Adoption Strategies for CCUS Business Models: Transaction Costs, Subsidies, and Evolutionary Dynamics in China's Coal Power

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Abstract. Coal-fired power plants (CFPPs) face increasing pressure to adopt carbon capture, utilization, and storage (CCUS) under China's dual-carbon goals. This study develops an evolutionary game model between the government and CFPPs to examine how transaction costs and subsidies affect the adoption of three CCUS business models: vertical integration, CO_2 transporter, and joint venture. Results show that high transaction costs favor vertical integration through risk internalization, while lower costs make specialized models feasible and allow the CO_2 transporter model to outperform joint ventures. Subsidies shift transaction cost thresholds, supporting early commercialization but potentially reinforcing vertical integration and path dependence if overused. Simulations show that carbon utilization subsidies promote the transporter model, whereas storage subsidies may delay specialization. Policy should therefore shift toward carbon-market-based incentives and gradual subsidy withdrawal.

Keywords: Business model, CCUS, CFPP, Evolutionary game.

1 Introduction

Human activities have caused global warming [1], and China has committed to peaking CO_2 emissions by 2030 and achieving carbon neutrality by 2060 [2]. Since premature CFPP retirement may cause resource waste and energy security risks [3-5], CCUS is regarded as a key pathway for coal-power decarbonization [6-9]. Although China has operated over 50 CCUS demonstration projects with about 4 million tons of annual capture capacity [10], fewer than 10% have been commercialized [11]. This gap shows that CCUS commercialization depends not only on technology but also on business model design. Given the cross-sectoral CCUS chain, this paper examines how subsidies and transaction costs affect CFPPs adoption of vertical integration, CO_2 transporter, and joint venture models through an evolutionary game between the government and CFPPs.

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2 Business Model Design and Assumptions

Existing CCUS demonstration projects in China are mainly led by state-owned capital and often adopt a vertical integration model that internalizes external market transactions [12]. Since CCUS commercialization depends on the formation of CO2 value, CO2 transactions between CFPPs and oil companies require an explicit CO2 sales price.The following is an introduction to the three business models referred to in this article. Considering that the CO2-EOR technology of China has approached commercial application, the carbon utilization in our research only refers to CO2-EOR.

2.1 Vertical Integration Model

In this model, capture, transportation, utilization, and storage are handled by different departments in one enterprise. Let p denote the internal CO2 transfer price. The oilfield's willingness to pay for one unit of CO2 is denoted by θ, which follows a uniform distribution on [0,1] [13]. The oilfield also bears the CO2-EOR cost c_e and storage cost c_s.

It is assumed that the net utility of the oilfield purchasing CO2 is:

$$u_V=\theta-p-c_e-c_s \tag{1}$$

The profit of CFPPs under this model is:

$$\Pi_V=\omega_1(p+W-C_1)q_1 \tag{2}$$

Where C_1 is the unit CO2 capture cost, q_1 is the captured CO2 amount, and ω_i represents transaction efficiency under model i, with $0 < \omega_i \leq 1$. A larger ω_i indicates lower transaction costs and easier cooperation. For vertical integration, transaction costs are internalized, for the convenience of comparison, it is assumed that the transaction cost in this model is 0, i.e.$\omega=1$.

2.2 CO2 Transporter Model

Under the CO2 transporter model, CFPPs are responsible for CO2 capture and sell captured CO2 to oilfields through a specialized transporter. Let f denote the CO2 sales price. The oilfield's net utility is:

$$u_T=\theta-f-\alpha c_e \tag{3}$$

Where α (0<α<1) measures the cost coefficient under specialized transportation. A smaller α indicates stronger cost-saving effects from specialization. The profit of CFPPs under this model is:

$$\Pi_T=\omega_2(f+W-\alpha C_2)q_2 \tag{4}$$

where C_2 is the unit cost of CO2 capture and transportation, and q_2 is the captured CO2 amount under this model.

2.3 Joint Venture Model

In the joint venture model, CFPPs, transporters, and CO2 users jointly establish a co-operative entity responsible for capture, transportation, storage, or CO2 sales. This model can reduce transaction uncertainty through long-term cooperation and equity linkage.Let l denote the CO2 sales price under the joint venture agreement, and let λ denote the CFPP's shareholding ratio, where $0 < \lambda < 1$. The oilfield's net utility is:

$$u_j=\theta-l-\beta c_e \tag{5}$$

The profit of the CFPP in this model can be expressed as:

$$\Pi_j=\omega_3\lambda(l+W-\beta C_3)q_3 \tag{6}$$

Where $\beta(0<\beta<1)$ denotes the technical cost-effectiveness of the joint venture model due to the specialization of the division of labor, and $\alpha<\beta$, C_3 denotes the cost of capture, transportation, and removal of oil required by the joint venture to capture a unit amount of CO2 due to the more refined division of labor in CO2 transporter model, and$C_3>C_2>C_1$,q_3 denotes the amount of carbon captured in this model.

Assuming that the utility of oilfield adopting enhanced oil drive is u_j $(j \in \{V,T,J\})$. Only if the utility of using CO2 for oil repelling or for its storage exceeds the other options will the oilfield purchase CO2 without loss of generality, set $u_j = 0$.

3 Decision Analysis Under Each Business Model

3.1 Decision Analysis in the Vertical Integration Model

In this model, the CFPP first sets the CO2 sales price p, and the oil field then makes the purchase decision based on the price. According to the inverse solution method, the demand function is first derived at a given sales price. Since the oilfield will choose to purchase CO2 only when the effectiveness of purchasing CO2 is greater than that of other oil-repellent methods (i.e.,$u_v \geq 0$), it can be obtained by making $u_v = 0$.

$$\theta_V=p+c_e+c_s \tag{7}$$

The oilfield chooses to buy CO2 only when$\theta \geq \theta_v$, and vice versa, it does not buy CO2. Since θ obeys the uniform distribution of [0,1], the demand for CO2 is $q_1 = 1-\theta_V$, so the demand function in vertical integration model is:

$$q_1=1-p-(c_e+c_s) \tag{8}$$

Substituting Eq. (8) into Eq. (2) yields the decision model of CFPP in vertical integration model:

$$\max_{p} \Pi_V = (p+W-C_1)(1-p-c_e-c_s) \tag{9}$$

Derivation of equation (9) yields the optimal price as:

$$p^* = 1+C_1-W-c_s-c_e/2 \tag{10}$$

This is obtained by substituting equation (10) into equations (8) and (2):

$$q_1^* = 1+W-C_1-c_s-c_e/2 \tag{11}$$

$$\Pi_V^* = (1+W-C_1-c_s-c_e)^2 / 4 \tag{12}$$

3.2 Decision Analysis in CO2 Transporter Model

In this model, the CFPP first sets the CO2 sales price f , and the oil field then bases its purchase decision on the price. Based on the same demand function solution idea. Make $u_T = 0$, can be obtained $\theta_T = f$, when $\theta = \theta_T$, the purchase and do not buy the utility is equal; when $\theta > \theta_T$, the oilfield will choose to buy CO2, and vice versa, do not buy CO2. Because θ obeys the uniform distribution of [0,1], the demand for CO2 is $q_2 = 1 - \theta_T$, so the demand function in this model is:

$$q_2 = 1-\alpha c_e-f \tag{13}$$

Substituting Eq. (13) into Eq. (4) yields the decision model in CO2 transporter model:

$$\max_{f} \Pi_T = \omega_2(f+W-\alpha C_2)(1-\alpha c_e-f) \tag{14}$$

Derivation of equation (14) yields the optimal price as:

$$f^* = 1+\alpha C_2-W-\alpha c_e/2 \tag{15}$$

This is obtained by substituting equation (15) into equations (13) and (4):

$$q_2^* = 1-\alpha C_2+W-\alpha c_e/2 \tag{16}$$

$$\Pi_T^* = \omega_2(1-\alpha C_2+W-\alpha c_e)^2/4 \tag{17}$$

3.3 Decision Analysis in the Joint Venture Model

In this model, the CFPPs first sets the CO2 sales price   , and the oilfield then bases its purchasing decision on the price. Based on the same idea as in the previous section. Let $u_J=0$, we can get $\theta_J=l$, when $\theta=\theta_J$, the utility of purchasing or not purchasing CO2 is equal; when $\theta > \theta_J$, the oilfield will choose to purchase CO2 to drive oil. Since θ obeys the uniform distribution of [0,1], the demand for CO2 is $_3 = 1 -$ $_J$, so the demand function is as follows:

$$q_3\text{=}1\text{-}\beta c_e\text{-}l \tag{18}$$

Substituting Eq. (18) into Eq. (6) yields the decision model in joint venture model:

$$\max_l \Pi_J = \omega_3\lambda(l+W\text{-}\beta C_3)(1\text{-}\beta c_e\text{-}l) \tag{19}$$

Derivation of equation (19) yields the optimal price as:

$$l^*=1+\beta C_3\text{-}W\text{-}\beta c_e/2 \tag{20}$$

This is obtained by substituting equation (20) into equations (18) and (6):

$$q_3^*=1\text{-}\beta C_3+W\text{-}\beta c_e/2 \tag{21}$$

$$\Pi_J^*=\lambda\omega_3(1\text{-}\beta C_3+W\text{-}\beta c_e)^2/4 \tag{22}$$

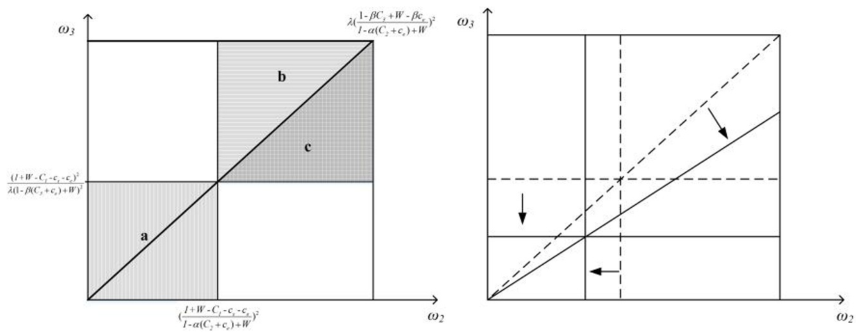
3.4 Comparison

Based on the optimal profits derived above, this section compares the critical conditions for CFPPs to adopt different CCUS business models under government subsidies.

Proposition 1: (i)When $W > C_1 + c_e + c_s - 1$, if $\omega_2 < (1 + W - C_1 - c_s - c_e/1 - \alpha(C_2 + c_e) + W)^2$ and $\omega_3 < (1 + W - C_1 - c_s - c_e)^2/\lambda(1 - \beta(C_3 + c_e) + W)^2$, the vertical integration model is the optimal choice for CFPPs;

(ii) When $W > \alpha(C_2 + c_e) - 1$, if $\omega_2 > (1 + W - C_1 - c_s - c_e/1 - \alpha(C_2 + c_e) + W)^2$ and $\omega_2/\omega_3 > \lambda(1 - \beta C_3 + W - \beta c_e/1 - \alpha(C_2 + c_e) + W)^2$, CO2 transporter model is the optimal choice for CFPPs;

(iii) When $W > \beta(C_3 + c_e) - 1$, if $\omega_3 > (1 + W - C_1 - c_s - c_e)^2/\lambda(1 - \beta(C_3 + c_e) + W)^2$ and $\omega_2/\omega_3 < \lambda(1 - \beta C_3 + W - \beta c_e/1 - \alpha(C_2 + c_e) + W)^2$, the joint venture model is the optimal choice for CFPPs.



(i) (ii)

Fig. 1. Critical conditions of business model

Fig. 1 plots the critical boundaries of business model choice under subsidized and non-subsidized scenarios. Regions a, b, and c represent the vertical integration, CO_2 transporter, and joint venture models, respectively. The results show that transaction costs determine CFPPs' adoption of CCUS business models: high transaction costs favor vertical integration, whereas lower transaction costs make specialized models feasible. When the transaction costs of the CO_2 transporter and joint venture models are similar, the CO_2 transporter model becomes preferable due to its higher specialization and cost efficiency. Comparing Fig. 1(i) and Fig. 1(ii), subsidies expand the vertical integration region and reduce specialized-model regions, making joint ventures relatively more attractive while weakening the CO_2 transporter model.

4 Analysis of Evolutionary Game

4.1 Stability Strategy

Based on the optimal profits and critical conditions derived above, an evolutionary game is constructed between the government and CFPPs. The government chooses either to subsidize or not subsidize, while CFPPs choose among three CCUS business models: vertical integration, CO2 transporter, and joint venture. Let x and 1-x denote the probabilities of government subsidy and no subsidy, respectively. Let y_1, y_2, and 1-y_1 -y_2 denote the probabilities that CFPPs choose the vertical integration model, CO2 transporter model, and joint venture model, respectively. The superscript "^" denotes the profit without subsidies. The payoff matrix is shown in Table 1, where G represents the government benefit from CCUS retrofits, such as environmental benefits from emission reductions.

Table 1. Payoff matrix for both players

		CFPPs		
		Vertical integration	CO_2 Transporter	Joint venture
governments	subsidize	$(G\text{-}W)q_i,\Pi_V$	$(G\text{-}W)q_2,\Pi_T$	$(G\text{-}W)q_3,\Pi_J$
	unsubsidized	Gq_1,Π_V	Gq_2,Π_T	Gq_3,Π_T

The expected profits of the CFPPs choosing the vertical integration model, CO2 transporter model and the joint venture model are $\Pi_1 = x\Pi_V + (1-x)\Pi_V$, $\Pi_2 = x\Pi_T + (1-x)\Pi_T$, and $\Pi_3 = x\Pi_J + (1-x)\Pi_J$, so the average expected profits of the CFPPs are as follows:

$$\overline{\Pi}=y\Pi_1+y_2\Pi_2+(1\text{-}y_1\text{-}y_2)\Pi_3 \tag{23}$$

Similarly, the government's expected payoffs under subsidy and no subsidy are:

$$\pi_1=y_1(G\text{-}W)q_1+y_2(G\text{-}W)q_2+(1\text{-}y_1\text{-}y_2)(G\text{-}W)q_3 \tag{24}$$

$$\pi_2=y_1Gq_1+y_2Gq_2+(1\text{-}y_1\text{-}y_2)Gq_3 \tag{25}$$

Therefore, the government's average expected profit is as follows:

$$\bar{\pi} = x\pi_2 + (1-x)\pi_2 \tag{26}$$

According to the replicated dynamic evolution equations, the dynamic system of the evolutionary game can be obtained as follows:

$$\begin{cases} F_1(x,y_1,y_2) = dx/dt = x(\pi_1\text{-}\bar{\pi}) \\ F_2(x,y_1,y_2) = dy_1/dt = y_1(\Pi_1\text{-}\bar{\Pi}) \\ F_3(x,y_1,y_2) = dy_2/dt = y_2(\Pi_2\text{-}\bar{\Pi}) \end{cases} \tag{27}$$

Joining the above dynamic equations gives the equilibrium point $(\bar{x},\bar{y}_1,\bar{y}_2)$ such that $dx/dt=0, dy_1/dt=0, dy_2/dt=0$, holds simultaneously. Let $M_i=(G\text{-}W)q\text{-}Gq_i (i \quad \{1,2,3\})$, the joint equation is calculated to get nine equilibrium points:

$$(-\frac{\Pi_J-\Pi_T}{-\Pi_T+\Pi_T+\Pi_J-\Pi_J},0,-\frac{M_3}{M_2+M_3}),(-\frac{\Pi_J-\Pi_V}{-\Pi_V+\Pi_V+\Pi_J-\Pi_J},-\frac{M_3}{M_1+M_3},0),$$

$$(-\frac{\Pi_T-\Pi_V}{\Pi_T-\Pi_T-\Pi_V+\Pi_V},\frac{M_2}{M_2-M_1},-\frac{M_1}{M_2-M_1}),(0,0,0),(1,0,0),(0,1,0),(0,0,1),(1,0,1),(1,1,0)$$

To analyze the stability of the equilibrium point, a theorem for autonomous systems of differential equations is first invoked: For an autonomous system of differential equations $\frac{dX}{dt}=J(X)+O(X)$, where J is a constant matrix, and $O(X)$ is a higher term of X, i.e., satisfies $\lim_{|X|\to 0}\frac{|O(X)|}{|X|}=0$. If all the eigenroots of J have negative real parts, the zero solution of the system is asymptotically stable; if at least one of the eigenroots of J has a positive real part, the zero solution of the system is unstable.

Based on this theorem, the dynamical system (27) can be written as $dF/dt=J(\bar{x},\bar{y}_1,\bar{y}_2)[x,y_1,y_2]^T$, where J can be written:

$$J(\bar{x},\bar{y}_1,\bar{y}_2)=\begin{bmatrix} \frac{\partial F_1}{\partial x} & \frac{\partial F_1}{\partial y_1} & \frac{\partial F_1}{\partial y_2} \\ \frac{\partial F_2}{\partial x} & \frac{\partial F_2}{\partial y_1} & \frac{\partial F_2}{\partial y_2} \\ \frac{\partial F_3}{\partial x} & \frac{\partial F_3}{\partial y_1} & \frac{\partial F_3}{\partial y_2} \end{bmatrix} \tag{28}$$

When $(\bar{x},\bar{y}_1,\bar{y}_2)$ is a given point (i.e., the above nine equilibrium points), the matrix is a constant matrix, so the stability of the dynamic system can be determined by the above theorem.

Proposition 2: (i) When $W > G + \beta(C_3 + c_e) - 1$, if $\omega_3 > (1 - C_1 - c_s - c_e)^2/\lambda(1 - \beta(C_3 + c_e))^2$ and $\omega_2/\omega_3 < \lambda(1 - \beta C_3 - \beta c_e/1 - \alpha(C_2 + c_e))^2$, (0, 0, 0) is a stable equilibrium;

(ii) when $W > G + \alpha(C_2 + c_e) - 1$, if $\omega_2 > (1 - C_1 - c_s - c_e/1 - \alpha(C_2 + c_e))^2$ and $\omega_2/\omega_3 > \lambda(1 - \beta C_3 - \beta c_e/1 - \alpha(C_2 + c_e))^2$, (0, 0, 1) is a stable equilibrium;

(iii) when $W > G + C_1 + c_e + c_s - 1$, if $\omega_2 < (1 - C_1 - c_s - c_e/1 - \alpha(C_2 + c_e))^2$ and $\omega_3 < (1 - C_1 - c_s - c_e)^2/\lambda(1 - \beta(C_3 + c_e))^2$, (0, 1, 0) is a stable equilibrium;

(iv) when $\beta(C_3 + c_e) - 1 < W < G + \beta(C_3 + c_e) - 1$, if $\omega_3 > (1 + W - C_1 - c_s - c_e)^2/\lambda(1 - \beta(C_3 + c_e) + W)^2$ and $\omega_2/\omega_3 < \lambda(1 - \beta C_3 + W - \beta c_e/1 - \alpha(C_2 + c_e) + W)^2$, (1, 0, 0) is a stable equilibrium;

(v) when $\alpha(C_2 + c_e) - 1 < W < G + \alpha(C_2 + c_e) - 1$, if $\omega_2 > (1 + W - C_1 - c_s - c_e/1 - \alpha(C_2 + c_e) + W)^2$ and $\omega_2/\omega_3 > \lambda(1 - \beta C_3 + W - \beta c_e/1 - \alpha(C_2 + c_e) + W)^2$, (1, 0, 1) is a stable equilibrium;

(vi) when $C_1 + c_e + c_s - 1 < W < G + C_1 + c_e + c_s - 1$, if $\omega_2 < (1 + W - C_1 - c_s - c_e/1 - \alpha(C_2 + c_e) + W)^2$ and $\omega_3 < (1 + W - C_1 - c_s - c_e)^2/\lambda(1 - \beta(C_3 + c_e) + W)^2$, (1, 1, 0) is a stable equilibrium.

Proposition 2 reflects the evolutionary equilibrium between government subsidies and the CCUS business model of CFPPs. Each equilibrium point in Proposition 2 corresponds to a different strategy, e.g., (0, 0, 1) represents the equilibrium strategy in which the government does not subsidize (i.e., $x = 0$) and the CFPPs adopt the CO2 transporter model (i.e., $y_2 = 1$).

4.2 Result and Discussion

Combining Propositions 1 and 2, transaction cost is the decisive factor in CFPPs CCUS model selection. Currently, high transaction costs necessitate vertical integration to internalize coordination expenses and ensure profitability. Conversely, declining transaction costs render joint venture and CO2 transporter models feasible, with the latter being preferable due to superior specialization and efficiency.

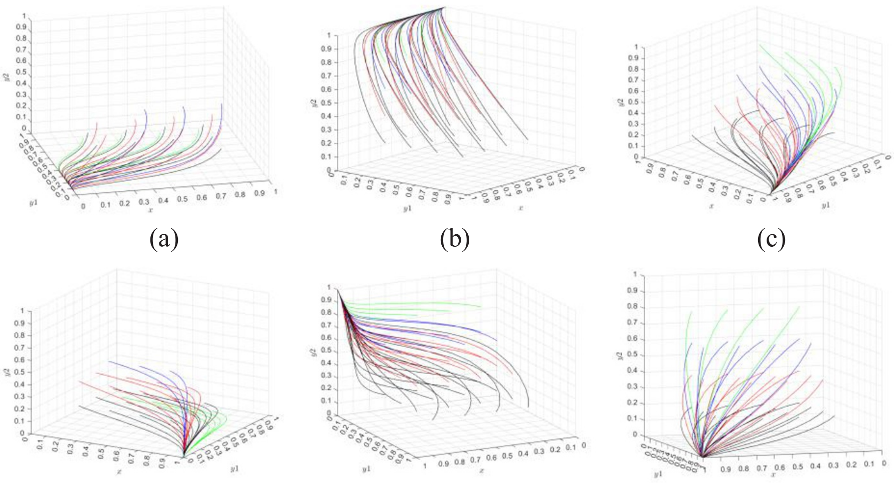
Subsidies alter transaction cost thresholds. While direct subsidies boost profit margins, they may inadvertently incentivize a shift toward vertical integration, potentially hindering specialized models. Thus, subsidies should be applied cautiously as transaction costs fall and gradually withdrawn upon CCUS projects achieving commercial viability.

4.3 Simulation Analysis

The simulation aims to verify the equilibrium conditions in Proposition 2 and observe the evolutionary process under different initial values of x, y_1, and y_2. Based on existing studies, the carbon capture cost is about 57 USD/t CO2 [11], which equals 387.6 CNY/t CO2 at an exchange rate of 6.8. The average transportation distance is 86 km, with a unit transportation cost of 100 CNY/100 km, and the subsidy is set at 31 USD/t CO2 [14]. The unit storage cost is about 50 CNY/t CO2 [15], giving $C_1 = 387.6$, $C_2 = 473.6$, $C_3 = 523.6$, $c_s = 50$, and W = 210.8. The CO2-EOR cost is 12 USD/t CO2 [12], namely $c_e = 85$. The CFPPs shareholding ratio in the joint venture model is set as $\lambda = 0.5$. After normalization, the basic parameters are $C_1 = 0.7$, $C_2 = 0.9$, $C_3 = 1$, $c_s = 0.1$,

$c_e = 0.2$, and $W = 0.4$. To cover all six cases in Proposition 2, the adjustment parameters are set as $G = 10$, $\alpha = 0.5$, $\beta = 0.6$, $\omega 2 = 0.4$, and $\omega 3 = 0.6$.

Fig. 2 verifies Proposition 2 by showing the evolutionary paths under six equilibrium cases. Subfigures (a)-(c) correspond to the no-subsidy equilibria under the joint venture, CO_2 transporter, and vertical integration models, while subfigures (d)-(f) correspond to the subsidized equilibria under the same three models. Although the paths vary with different initial values of x, y_1, and y_2, all trajectories converge to their corresponding equilibria, confirming the validity of Proposition 2. To further examine subsidy heterogeneity, storage and carbon utilization subsidies are introduced, where is and iu denote the storage and utilization subsidy coefficients, and S and U denote the corresponding CO_2 storage and utilization amounts. Based on geological storage and CO_2-EOR subsidies [14], these parameters are incorporated into the dynamic system with initial probabilities of $x = 0.5$, $y_1 = 1/3$, and $y_2 = 1/3$.

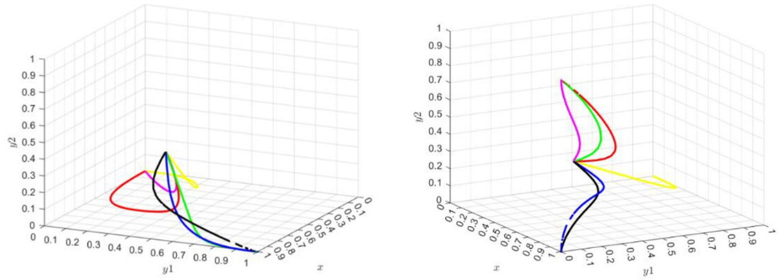


(a) (b) (c)

(d) (e) (f)

Fig. 2. Evolutionary game equilibria

Fig. 3(a) shows the evolution paths under storage subsidy coefficients of 28, 39, 50, 61, 72, and 83, represented by black, blue, green, red, magenta, and yellow lines, respectively. The critical transition occurs between 50 and 61, where the power plant's strategy fluctuates between the vertical integration and joint venture models, and the government strategy oscillates between subsidy and no subsidy. Fig. 3(b) uses the same color order for carbon utilization subsidy coefficients of 17, 26, 35, 44, 53, and 62. The critical transition occurs between 26 and 35, where the strategy shifts from the joint venture model to the CO2 transporter model, indicating that carbon utilization subsidies promote specialized CCUS business models and CO2 utilization commercialization.



(a) (b)

Fig. 3. Effect of subsidy policy on evolutionary game equilibria

5 Conclusion and Policy Implications

This study shows that transaction costs are the key factor affecting CCUS business model adoption in China's CFPPs. High transaction costs favor vertical integration because it internalizes coordination risks, while lower transaction costs promote specialized models, especially the CO2 transporter model. Subsidies support early commercialization but may reinforce vertical integration and path dependence if overused, whereas carbon utilization subsidies are more effective in promoting specialization. Accordingly, CCUS policy should shift from state-led integrated demonstrations to carbon-market incentives, specialized transport networks, tax credits, green finance, and gradual subsidy withdrawal once projects become commercially viable.

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