c}) = \frac{\alpha_{c}}{\alpha_{c} + \alpha_{o} - 1} \cdot \frac{r(1 - K)I_{t} + C_{e}^{tra} + C_{t}}{r_{o} \cdot r \cdot H} \quad (44)
\]

Therefore, the investment option value of the CCUS project when CO\(_2\) supply exceeds the demand is represented by \(F^{(2)}(P_{c}, P_{o})\), as indicated by the following formula:

\[
F^{(2)}(P_{c}, P_{o}) = \begin{cases} 
\eta_{2}(P_{c})^{a_{c}}(P_{o})^{a_{o}} \\
\frac{r(1-K)I_{t} + C_{e}^{tra} + C_{t}}{r_{o} \cdot r \cdot H}
\end{cases}
\]

where \(\eta_{2} = \frac{1}{(p_{c}^{(2)})^{a_{c}} (p_{o}^{(2)})^{a_{o}}} \cdot \frac{r(1-K)I_{t} + C_{e}^{tra} + C_{t}}{r_{o} \cdot r \cdot H} \)

\[
3.2.3. \text{Demand Exceeds Supply}
\]

If \(Q_{t}^{CCS} < Q_{t}^{EOR}\), the investment cost rises compared with the equal supply and demand. \(C'_{t}\) denotes the increased cost and includes the additional cost of CO\(_2\) transportation and purchase required, and the calculation equation is as follows:

\[
C'_{t} = (UC_{par} + UC_{tra}) \cdot (Q_{t}^{EOR} - Q_{t}^{CCS})
\]

Investment benefits include carbon trading benefits, oil trading benefits, and investment subsidies, which are similar when the supply and demand are equal. The expected value of a CCUS project when the supply of CO\(_2\) is less than the demand is represented by \(\phi^{(3)}\), as indicated by the following formula:

\[
\phi^{(3)} = E \left[ \int_{t}^{t+T} (\tau_{t}^{CO2} + \tau_{t}^{oil} - C_{e}^{tra} - C_{t}') e^{-r(f-t)} df - (1 - K)I_{t} \right]
\]

\[
P_{c}^{(3)*}(P_{c})\) denotes the investment threshold of the CCUS project when CO\(_2\) supply is less than the demand, which is expressed as the following equation:

\[
P_{c}^{(3)} = \frac{\alpha_{c}}{\alpha_{c} + \alpha_{o} - 1} \cdot \frac{r(1 - K)I_{t} + C_{e}^{tra} + C_{t}'}{r_{c} \cdot r} \quad (48)
\]

\[
P_{o}^{(3)*}(P_{c})\) = \frac{\alpha_{o}}{\alpha_{c} + \alpha_{o} - 1} \cdot \frac{r(1 - K)I_{t} + C_{e}^{tra} + C_{t}'}{r_{o} \cdot r \cdot H} \quad (49)
\]

Therefore, the project’s investment option value when CO\(_2\) supply is less than the demand is represented by \(F^{(3)}(P_{c}, P_{o})\), as indicated by the following formula:

\[
F^{(3)}(P_{c}, P_{o}) = \begin{cases} 
\eta_{3}(P_{c})^{a_{c}}(P_{o})^{a_{o}} \\
\frac{r(1-K)I(t) + C_{e}^{tra} + C_{t}'}{r_{o} \cdot r \cdot H}
\end{cases}
\]

where \(\eta_{3} = \frac{1}{(p_{c}^{(3)})^{a_{c}} (p_{o}^{(3)})^{a_{o}}} \cdot \frac{r(1-K)I(t) + C_{e}^{tra} + C_{t}'}{r_{o} \cdot r \cdot H} \)

4. Case Study

4.1. Data

This section uses a CCUS project in Guangdong Province, China, as an example to explore the value of the formation of industrial symbiosis between a CFPP and an oil company entering into a cooperative CCUS project. Some of the data and conclusions obtained below are based on this project. Table 1 presents the main parameters and data for empirical analysis. The CFPP’s installed capacity is set to 600 MW, and the CCS project has been operating for 15 years [51]. The annual utilization hours of CFPPs are 4379 h, based on the average annual utilization hours of CFPPs in China in 2022 [31,46]. Referencing Li et al., we set the initial CCS investment cost to USD 60.22 million, and the transportation and storage costs for CO\(_2\) are 14.08 USD/t and 7.04 USD/ton, respectively [41]. The CO\(_2\) emission factor is 762 g/kWh, the CO\(_2\) capture efficiency is 0.9, and unit efficiency is...
0.94 [30]. Referencing Fan et al., the CCS technical progress rate is 2.02% [46]. In 2022, the national carbon market had a total volume of more than 50.889 million tons, the total market turnover was about USD 396 million, and the average carbon trading price was 7.8 USD/ton. As a result, we set the initial carbon trading price as 7.8 USD/ton, and the volatility and expected growth rate of the carbon trading price are 0.03 and 0.025, respectively [47]. The data for the EOR project are also obtained from previous research. The EOR project has been operating for 15 years, and the investment cost of the oil drive system is USD 27.25 million [41]. Referencing Liu et al., we set the EOR technological progress rate to 4.2%. The price of industrial CO₂ is usually in the range of 28.2–70.4 USD/ton, and the intermediate value is 49.3 USD/ton [2]. Song et al. indicated that every 0.58 tons of injected CO₂ can replace 1 barrel of oil; therefore, the ratio of incremental production is set to 0.58 [46]. This study takes the average price of West Texas Intermediate (WTI) in 2021 and 2022 as the initial oil price, as shown in Figure 2, setting an initial oil price of 80.9 USD/barrel [50]. Oil price volatility and expected growth rates are 0.21 and 0.04, respectively [43].

Table 1. Basic parameter assumptions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC</td>
<td>Installed capacity of the CFPP (MW)</td>
<td>600</td>
<td>[31]</td>
</tr>
<tr>
<td>φ</td>
<td>Unit efficiency (%)</td>
<td>94</td>
<td>[30]</td>
</tr>
<tr>
<td>RT</td>
<td>Average annual utilization hours (h)</td>
<td>4379</td>
<td>[31]</td>
</tr>
<tr>
<td>EF</td>
<td>CO₂ emission factor (g/kWh)</td>
<td>762</td>
<td>[30]</td>
</tr>
<tr>
<td>CR</td>
<td>CO₂ capture efficiency (%)</td>
<td>90</td>
<td>[30]</td>
</tr>
<tr>
<td>UCₜₚₚ</td>
<td>Unit transportation cost for CO₂ (USD/ton)</td>
<td>14.08</td>
<td>[41]</td>
</tr>
<tr>
<td>UCₛₜ</td>
<td>Unit storage cost for CO₂ (USD/ton)</td>
<td>7.04</td>
<td>[41]</td>
</tr>
<tr>
<td>α</td>
<td>Technological progress rate for CCS (%)</td>
<td>2.02</td>
<td>[46]</td>
</tr>
<tr>
<td>T1</td>
<td>The operation time of the CCS project (years)</td>
<td>15</td>
<td>[46]</td>
</tr>
<tr>
<td>I1</td>
<td>Initial investment for the CCS project (million USD)</td>
<td>60.22</td>
<td>[41]</td>
</tr>
<tr>
<td>K1</td>
<td>Investment subsidy ratio for the CCS project</td>
<td>0.1</td>
<td>[31]</td>
</tr>
<tr>
<td>μc</td>
<td>Carbon trading price expected growth rate</td>
<td>0.025</td>
<td>[47]</td>
</tr>
<tr>
<td>σc</td>
<td>Carbon trading price volatility</td>
<td>0.03</td>
<td>[51]</td>
</tr>
<tr>
<td>I2</td>
<td>Initial investment for the EOR project (million USD)</td>
<td>27.25</td>
<td>[41]</td>
</tr>
<tr>
<td>K2</td>
<td>Investment subsidy ratio for the EOR project</td>
<td>0.1</td>
<td>[2]</td>
</tr>
<tr>
<td>β</td>
<td>Technological progress rate for EOR (%)</td>
<td>4.2</td>
<td>[2]</td>
</tr>
<tr>
<td>H</td>
<td>Ratio of incremental production (million tons of CO₂/barrel)</td>
<td>0.58</td>
<td>[46]</td>
</tr>
<tr>
<td>UCₚₚ</td>
<td>Unit purchase cost for CO₂ (USD/ton)</td>
<td>49.3</td>
<td>[2]</td>
</tr>
<tr>
<td>T2</td>
<td>The operation time of the EOR project (years)</td>
<td>15</td>
<td>[41]</td>
</tr>
<tr>
<td>μo</td>
<td>Oil price expected growth rate</td>
<td>0.04</td>
<td>[43]</td>
</tr>
<tr>
<td>σo</td>
<td>Oil price volatility</td>
<td>0.21</td>
<td>[43]</td>
</tr>
<tr>
<td>ρ</td>
<td>Correlation coefficient</td>
<td>0.072</td>
<td>[8]</td>
</tr>
<tr>
<td>T</td>
<td>The operation time of the CCUS project (years)</td>
<td>15</td>
<td>[8]</td>
</tr>
<tr>
<td>K</td>
<td>Investment subsidy ratio for the CCUS project</td>
<td>0.1</td>
<td>[2]</td>
</tr>
</tbody>
</table>

Figure 2. International oil price trends in 2021 and 2022 (International Energy Agency (IEA), 2023) [50].
4.2. Results and Discussion

4.2.1. Investment Thresholds and Option Values

1. Independent investment mode

Figures 3 and 4 reflect the investment thresholds, option values, and expected values for CCS and EOR projects.

![Figure 3. Investment threshold and option value of the CCS project.](image1)

![Figure 4. Investment threshold and option value of the EOR project.](image2)

In Figure 4, $P_c^*$ is 45.95 USD/ton, and the investment option value of the CCS project is USD 33.86 million. In Figure 3, $P_o^*$ is 101.53 USD/barrel, and the investment option value of the EOR project is USD 35.93 million. According to the RO decision theory, when $P_c$ exceeds 45.95 USD/ton, the CFPP will choose to invest in the CCS project immediately; otherwise, it will decide to wait until $P_c^*$ is achieved. Similarly, once $P_o$ exceeds 101.53 USD/barrel,
the oil company will invest in the EOR project immediately; otherwise, it will decide to wait until \( P_r^* \) is achieved.

2. Cooperative investment mode

Under the cooperative investment mode, we set the parameter \( \lambda \) to denote the ratio of \( \text{CO}_2 \) supplied by the CFPP to the \( \text{CO}_2 \) the oil company requires for use, i.e., \( \lambda = \frac{Q_{t, \text{CCS}}}{Q_{t, \text{EOR}}} \). When \( \lambda = 1 \), supply and demand are equal, when \( \lambda > 1 \), supply exceeds demand, and when \( \lambda < 1 \), supply is less than demand. Furthermore, when \( \lambda > 1 \), a larger \( \lambda \) value indicates a higher degree of supply than demand; when \( \lambda < 1 \), a smaller \( \lambda \) value indicates a lower degree of supply than demand. Accordingly, we set \( \lambda = 1, \lambda = 1.4, \) and \( \lambda = 0.6 \). Based on the parameters in Section 4.1, the results of the CCUS project’s investment option values and thresholds for each value of \( \lambda \) are presented in Figure 5.

![Figure 5](image)

**Figure 5.** (a) Investment option values of the CCUS project when \( \lambda = 1 \); (b) Investment option values of the CCUS project when \( \lambda > 1 \); (c) Investment option values of the CCUS project when \( \lambda < 1 \); (d) Investment thresholds of the CCUS project.

Figure 5 a–c present the investment option values of the CCUS project for the three values introduced, and Figure 5d presents the investment threshold of the CCUS project corresponding to the values of \( \lambda \). The investment option values for the CCUS project are at least USD 78.82 million, USD 73.45 million, and USD 71.12 million for \( \lambda = 1, \lambda = 1.4, \) and \( \lambda = 0.6 \), respectively. With a carbon trading price of 45.95 USD/ton, the oil prices required for immediate investment in the CCUS project at \( \lambda = 1, \lambda = 1.4, \) and \( \lambda = 0.6 \) are at least 75.72 USD/barrel, 85.65 USD/barrel, and 89.85 USD/barrel, respectively; therefore, it is more likely for the CFPP and the oil company to invest in the CCUS project when \( \lambda = 1 \).

The sum of the investment option values for the CCS and EOR projects is USD 69.79 million. Therefore, regardless of the value assigned to \( \lambda \), the CCUS project’s investment option value is higher and the investment threshold is lower than that of the project under independent investment mode. Accordingly, industrial symbiosis can increase the CCUS project investment option value, reduce the investment threshold, and promote CCUS project development.

3. The effect of \( \lambda \) on investment thresholds

\( \lambda \) is a significant influencing factor in CCUS project cooperative investment. To verify that \( \lambda = 1 \) is more likely to trigger CCUS project investment, we set \( \lambda = 1.2 \) and \( \lambda = 0.8 \) to
assess the effect of $\lambda$ on the CCUS project investment threshold, and the results are shown in Figure 5.

Figure 5 reveals that the investment threshold of the CCUS project is lowest in the cooperative investment model under the industrial symbiosis perspective when $\lambda = 1$, and the investment threshold increases when $\lambda$ does not equal 1. If $\lambda > 1$, a larger value of $\lambda$ yields a higher investment threshold and higher carbon and oil prices are required to trigger the investment. If $\lambda < 1$, a smaller value of $\lambda$ yields a lower investment threshold. With the same degree of inequality, the investment threshold is greater at $\lambda < 1$ than $\lambda > 1$. Different values of $\lambda$ correspond to the investment thresholds and option values for the CCUS project, as shown in Table 2.

**Table 2. Investment thresholds and option values for different values of $\lambda$.**

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>Investment Threshold (USD/Barrel)</th>
<th>Investment Threshold (Million USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75.72</td>
<td>78.82</td>
</tr>
<tr>
<td>1.2</td>
<td>81.45</td>
<td>74.87</td>
</tr>
<tr>
<td>0.8</td>
<td>83.82</td>
<td>73.95</td>
</tr>
<tr>
<td>1.4</td>
<td>85.65</td>
<td>73.45</td>
</tr>
<tr>
<td>1.6</td>
<td>89.85</td>
<td>71.12</td>
</tr>
</tbody>
</table>

4. Impact of investment subsidy ratio on investment thresholds

In the initial stage of CCUS development, the government provides investment subsidies that reduce the project’s investment cost, promoting project investment. This section examines the threshold of decreased investment under different investment subsidy ratios compared with the threshold without investment subsidies. The magnitude of the decline in investment thresholds for CCS, EOR, and CCUS projects with different investment subsidy ratios is presented in Figure 6.

![Figure 6. The effect of $\lambda$ on investment thresholds for the CCUS project.](image)

Figure 7 shows that, as investment subsidy ratios increase, the magnitude of the decrease in the projects’ investment thresholds also increases [39]. Among them, the effect of the investment subsidy ratio on the decrease in the CCUS project investment threshold is higher than that of the CCS and EOR projects, indicating that industrial symbiosis can
effectively reduce investment thresholds. The effect of the investment subsidy ratio on investment threshold reduction is greater in the CCS project than in the EOR project. When the ratio is 0.3, the investment threshold for the CCS project decreases by 29% and that of the EOR project decreases by 24%, which occurs because the initial investment cost is a significant portion of the CCS project’s investment cost. For the CCUS project, the investment threshold decreases the most when \( \lambda = 1 \). When \( \lambda > 1 \), the investment threshold reduction is higher than when \( \lambda < 1 \) due to the CCS project’s high initial cost. Therefore, a balanced CO\(_2\) supply and demand can significantly reduce the CCUS project’s investment threshold from an industrial symbiosis perspective.

![Graph showing Decreased project investment thresholds under different investment subsidy ratios.](image)

**Figure 7.** Decreased project investment thresholds under different investment subsidy ratios.

To compare the projects’ feasible investment thresholds for different investment subsidy ratios, two different scenarios are set in Table 3. The first scenario is when the investment subsidy ratio is high (0.6) and the second scenario is when the investment subsidy ratio is low (0.2). Table 3 shows significant differences in the investment threshold values between projects with high and low ratios of investment subsidies. However, although the high-ratio investment subsidy can effectively reduce the investment threshold, this role is limited to the early stages of project development because it can increase the government’s fiscal expenditure [37].

<table>
<thead>
<tr>
<th>Investment Subsidy Ratio</th>
<th>CCS</th>
<th>EOR</th>
<th>CCUS((\lambda=1))</th>
<th>CCUS((\lambda=1.2))</th>
<th>CCUS((\lambda=0.8))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>26.53</td>
<td>80.57</td>
<td>75.41</td>
<td>78.92</td>
<td>79.31</td>
</tr>
<tr>
<td>0.2</td>
<td>40.32</td>
<td>91.43</td>
<td>83.63</td>
<td>87.35</td>
<td>88.72</td>
</tr>
</tbody>
</table>

4.2.2. Market Uncertainty’s Impact

1. Carbon market

The carbon market determines the carbon trading price, and its fluctuation can lead to instability in the carbon trading price [39]. Carbon prices impact carbon trading in-
come, which is a crucial component of the investment benefits for CCS and CCUS projects; therefore, the carbon market has a substantial influence on investment decisions for these projects through the carbon trading price. We use carbon trading price volatility to reflect the influence of the carbon market on project investment decisions under different investment modes. Based on the parameters set in Section 4.1, the influence curve of $\sigma_c$ on the investment thresholds and CCS and the CCUS project investment probability are shown in Figure 8.

Figure 8 reflects how the investment thresholds and investment probability for CCS and CCUS projects change as $\sigma_c$ increases from 0.01 to 0.05. The figure shows that $\sigma_c$ has a significant positive impact on the projects’ investment thresholds. Specifically, the CCS project’s investment threshold increases from 24.91 USD/ton to 68.85 USD/ton when $\sigma_c$ increases from 0.01 to 0.03, respectively. For the CCUS project, in case $\lambda = 1$, when $\sigma_c$ increases from 0.01 to 0.05, the project’s investment threshold increases from 17.21 USD/ton to 35.74 USD/ton; in case $\lambda = 1.2$, the project’s investment threshold increases from 22.36 USD/ton to 53.82 USD/ton; and in case $\lambda = 0.8$, the project’s investment threshold increases from 19.91 USD/ton to 47.23 USD/ton, respectively. A larger $\sigma_c$ increases the uncertainty of the project’s benefits, and a higher carbon trading price is required to trigger the investment. Regardless of how the volatility of the carbon trading price changes, the investment threshold of the cooperative CCUS project investment is always lower than that of projects under the independent investment model. Furthermore, changes in carbon trading price volatility have a greater impact on the independent project investment threshold because the CFPP and the oil company form industrial symbiosis, reducing the risk of increased carbon trading price volatility. Under the cooperative investment mode, the investment threshold of the project is the lowest when CO$_2$ supply and demand are balanced, and an investment is more likely to be triggered, which is consistent with the inferred results in Section 3.2. Additionally, as $\sigma_c$ increases, the CCS and CCUS projects’ investment probabilities decrease. Industrial symbiosis causes a decrease in the CCS project’s investment probability that is higher than the decline in the CCUS project’s investment probability.
Figure 9 shows the changes in the investment option values for the CCS and CCUS projects as $\sigma_c$ increases from 0.01 to 0.05. For the CCS project, when $\sigma_c$ increases from 0.01 to 0.037, the investment option value of the project increases from USD 19.2 million to USD 33.4 million, respectively; when $\sigma_c$ increases from 0.037 to 0.05, the investment option value of the project decreases to USD 24.6 million. For the CCUS project, when $\sigma_c$ rises from 0.01 to 0.04, the investment option value of the CCUS project increases, and when $\sigma_c$ rises from 0.04 to 0.05, the investment option value of the project decreases. That is because industrial symbiosis reduces the uncertainty created by the carbon market. In summary, we find that a stable carbon price can promote CCUS project investment, and industrial symbiosis can offset some of the uncertainty.

Figure 9. The effect of carbon trading price volatility on investment option values.

2. Oil market

The oil market determines the oil price. Oil prices impact oil trading income, which is a crucial component of the investment benefits for EOR and CCUS projects; therefore, the oil market has a substantial influence on investment decisions for these projects through the oil price. We use oil price volatility to reflect the influence of the oil market on project investment decisions under different investment modes. The influence curve of $\sigma_o$ on the investment thresholds and EOR and the CCUS project investment probability are shown in Figure 10.

From Figure 10, the EOR project’s investment threshold increases from 94.81 USD/barrel to 184.93 USD/barrel when $\sigma_o$ increases from 0.1 to 0.5, respectively. For the CCUS project, when $\sigma_o$ increases from 0.1 to 0.5, in case $\lambda = 1$, the project’s investment threshold increases from 77.36 USD/barrel to 129.28 USD/barrel; in case $\lambda = 1.2$, the project’s investment threshold increases from 86.85 USD/barrel to 143.72 USD/barrel; in case $\lambda = 0.8$, the project’s investment threshold increases from 87.92 USD/barrel to 147.81 USD/barrel, respectively. $\sigma_o$ has a significant positive impact on the investment thresholds and investment probability of the projects. Similar to the carbon price, no matter how $\sigma_o$ changes, the investment threshold of the cooperative CCUS project investment is always lower than that of projects under the independent investment mode. The change in oil price volatility has a greater impact on the project investment threshold of the independent investment mode. That is because industrial symbiosis helps to reduce the risks associated with increased oil price volatility. Meanwhile, as $\sigma_o$ increases, the investment probability of EOR and CCUS projects decreases. Due to the formation of industrial symbiosis, the degree of decrease in the investment probability of the EOR project is slightly higher than the degree of decline in the investment probability of the CCUS project.
Figure 10. The effect of oil price volatility on investment thresholds and probability.

Figure 11 shows the fluctuations in investment option values for the EOR and CCUS projects as $\sigma_o$ increases from 0.1 to 0.5. For the EOR project, when $\sigma_o$ increases from 0.1 to 0.33, the investment option value of the project increases from USD 18.42 million to USD 29.61 million, respectively; when $\sigma_o$ increases from 0.33 to 0.5, the investment option value of the project decreases to USD 22.73 million. For the CCUS project, when $\sigma_o$ rises from 0.1 to 0.35, the investment option value of the CCUS project increases. When $\sigma_o$ rises from 0.35 to 0.5, the investment option value of the project decreases. When $\sigma_o$ is less than 0.33, the investment option value of the EOR project increases as $\sigma_o$ increases. That is because industry symbiosis reduces the uncertainty caused by the oil market. Therefore, a stable oil price can promote investment in CCUS projects.

Figure 11. The effect of oil price volatility on investment option values.
3. Market correlation

When the CFPP and the oil company initiate a collaborative investment in the CCUS project from the industrial symbiosis perspective, it is crucial to consider the correlation between carbon trading and oil markets. Therefore, we next analyze the impact of the correlation coefficient on the investment threshold. Using the example of the CCUS project at $\lambda = 1$, we determine the influence curve of the correlation coefficient between carbon trading price and oil price on the investment threshold of the project, as shown in Figure 12.

In Figure 12, $\rho$ has a positive effect on the CCUS project’s investment threshold, where the investment threshold rises as $\rho$ increases. Specifically, the carbon trading price is 18 USD/ton, the oil price is at least 74.33 USD/barrel when $\rho = 0.05$; when $\rho = 0.1$, the oil price is at least 84.65 USD/barrel, and when $\rho = 0.15$, the oil price is at least 98.24 USD/barrel. An increase in the correlation coefficient between carbon trading and oil prices raises the investment threshold. This finding is consistent with the correlation conclusion of the portfolio theory contending that, as the degree of correlation in a portfolio increases, risk diversification decreases.

4.2.3. Technological Progress Uncertainty’s Impact

It is crucial to reduce the initial investment cost of CCUS projects to promote project development. The rationale for this is that the initial investment cost constitutes a significant proportion of the overall investment cost, which affects projects’ investment decisions. The technological progress rate indicates the impact of the initial investment cost on projects’ investment decisions. Figure 13 illustrates the effect of changes in CCS technological progress on the investment threshold and probability of CCS and CCUS projects. Similarly, Figure 14 shows the impact of changes in EOR technological progress on the investment threshold and probability of EOR and CCUS projects.

Figure 13 reveals that CCS technological progress negatively affects the investment thresholds of CCS and CCUS projects, where, when $\alpha$ increases, the projects’ investment thresholds decrease. Specifically, for the CCS project, an increase from 2% to 10% decreases the project’s investment threshold from 59.86 USD/ton to 40.82 USD/ton, respectively. For the CCUS project, when $\alpha$ rises from 2% to 10%, in case $\lambda = 1$, the project’s investment threshold decreases from 34.81 USD/ton to 23.83 USD/ton; in case $\lambda = 1.2$, the project’s investment threshold decreases from 38.81 USD/ton to 30.28 USD/ton; and in case $\lambda = 0.8$,
the investment threshold of the project decreases from 40.34 USD/ton to 30.28 USD/ton, respectively. Therefore, as $\alpha$ increases, the project’s initial investment cost and the total investment cost are lowered, causing the investment to have a lower carbon trading price. However, as seen in Figure 9, as $\alpha$ increases, its impact on the project’s investment threshold decreases. Additionally, the CCS and CCUS projects’ investment probabilities rise as the value of $\alpha$ increases, and the magnitude of investment probability growth also rises.

![Figure 13](image1.jpg)

**Figure 13.** The effect of CCS technological progress on investment thresholds and probability.

![Figure 14](image2.jpg)

**Figure 14.** The effect of EOR technological progress on investment thresholds and probability.
Figure 14 shows that the EOR technological progress negatively affects the EOR and CCUS projects’ investment thresholds. Specifically, for the EOR project, when $\beta$ increases from 2% to 10%, the EOR project investment threshold decreases from 119.71 USD/barrel to 89.92 USD/barrel, respectively. For the CCUS project, when $\beta$ increases from 2% to 10%, in case $\lambda = 1$, the project’s investment threshold decreases from 99.21 USD/barrel to 68.33 USD/barrel; in case $\lambda = 1.2$, the project’s investment threshold decreases from 110.95 USD/barrel to 79.21 USD/barrel; and in case $\lambda = 0.8$, the project’s investment threshold decreases from 108.25 USD/barrel to 76.24 USD/barrel, respectively. Therefore, as $\beta$ increases, the initial project investment cost lowers, and the oil price triggering the project’s investment will decrease. Similarly, as $\beta$ increases, the extent of its influence on the investment threshold decreases. Additionally, the EOR and CCUS projects’ investment probabilities rise as the value of $\beta$ increases, and the magnitude of the investment probability growth increases slightly. However, comparing the degree of influence of $\alpha$ and $\beta$ on the projects’ investment thresholds, $\alpha$ has a more significant influence. This is because the initial investment cost accounts for a relatively larger proportion of the total CCS and CCUS projects’ investment costs; thus, CCS technological progress can affect the total investment cost rapidly.

5. Conclusions

This study analyzes CCUS project investment decisions of a CFPP and an oil company under industrial symbiosis based on the RO theory. Firstly, independent investment models are constructed under the independent investment mode. Secondly, the study examines the costs and benefits of cooperative CCUS projects for the CFPP and the oil company under industrial symbiosis, constructing option value functions based on the quantity difference between the supply and demand of CO$_2$ to determine optimal investment thresholds and option values. Finally, we apply the model to the actual case of a CCUS project in Guangdong Province and make relevant policy suggestions. The primary conclusions according to the project’s simulation results are outlined below:

1. Industrial symbiosis can effectively reduce investment thresholds and increase the values of CCUS projects. Current carbon trading and oil prices have not yet reached the investment thresholds; however, the cooperative investment mode under industrial symbiosis significantly decreases the CCUS project’s investment thresholds while increasing the project’s value. This finding provides valuable insights to promote the development of CCUS projects.

2. The balance between the supply and demand of CO$_2$ is the best scenario for triggering cooperative investment in CCUS projects between the CFPP and the oil company from an industrial symbiosis perspective. Achieving a balance between supply and demand requires the establishment of a network of industry collaboration to facilitate a more efficient development of CCUS projects and ensure the realization of dual carbon goals.

3. The volatility of carbon trading and oil prices largely affects the investment thresholds and investment option values of CCUS projects. The higher the price volatility, the higher the investment risk, the higher the investment threshold will be, and in extreme cases, investors may give up their investment. Therefore, the government should introduce relevant policies to stabilize oil and carbon trading prices and enhance investors’ confidence in stabilizing market expectations.

4. Technological progress can lower the investment threshold by reducing the initial investment cost. Since the cost of carbon capture accounts for a high proportion of the initial investment, and the current rate of technological progress in carbon capture technology is at a low level, it is possible to promote the development of CCUS projects by accelerating the R&D of carbon capture technology so as to encourage investment in CCUS projects.

CCUS is a key technology for promoting the low-carbon transition of energy-intensive enterprises, and its large-scale development is crucial for achieving “carbon
neutrality”. Based on the results of this study, the following policy recommendations are proposed to promote the development of CCUS. Firstly, governments need to encourage coal-fired power plants and oil companies to establish industrial symbiosis. For example, governments can provide CO\textsubscript{2} trading subsidies or penalties to incentivize companies to actively participate in industrial symbiosis. Secondly, the government can build an industrial collaboration network and expand the participating entities to realize the balance of CO\textsubscript{2} supply and demand. Finally, the government can increase the investment in R&D of CCUS technology to promote its development.

Although the models proposed in this study reveal that industrial symbiosis can effectively promote the application of CCUS project investments, some undeniable limitations remain. First, this study does not quantify the ecological benefits of industrial symbiosis with the CCUS project. Future research should consider ecological benefits to yield more comprehensive findings. Second, to simplify the calculations, this study assumes that the price of industrial CO\textsubscript{2} is fixed; however, the price of industrial CO\textsubscript{2} is uncertain in reality. Therefore, future research should use stochastic models to reflect this uncertainty and produce more accurate results.

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