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Research on Incentive Measures of CCUS Power Plant under Evolutionary Game Theory

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ABSTRACT

As the power and heating industry is the sector with the largest incremental CO_2 emissions globally, CCUS retrofitting by power companies is important to achieve the national carbon dioxide emission reduction macro policy. With the aim of exploring the interaction and choice of strategy between government, public and coal plants and to further explore the influence of incentives on coal plant behaviour so as to realize investment in CCUS retrofitting by coal plants, in this paper, we take the government, the public, and coal plants as three stakeholders, constructs the game model, construct the payoff matrix based on evolutionary game theory, calculate the replicator dynamics equations of each stakeholders, and the evolutionary stabilization strategy of the system is analyzed. In addition, this paper establishes the SD simulation model according to the concept of system dynamics, simulates the behavior evolution path of three stakeholders using Vensim software, and conducts sensitivity analyses on incentive policies and key parameters. The results show that: (1) There exists a stabilization strategy in the evolutionary game model, i.e., both the government and the public choose not to regulate and coal plants choose to invest in CCUS; (2) For China's current domestic context in which only a carbon trading market exists, China has a significant advantage in the imposition of a carbon tax, which has a great motivator for coal plants to choose to invest in CCUS; (3) In terms of energy policy, the government can motivate coal plants to invest early in CCUS retrofits in order to implement carbon dioxide emission reduction technologies by increasing tariff subsidies for clean electricity; (4) By increasing penalties, the government can also motivate coal plants to invest in CCUS retrofits to promote the deploy CCUS.

Keywords: coal plants, CCUS, evolutionary game, system dynamics

1. INTRODUCTION

As the power and heating industry is the sector with the largest incremental CO_2 emissions globally, CCUS retrofitting by power companies is important to achieve the national carbon reduction macro policy. CCUS technology is very costly and cannot be invested in immediately under China's existing pricing and incentive policies, meaning that the economic viability of CCUS technology is low and calls for more effective incentive policies. Comparing foreign low carbon technologies and domestic policy documents related to new energy generation, it is found that China currently has no incentive policy for CCUS technology. This paper uses the relevant domestic and international incentives as a reference to study the investment decision problem of CCUS technology. In terms of research methods, they are mainly divided into real options pricing methods and dynamic planning methods. With the idea of game theory being introduced into option pricing models, option game models have become a new method for studying project investment decisions, and system dynamics provides an effective aid for dynamic evolutionary game analysis under incomplete information.

The study explores the incentives for CCUS power plants based on evolutionary games and system dynamics. The contributions of this study are: firstly, in the study of the economic viability of CCUS technology, previous literature has focused on the use of real options methods, whereas this paper is based on a tripartite evolutionary game model combined with a system dynamics approach; secondly, the data setting of the main parameters in previous literature is subjective, whereas this paper sets the values of the main

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parameters with reference to realistic data; thirdly, previous literature has focused on the use of government subsidies to promote the deployment of CCUS technology, whereas this paper discusses the importance of government subsidies, penalty mechanisms and cost control for the effective deployment of CCUS technology.

2. MODEL CONSTRUCTION AND SOLUTION OF THE THREE-PARTY EVOLUTIONARY GAME

2.1 Model assumption

(1) It is assumed that the participants are the government, the public, and the coal plants, and all three parties are “economic man”.

(2) The participants are limited rational and dynamically adjust their strategies according to the strategies of other participants, and the information is incomplete.

(3) In this evolutionary game model, each participant has two strategies to choose from: the government's strategy set is "regulate, non-regulate," the public's strategy set is "regulate, non-regulate," and the coal plants' strategy set is "invest in a CCUS retrofit, non-invest in a CCUS retrofit . "

(4) The probability of the government choosing a regulatory strategy is x, and the probability of choosing a non-regulation strategy is $1-x$; the probability of the public choosing a regulatory strategy is y, and the probability of choosing a non-regulation strategy is $1-y$; the probability of a coal plants choosing to invest in a CCUS retrofit strategy is z, and the probability of choosing not to invest in a CCUS retrofit strategy is $1-z$. where $1 \geq x \geq 0$; $1 \geq y \geq 0$; $1 \geq z \geq 0$.

(5) This paper assumes that the public is more knowledgeable about the power plant, so when regulatory costs exist, the public's cost of regulating C_p is less than the government's cost of regulating C_g.

(6) Economic benefits to the public from coal plants when they have not invested in CCUS retrofitting π_{e1}; economic benefits to the public from CCUS plants when they have invested in CCUS retrofitting π_{e2}.We assumed in this paper that $\pi_{e1} < \pi_{e2}$.

TABLE 1 BASIC PARAMETER SYMBOLS AND PARAMETER DESCRIPTIONS

Parameter	*Descriptions*
C_g	The government's cost of regulating
C_o	The cost to the government of treating polluting gases emitted from coal-fired power plants
B_m	The penalty when coal plants generate pollutant gases
R_1	The benefit of the plant when the coal plant did not invest in CCUS retrofit
R_2	The benefit of the plant when the coal plant did invest in CCUS retrofit
C_1	The cost of the plant when the coal plant did not invest in CCUS retrofit
C_2	The cost of the plant when the coal plant did invest in CCUS retrofit
B_g	Coal-fired power plants receive government subsidies for investing in CCUS retrofits
C_p	The public's cost of regulating
π_{e1}	The economic benefits of coal-fired power plants on the public
π_{e2}	The economic benefits to the public from CCUS power plants
M	public regulation receives government incentive
x	Probability of the government choosing a regulatory strategy
y	Probability of the public choosing a regulatory strategy
z	Probability of the coal-fired power plant choosing to invest in a CCUS retrofit strategy

2.2 Evolutionary game analysis

Based on the above assumptions and the basic symbol table, the payoff matrix for the government, the public, and the coal plants are obtained, as shown in Table 2.

TABLE 2 PAYOFF MATRIX

Coal-fired power plant choose to invest in CCUS power plants（z）

Government	*Public* Regulatory（y）	No-regulatory（$1-y$）
Regulatory（x）	$-C_g-M-B_g$, $M-C_p+\pi_{e2}$, $R_2-C_2+B_g$	$-C_g-B_g$, π_{e2}, $R_2-C_2+B_g$
No-regulatory（$1-x$）	0, $-C_p+\pi_{e2}$, R_2-C_2	0, π_{e2}, R_2-C_2

Coal-fired power plant choose to not invest in CCUS power plants（$1-z$）

Government	*Public* Regulatory（y）	No-regulatory（$1-y$）
Regulatory（x）	$B_m-C_g-C_o-M$, $M-C_p+\pi_{e1}$, $R_1-C_1-B_m$	$B_m-C_g-C_o$, π_{e1}, $R_1-C_1-B_m$
No-regulatory（$1-x$）	$-C_o$, $-C_p+\pi_{e1}$, R_1-C_1	$-C_o$, π_{e1}, R_1-C_1

2.3.1 Expectation function for the government

The government's strategy choice set is "regulate, non-regulate", and its expected return is E_{x1} when it chooses to regulate and E_{x2} when it chooses not to regulate, resulting in an average return of E_x.

$$E_{x1}=yz(-C_g-M-B_g)+y(1-z)(B_m-C_g-C_o-M)+(1-y)z(-C_g-B_g)+(1-y)(1-z)(B_m-C_g-C_o) \quad (1)$$

$$E_{x2}=y(1-z)(-C_o)+(1-y)(1-z)(-C_o) \quad (2)$$

$$E_x=xE_{x1}+(1-x)E_{x2} \quad (3)$$

2.3.2 Expectation function for the public

The public's strategy choice set is "regulate, non-regulate", and the public's expected return is E_{y1} when they choose to regulate and E_{y2} when they choose not to regulate, resulting in an average return of E_y.

$$E_{y1}=xz(M-C_p+\pi_{e2})+x(1-z)(M-C_p+\pi_{e1})+(1-x)z(-C_p+\pi_{e2})+(1-x)(1-z)(-C_p+\pi_{e1}) \quad (4)$$

$$E_{y2}=xz(\pi_{e2})+x(1-z)(\pi_{e1})+(1-x)z(\pi_{e2})+(1-x)(1-z)(\pi_{e1}) \quad (5)$$

$$E_y=yE_{y1}+(1-y)E_{y2} \quad (6)$$

2.3.3 Expectation function for coal plants

The set of strategy choices for a coal plants is "invest in a CCUS retrofit, non-invest in a CCUS retrofit", and its expected return is E_{z1} when the plant chooses to retrofit and E_{y2} when they choose not to retrofit, resulting in an average return of E_z.

$$E_{z1}=xy(R_2-C_2+B_g)+x(1-y)(R_2-C_2+B_g)+(1-x)y(R_2-C_2)+(1-x)(1-y)(R_2-C_2) \quad (7)$$

$$E_{z2} = xy(R_1 - C_1 - B_m) + x(1-y)(R_1 - C_1 - B_m) + (1-x)y(R_1 - C_1) + (1-x)(1-y)(R_1 - C_1) \quad (8)$$

$$E_z = zE_{z1} + (1-z)E_{z2} \quad (9)$$

2.3.4 Replicator dynamic equations

According to the theory of evolutionary games, the replicator dynamic equations of the behavioral strategies of the government, the public, and coal plants can be obtained.

$$\begin{cases} F(x) = \frac{\partial x}{\partial t} = x(1-x)\left[(1-z)B_m - C_g - zB_g - yM\right] \\ F(y) = \frac{\partial y}{\partial t} = y(1-y)\left(xM - C_p\right) \\ F(z) = \frac{\partial z}{\partial t} = z(1-z)\left[(R_2 - R_1) - (C_2 - C_1) + xB_g + xB_m\right] \end{cases} \quad (10)$$

Ritzberger et al. (1995) find that for multi-party evolutionary games the evolutionary stability strategy is necessarily a local equilibrium point., thus making F(x)=0，F(y)=0，F(z)=0 be obtained to obtain eight local equilibrium points, which are $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$. According to the Lyapunov stability theory (Newton, 2018), the stability of the local equilibrium points can be judged using the eigenvalues of the Jacobi matrix. The Jacobi matrix is as follows, and the eigenvalues of the local equilibrium points are obtained accordingly.

$$J = \begin{bmatrix} (1-2x)\left[(1-z)B_m - C_g - zB_g - yM\right] & x(x-1)M & x(x-1)\left(B_m + B_g\right) \\ (1-y)yM & (1-2y)\left(xM - C_p\right) & 0 \\ z(1-z)\left(B_m + B_g\right) & 0 & (1-2z)\left[(R_2 - R_1) - (C_2 - C_1) + xB_g + xB_m\right] \end{bmatrix} \quad (11)$$

3. *SYSTEM DYNAMICS SIMULATION ANALYSIS*

3.1 SD simulation model

In order to analyse the behavioural development of the three stakeholders of the game, following the model set out above, the SD model of the evolutionary game between the government, the public and the coal plants was set up using Vensim software, and the dynamics of the investment system were simulated and analysed.

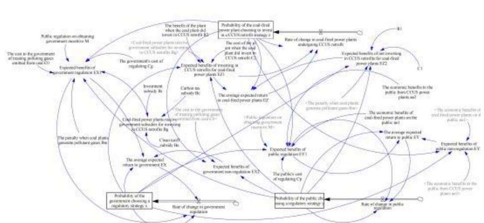

Fig. 1. SD simulation model

3.2 Data setting

In this paper, we set the installed capacity of both the coal plants and the modified CCUS power plant to 600 MW and set most of the parameters with reference to relevant literature. For variables that are difficult to quantify, such as bonus, penalties, and economic benefits, we determine their initial values according to reasonable assumptions and change their values during the simulation process for sensitivity analysis.

3.3 Simulation results

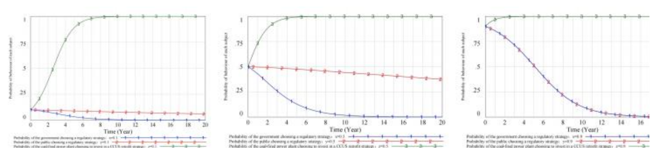

Fig. 2. Evolutionary trajectory

According to the initial values of the parameters, the initial values are adjusted by dividing the adjustment parameter $\rho = 10^9$, and then the evolutionary trajectory under the initial conditions is obtained, as shown in Fig. 3, where the simulation start time is 0, the end time is 20, and the step size is 0.0625.

If the initial strategy probabilities of x、y、z are set to 0.1, 0.5 and 0.9 respectively, Three stakeholders always adopt the strategy of $E_4(0,0,1)$. These results show that different initial strategy probabilities have a small impact on simulation outcomes, and the SD model of the evolving game among government, the public, and coal plants has a unique and stable point of evolutionary. The high cost of government and public regulation means that both stakeholders lack the will to regulate coal plants for CCUS upgrades because the revenue they receive can hardly compensate for their regulatory costs.

3.4 Stability analysis results

According to Lyapunov stability theory (Newton, 2018), we can see that $E_4(0,0,1)$ the only evolutionary stability strategy in the game between the government, the public, and the coal plants, in which both the government and the public choose not to regulate and the coal plants will choose to invest in a retrofit of the CCUS. The stability analysis results are consistent with the system dynamics simulation results.

TABLE 3 THE STABILITY OF EACH EQUILIBRIUM POINT

Equilibrium point	*The eigenvalues*			*Stability*
$E_1(0,0,0)$	-	-	+	Saddle-point
$E_2(1,0,0)$	+	0	+	Saddle-point
$E_3(0,1,0)$	-	+	+	Saddle-point
$E_4(0,0,1)$	-	-	-	Stable point
$E_5(1,1,0)$	+	0	+	Saddle-point
$E_6(1,0,1)$	+	0	-	Saddle-point
$E_7(0,1,1)$	-	+	-	Saddle-point
$E_8(1,1,1)$	+	0	-	Saddle-point

4. **SENSITIVITY ANALYSIS**

To explore the impact of key parameters on the behavior of the three stakeholders in the game, this paper presents only a few important analyses. Here, the initial values x、y、z are set to （0.5,0.5,0.5） respectively, and other parameters keep the initial values the same.

4.1 Impact of the clean tariff subsidy $P_c - P_s$

According to the notice of National Development and Reform Commission, this paper sets the difference between the clean tariff and the feed-in tariff as the clean tariff subsidy. Changes in the clean tariff subsidy affect the behaviour of the government, the public and coal plants.Clean tariff subsidies have increased and the willingness of government and the public to not regulate has become stronger, but coal plants have chosen to invest in CCUS. From the perspective of China's existing energy policy, the government can induce coal plants to invest early in CCUS retrofits in order to implement emissions-reduction technologies by increasing clean tariff subsidies.

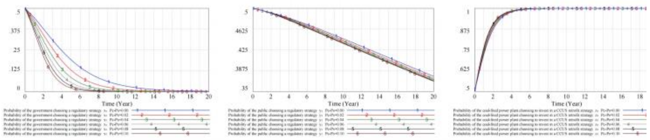

Fig. 3. Sensitivity analysis of the clean tariff subsidy

4.2 Impact of the carbon tax τ

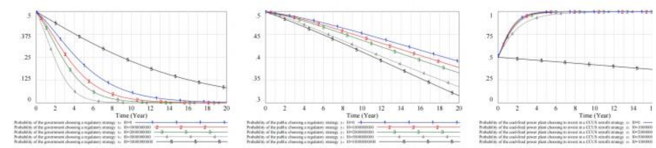

Fig. 6. Sensitivity analysis of the investment cost

Carbon trading and carbon tax, as two of the main policy tools to reduce carbon emissions, are actively used in many countries and regions. This paper considers the carbon tax as a government subsidy and conducts a sensitivity analysis. Increased carbon tax and a stronger willingness on the part of government and the public not to regulate, but a stronger willingness on the part of coal plants to choose to invest in CCUS. Given the current situation in China, where only a carbon trading market exists, the imposition of a carbon tax in China has a significant incentive for coal plants to choose to invest in CCUS retrofits.

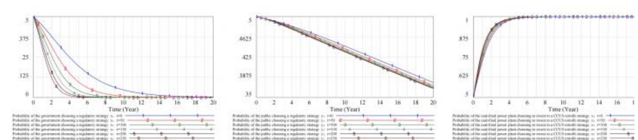

Fig. 4. Sensitivity analysis of the carbon tax

4.3 Impact of penalty when coal plants generate pollutant gases B_m

The penalties received by coal plants for generating polluting gases will be credited as a cost to the revenue of the coal plants and will therefore be a constraint on the behaviour of the coal plants. When the penalties are small, coal plants tend to choose not to invest in CCUS retrofits; when the penalties increase and coal plants are faced with large fines, they tend to behave in a 'invest in CCUS' strategy in order to maximise their profits. It follows that the government can promote the diffusion of emission reduction technologies by increasing certain nominal penalties to induce coal plants to invest in CCUS retrofits.

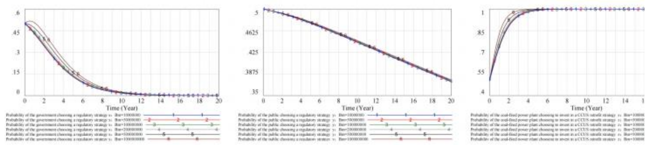

Fig. 5. Sensitivity analysis of the penalty

4.4 *Impact of the investment cost of CCUS technology during construction* I_0

As the cost of investing in CCUS becomes greater for coal plants, their willingness to invest decreases, and when the cost of investment is large enough, even fully subsidised coal plants will still choose not to invest. As can be seen, high costs are the reason why CCUS plants have struggled to gain widespread deployment, and cost control is important in advancing CCUS technology.

5. SUMMARY AND POLICY RECOMMENDATIONS

This study addresses a gap in the literature by employing evolutionary game and system dynamics methods to analyze the dynamical system involving the government, the public, and coal plants. By constructing an evolutionary game payoff matrix, replicator dynamics equations, and an evolutionary game model, we investigate the evolutionary stabilization strategy of the system. Simulations using Vensim software validate our theoretical results. We further analyze the impact of key parameters on the evolutionary trajectory. The results show that:

(1) The system has a unique and stable evolutionary stability point, where the government and public choose not to regulate, and coal plants invest in CCUS retrofit.

(2) Clean electricity subsidies, carbon tax subsidies, investment subsidy coefficients, and bonuses increase the government's willingness not to regulate, while fines and investment costs lower the probability of regulation.

(3) Subsidies for clean electricity, carbon tax, investment, and investment costs can accelerate public behavioral evolution towards not regulating, but if regulation incentives outweigh costs, the public may choose to regulate at first, then the public's willingness to regulate tends to decrease over time. Increasing investment cost decreases the probability of public regulation.

(4) Subsidies for clean electricity, carbon tax, and investment can encourage coal plants to invest in CCUS retrofitting. Penalties from regulation can motivate investment. However, increasing investment costs decrease coal plants' willingness to invest. If investment cost increases beyond a certain degree, coal plants will not invest in CCUS retrofitting.

Based on the above results, this paper makes the following recommendations:

(1) Levy a carbon tax. To reduce CO_2 emissions and avoid financial burdens, enterprises emitting CO_2 should be subject to a carbon tax, while those reducing CO_2 should receive subsidies. China, which currently only has a carbon trading market, will gradually levy the carbon tax in the future, and will have a significant incentive for coal plants to choose to invest in CCUS retrofit.

(2) Increase the clean electricity tariff subsidy. To achieve energy efficiency and reduce CO_2 emissions, increasing the level of clean electricity tariff subsidies is crucial. This will incentive power companies, particularly coal plants, to invest in CCUS retrofits and implement technologies that reduce CO_2 emissions. In line with China's existing energy policy, the government can increase clean electricity tariff subsidies to encourage coal plants to invest in CCUS retrofits at the earliest opportunity.

(3) Increase penalties. Penalties can effectively constrain coal plants and motivate them to consciously and actively adopt CCUS technologies. Increasing fines for polluting gases or other violations can incentive coal plants to invest in CCUS retrofits and promote emission reduction technologies.

(4) Control investment costs. If the investment cost is too high, it will affect the incentive for coal plants to invest in CCUS power plants. To advance the widespread deployment of CCUS technology, it is important to control the investment costs. The government can reduce the cost of using the technology by developing new technologies and improving management efficiency.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] International Energy Agency. Global Energy Review: CO2 Emissions in 2021; 2022.

[2] Intergovernmental Panel on Climate Change. IPCC special report on carbon dioxide carbon and storage; 2005.

[3] The Institute for Energy Economics and Financial Analysis. Holy grail of carbon capture continues to elude coal industry;2018.

[4] Vikara D, Shih C Y, Lin S M, et al. US DOE’ s economic approaches and resources for evaluating the cost of implementing carbon capture, utilization, and storage (CCUS). Journal of Sustainable Energy Engineering; 2017, 5(4): 307-340.

[5] Smets F. Exporting versus FDI: The effect of uncertainty, irreversibilities and strategic interactions. Yale University; 1991.

[6] Ritzberger K, Weibull J W. Evolutionary selection in normal-form games. Econometrica: Journal of the Econometric Society, 1995: 1371-1399.

[7] Newton J. Evolutionary game theory: A renaissance. Games, 2018, 9(2): 31.

[8] Zhang W, Dai C, Luo X, et al. Policy incentives in carbon capture utilization and storage (CCUS) investment based on real options analysis. Clean Technologies and Environmental Policy; 2021, 23: 1311-1326.

[9] National Energy Board (2013, October 16) APA citation. Notice of the National Development and Reform Commission on matters related to the adjustment of feed-in tariffs for power generation enterprises. Retrieved from http://www.gov.cn/zwgk/2013-10/16/content_2508002.htm .