

Article

An Evolutionary Game Study on Green Technology Innovation of Coal power Firms under the Dual-Regulatory System

Kai Ou ^{1,2}, Yu Shi ³ and Wenwen Zhou ^{3,*}

¹ School of Economics and Management, China University of Mining and Technology, Xuzhou 221116, China; ouw03@126.com

² CCTEG Chongqing Engineering (Group) Co., Ltd., Chongqing 400030, China

³ School of Economics and Management, Beijing University of Technology, Beijing 100124, China; shiyuu216@163.com

* Correspondence: zhouwenwen@bjut.edu.cn

Abstract: The transformation of Chinese coal power firms is crucial for achieving carbon emission reduction (CER) goals, and promoting green technology innovation (GTI) is the key for the achievement. To examine the interactive mechanism of central and local government regulatory behavior and coal power firms' GTI behavior under China's dual-regulatory system, this paper introduces environmental impact coefficients and develops a tripartite evolutionary game model (EGM) from the perspective of CER. The influencing factors and interactive relationships among them are analyzed. Additionally, through numerical simulation, the impacts of changes in central and local government S&P (subsidies and penalties) on the evolution of the system are also obtained. The findings indicate the following: (1) Enhancing the initial willingness can accelerate the system's attainment of an optimal state. The local government exhibits a slower pace of evolution. Coal power firms are more sensitive to changes in the initial willingness of the central government. (2) The local government is more sensitive to changes in the central government's S&P intensity rather than changes in the central government's initial willingness. Low levels of central government S&P and high penalties are ineffective, while high subsidies can lead to a sudden decrease in the local government's willingness. (3) Local government penalties have a positive correlation with their effectiveness in promoting GTI, whereas high subsidies are ineffective. (4) The separate implementation of subsidies or penalties by either the central or the local government is detrimental to achieving the optimal state. Such an approach renders the fluctuant or negative behavior of the local government and coal power firms.



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Keywords: tripartite evolutionary game; green technology innovation; coal power firms; dual-regulatory system

1. Introduction

Coal is a major source of energy and greenhouse gas emissions in the world. To limit global warming and achieve the Paris Agreement goals, coal use must be phased out before 2040 [1]. For China, India, Russia, and other countries where coal plays a fundamental role in energy, promoting the clean and efficient use of coal is the key to energy transformation [2,3]. China, as the largest developing country, needs a large amount of energy supply. In 2020, Chinese coal consumption was 82.27 EJ (82.27×10^{18} J), accounting for 54.3% of the global total in the BP World Energy Statistical Yearbook. And more than 40% of coal is used for power consumption in China [4]. The transformation of Chinese coal-fired power firms is crucial for global carbon emission reduction (CER) tasks. The large amount of carbon emissions brought about by coal power generation has caused ecological environmental pressure. China has also issued a series of measures to promote CER in coal power firms.

Innovation-driven green development has become the key to achieving industrial transformation and improving quality and efficiency in the new era [5]. Technological

innovation, as the primary engine of CER, provides a breakthrough for the government's CER [6]. Promoting coal power firms' green technology innovation (GTI) is essential for the achievement of the Chinese dual-carbon target. For coal power firms, GTI can promote their sustainable development and competitiveness [7]. But there is still a fungibility between green and non-green technologies, and most firms in heavily polluting industries are unwilling to implement GTI without external intervention [8]. The willingness of implementing GTI for coal power firms is unclear mainly due to the following reasons.

First, there is a need to balance resources between risk pressure management and GTI in the context of emission reduction requirements and rapid transition. China, as a major carbon-emitting country and the largest developing nation, has announced its dual-carbon goals of achieving carbon neutrality by 2060. This goal is closely tied to the Paris Agreement and plays a critical role in limiting global temperature rise below 1.5 °C. Compared with the carbon neutrality schedules of 71 years for the European Union and 43 years for the United States (14 October 2021, Foreign Ministry Spokesperson Zhao Lijian Hosts Regular Press Conference, Ministry of Foreign Affairs, http://newyork.fmprc.gov.cn/web/wjb_673085/zzjg_673183/gjs_673893/gjzz_673897/lhgyffz_673913/fyrth_673921/202110/t20211014_9552665.shtml, accessed on 14 October 2021), China has set only a 30-year target. This means that China will reach the world's highest CER intensity level (Xie Zhenhua: Implement the goal of carbon peak and carbon neutralization, accelerate green and low-carbon transformation and innovation, http://www.itibmic.com/info_main/20221129/271818.html, accessed on 11 October 2021). Therefore, it is crucial to expedite the swift transition of China's high-emission industries. However, this process may introduce both market uncertainties and considerable transformation pressure, which could result in significant market risks for coal power firms. Coal power firms need to increase resources to cope with market risks and uncertainties, which in turn affects their investment in GTI activities. Second, there is a mismatch between the costs and benefits of GTI. From a cost perspective, GTI often comes with high risks and costs [9], which will cause significant financial pressure on firms. From a revenue perspective, GTI has dual externalities, including an innovation spillover in the process of technology research and development and an environmental spillover effect at the adoption and diffusion stage, which is a central factor in reducing willingness to carry out GTI [10–12]. Third, a dilemma situation is caused by the contradiction between CER and development goals. Firms' development cannot be separated from energy supply, especially for coal power firms that require a large amount of coal combustion. With the outbreak of the energy crisis, China has also experienced a large-scale power crisis. Ensuring the stability of the electricity supply has become the primary consideration for decision-makers, which also emphasizes the importance of coal power firms. Moreover, as the market economy recovers in the era of the epidemic, firms may pursue development opportunities while ignoring CER. Development and CER goals create a difficult trade-off for coal power firms. In addition, the dual-regulatory system has an impact on coal power firms' GTI. Government regulation is important in ensuring the sustainable development of the energy sector [13], and it frequently affects enterprises' capital flow and innovative investment. Government subsidies, as a source of funding for enterprises, can promote their GTI. However, the innovation risks brought by policy uncertainty can also deter enterprises [14]. The uncertainty of the intensity of government responsibility execution in environmental regulations puts coal power firms in a wait-and-see state.

China's existing "commission agency" system may lead to environmental execution alienation. In terms of decentralization of environmental supervision, an improvement in the level of decentralization gives local governments greater autonomy in establishing environmental management systems and environmental law enforcement [15]. For the central government, the fragmentation of environmental responsibilities may lead to inadequate supervision. Given the difficulty and high cost of supervision, the central government sometimes has to adjust the supervision method and intensity [16], which may lead to the relaxation of central government supervision over local governments, resulting in ineffective implementation of environmental goals. For local governments, the

contradiction between the externality of environmental policy effect and the internality of policy cost always exists [17], which may lead them to choose negative strategies. Moreover, the cost of peer-to-peer regulation of firms is huge, which will put financial pressure on local governments. Existing local government assessment system has an obvious GDP trend [18], and local governments may ignore CER in the case of unbalanced returns and pursuit of economic recovery. Therefore, under the dual-supervision system, there is a certain tension between the central government's environmental deployment of CER and the implementation of local governments, showing a game relationship.

In summary, there is a clear game relationship between the central government, local government, and coal power firms. Furthermore, current research is mostly conducted between coal power firms and the local government or multi-type game players, and the parameter settings are relatively macro. Focusing on exploring how to ensure the accurate implementation of regulatory tasks and effectively promote GTI in coal power firms under the dual-regulatory system, this paper builds a tripartite evolutionary game model (EGM) to examine the relationship among them. Additionally, this study innovatively considers micro-level parameters measured by carbon emissions and examines the impacts of carbon emissions on both external environments and internal operations of the firms, thus addressing a research gap in previous studies. The following questions will be answered: (i) What are the factors that affect the control measures of the central and local governments under the dual-regulatory system? What are the factors that affect the GTI of coal power firms? (ii) How should the central government regulate regulatory measures against local governments to urge them to implement emission reduction targets? (iii) How should local governments regulate the rewards and punishments for enterprises to effectively promote their GTI and achieve the lowest cost control?

The following sections appear below: Section 2 reviews the literature and emphasizes the contribution of this paper. Section 3 is the model hypothesis and construction. Section 4 presents the model analysis. Section 5 presents a numerical simulation and discusses the results. Section 6 is the conclusions and implications.

2. Literature Review

Coal power generation is a major source of GHGs and harmful airborne emissions globally [19]. In the short term, coal is China's primary source of electricity [20]. With the promotion of the dual-carbon target, achieving CER in coal power firms has become the priority. Many scholars have studied the influencing factors of coal power firms' CER, finding that location, fuel, and technology will have an impact on it. Jeon et al. (2010) [21] evaluated the characteristics of GHG emissions from power plants. Bituminous coal, anthracite coal, and sub-bituminous coal were used as fuel in the inspected power plants. The results showed that compared with the IPCC data, the carbon emission of anthracite was 10.8% higher, that of bituminous coal was 5.5% lower, and that of sub-bituminous coal was 1.9% higher. Li et al. (2020) [22] created a high-resolution list of emission variables for the coal power sector in China and created provincial emission factors. Additionally, the external contributions of four internal coal power sector policies to renewable energy development in various Chinese provinces were presented. Due to regional variations, it was necessary to tailor the strategy for continued decarbonization after 2020 to the unique characteristics of each province. Du et al. (2021) [23] used 2158 coal-fired power units of various types from 833 CFPPs in 24 Chinese provinces as research samples. The synergy between the structure and technical emission reduction in CFPPs was assessed and evaluated using top-down structural emission reduction analysis and bottom-up technical emission reduction analysis. It was found that reducing structural emissions was a crucial strategy for achieving CER goals.

In addition, considering both green and innovative characteristics, GTI can effectively improve the energy utilization and enhance the competitiveness and economic performance of firms. Many scholars have found that promoting GTI is the key to coal power firms' CER. For example, Yu et al. (2011) [24] established a bottom-up model to

evaluate the performance of the Chinese coal power industry in terms of resource consumption and environmental emissions. Technological innovation was proved to be the decisive factor in reducing the resource use and environmental impact of power production. Zhao et al. (2019) [25] estimated China's electricity demand from 2020 to 2040 and calculated the CER by using support vector machines and UNFCCC's carbon emission calculation method. It was found that the traditional clean coal power generation technology could only reduce carbon emissions to a certain extent, while achieving greater CER may depend on carbon capture and storage and renewable energy. Xu et al. (2021) [26] adopted the system dynamics method and found that the coal market environment restricted the improvement of the green and low-carbon development levels of coal firms. Improving the innovation level is the most effective way for coal firms to solve these problems. Therefore, it is necessary to promote GTI to achieve CER in coal power firms.

GTI is less of a market incentive than other innovations, and governments' environmental policy tools will be conducive to it [27]. Many scholars have studied the influence factors of coal power firms' GTI and found that environmental regulation plays a key role. Considering government policies, Ding et al. (2018) [28] established a model to investigate the opportunities for outsourcing pollutant reduction services to meet environmental constraints. The results indicated that the price of green service outsourcing was related to government incentive policies, which defined the share of two partners. Sun et al. (2022) [29] analyzed the strategies of the government and coal enterprises in resource integration from the perspective of government regulation. The results indicated that the combination of government regulations helped to improve the efficiency of strategic choices for coal enterprises. Therefore, there was a strong interactive relationship between the government and coal power firms, and they were important stakeholders under the dual-carbon target. Moreover, evolutionary game theory (EGT) is an effective means to study the strategic decision-making of relevant stakeholders [30].

EGT believes that subjects are bounded rational [31]. It uses the percentage of individuals who choose different pure strategies to replace the mixed strategies in game theory and is widely used to analyze the decision-making of different subjects [32]. Many scholars have used EGT to study the interaction between coal power firms and the local government. For example, Fan et al. (2021) [33] constructed a tripartite EGM for local governments, the power industry, and coal enterprises. It was found that strengthening environmental supervision by local governments was an inevitable choice to promote the transformation and upgrading of the coal and power industries. Liu et al. (2022) [34] analyzed the equilibrium state, evolution trajectory, and corresponding critical conditions of the government and coal power firms based on the EGT. It was found that the carbon trading scheme could directly promote the upgrading of coal and electricity, and it could be improved by establishing the electricity market trading mechanism.

However, in reality, the CER process of coal power firms often involves multiple subjects. Many scholars have explored the interactive relationship between coal power firms and multiple subjects by constructing a tripartite EGM. For example, Wang et al. (2021) [35] proposed a cooperation relationship among CEs, solar power plants (SPPs), and coal-fired thermal power plants (TPPs). Based on Chinese current policies, the evolution process was simulated and discussed by using the tripartite EGM. Wang et al. (2023) [36] proposed a public-private partnership project including the government, coal-fired power plants (CTPPs), and solar photovoltaic power plants (PVPPs) and used EGM to evaluate the impact of typical factors on the project when all participants cooperated. The results showed that increasing subsidies could enhance the willingness of CTPP to participate but reduced the willingness of the government to participate. Moreover, in reality, the central government will supervise the CER work of local governments, which will have a certain impact on their behavior strategies. Local governments' measures will also directly affect coal power firms' GTI. But few studies have been conducted between the central government, local governments, and coal power firms.

The literature review shows that current research is mostly conducted between coal power firms and local government or multi-type game players, and the parameter settings are relatively macro. Therefore, based on the interaction between the three parties, this study explored their complex behaviors and interaction mechanisms by constructing a tripartite EGM to provide reasonable and effective policy guidance for the coal power firm and government supervision under the dual-carbon target. The main contributions of this study are threefold, as follows: (i) By building a tripartite EGM of “central government–local government–coal power firm”, this paper highlights the dynamic interaction among them and reveals the slowest evolution speed of the local government. (ii) By adopting a carbon emissions perspective to parameterize and introducing an environmental impact coefficient, this paper quantifies the effects of GTI behavior on firms’ internal and societal benefits. (iii) Through numerical simulations, this study reveals the ineffectiveness of the central government’s low S&P (subsidies and penalties) and the local government’s high subsidies. Additionally, this paper identifies the importance of concurrent implementation of S&P, particularly of central government measures.

3. Model Building

3.1. Game Mechanism for Each Participant

(1) The central government. Under the dual-regulatory system, the central government formulates unified environmental policies that are implemented by local governments within their respective jurisdictions [37]. The central government has integrated the implementation of these policies by local governments into a supervisory system and established S&P accordingly (Guiding Opinions of the Central People’s Government of the People’s Republic of China on Strengthening the Source Prevention and Control of Ecological Environment in High Energy Consumption and High Emission Construction Projects, https://www.gov.cn/zhengce/zhengceku/2021-06/01/content_5614531.htm, accessed on 30 May 2021), which also entails high regulatory costs. Additionally, the presence of numerous local governments may result in incomplete supervision by the central government. As a result, the central government has two behavioral strategies: “actively supervise” and “passively supervise”.

(2) The local government. In response to central supervision, local governments may adopt active implementation to avoid punishment. Excessive carbon emissions (ECEs) can cause environmental pollution issues, prompting local governments to actively implement and prevent environmental crises. When local governments engage in active implementation, they provide subsidies to energy companies for GTI, aiming to mitigate their negative impacts on the environment [18]. Furthermore, local governments will strengthen regulations for coal power firms and impose penalties for ECEs.

However, the process of achieving economic benefits through environmental improvements is typically time-consuming, and the performance evaluation system of the Chinese government often prioritizes the GDP. Consequently, local governments may prioritize regional economic development over stringent regulation, leading to passive implementation [18]. Under passive implementation, local governments tend to lessen their focus on the carbon emissions of coal power firms. Loosening regulations can result in firms neglecting their CER efforts, which poses environmental governance challenges.

(3) Coal power firms. For coal power firms, there exist two behavioral strategies: “implement GTI” and “not implement GTI”. GTI brings new processes and technologies that are effective for CER and bring benefits to coal power firms. Commercializing green technology and adopting product recycling, reproduction, and transformation contribute to profit generation from GTI [38]. These will drive coal power firms to implement GTI. However, GTI carries significant risks and costs [9], exerting substantial financial pressure on enterprises. Additionally, GTI entails dual externalities [10–12]. These factors may lead coal and power companies to choose not to implement GTI.

3.2. Model Assumptions

Based on the interaction among the three parties, the assumptions provided in this study are as follows.

Assumption 1. The central government has two behavioral strategies: “actively supervise” and “passively supervise”, with the probabilities being x and $1 - x$, respectively ($0 \leq x \leq 1$).

Assumption 2. The local government has two behavioral strategies: “actively implement” and “passively implement”, with the probabilities being y and $1 - y$, respectively ($0 \leq y \leq 1$).

Assumption 3. A coal power firm has two behavior strategies: “implement GTI” and “not implement GTI”, with the probabilities being z and $1 - z$, respectively ($0 \leq z \leq 1$).

Assumption 4. When the central government actively supervises, it will give reward D_2 to the local government for active implementation and a certain penalty S_2 to the local government for passive implementation.

Assumption 5. When the coal power firm implements GTI, carbon emissions will be reduced and lower than the quota. ΔH_1 depicts the CER due to the coal power firm’s GTI. Coal power firms will benefit from the CER as well as the advancement and application of green technologies. The cost and benefit of reducing each unit of carbon emissions are identified as C and P , respectively. That is, the cost generated by the coal power firm’s GTI is $C\Delta H_1$, while the benefit obtained is $P\Delta H_1$.

Conversely, when the coal power firm does not implement GTI, its carbon emission will be higher than the quota set by local government, and the ECE is recorded as ΔH_2 . Additionally, the net income of a coal firm without GTI is denoted as C_1 .

Assumption 6. Only when the local government actively supervises will it concentrate on the carbon emissions of the coal power firms and give rewards or penalties based on their carbon emissions. V represents the local governmental reward for each unit of CER, while U represents the penalty for each unit of ECE. That is, when the local government actively implements, it will closely monitor the firm’s carbon emission behavior and provide incentives $V\Delta H_1$ to a coal power firm that implements GTI while penalizing a coal power firm $U\Delta H_2$ that does not implement GTI. The cost of active implementation by the local government is denoted as C_3 .

Assumption 7. The cost of active supervision by the central government is S_1 . Only when the central government actively supervises will it pay attention to the implementation of the local government and reward or penalize it based on its performance. The central governmental subsidy to a local government that actively implements is denoted as D_2 . S_2 represents the central governmental punishment for a local government that passively implements.

Assumption 8. CER is beneficial to the environment. The environmental benefit brought by CER per unit is denoted as R . ECEs will have specific environmental negative effects, and the unit environmental negative effects are recorded as L . That is, when a coal power firm implements GTI, the environmental benefit to the local government is $R\Delta H_1$. When a coal power firm does not implement GTI, it will impose a certain environmental burden $L\Delta H_2$ on the local government.

Assumption 9. Furthermore, a coal power firm’s carbon emissions will have an impact on the central government. The positive environmental benefit coefficient of a coal power firm’s GTI on the central government is α , and the negative environmental impact coefficient of a coal power firm’s ECE behavior on the central government is β . That is, when a coal power firm implements GTI, the central government gains environmental benefits $\alpha R\Delta H_1$. When a coal power firm does not implement GTI, the central government will obtain negative environmental effects $\beta R\Delta H_2$ due to ECEs. Moreover, considering the influence of

each party on the outcome, $\alpha = 1$ is set when all three parties of the game are in a positive state, and $\beta = 1$ when all three parties of the game are in a negative state.

Therefore, in terms of parameter settings, this study takes into full consideration the S&P measures and responsibility under the dual-regulatory system, as well as the impact of GTI behavior by coal power firms on the internal operations and external environment. Additionally, carbon emissions have temporal and spatial externalities, with their impacts on global climate change being global in nature. Therefore, we introduce positive and negative environmental impact coefficients for coal power firms on local and central governments. Moreover, based on current local government S&P measures (Notice on the Application of Subsidy Funds for the Green Transformation and Upgrading Project in Tongzhou District in 2022, Tongzhou District People's Government, Beijing <http://www.bjtz.gov.cn/bjtz/xxfb/202208/1610458.shtml>, accessed on 9 August 2022; Beijing fined up to 250 yuan per ton for exceeding carbon emissions, National Energy Administration, http://www.nea.gov.cn/2013-12/30/c_133006477.htm, accessed on 30 December 2013), we approach parameter settings from a more micro perspective by utilizing carbon emissions as the measurement unit. This ensures that the parameter settings align with actual conditions and allows for quantifying the intensity and impact of GTI. Unlike previous studies [39–42], this paper introduces the environmental coefficient in units of CER or ECEs to further refine the impact of carbon emissions under GTI behavior. Table 1 summarizes the parameter settings based on the assumptions.

Table 1. Parameter setting of the game model.

Symbol	Stakeholders	Description
x	Central government	The probability that the central government actively supervises
S_1		The cost of active supervision by the central government
D_2		Subsidies provided by the central government to the local government for active implementation
S_2		Penalties imposed by the central government on the local government for passive implementation
α		The environmental positive benefit coefficient of a coal power firm on the central government
$1 - x$		The probability that the central government passively supervises
β		Negative environmental influence coefficient of a coal power firm on the central government
y	Local government	The initial probability of a local government that actively implements
C_3		The cost of active implementation by the local government
V		Subsidies for a coal power firm's CER per unit
U		Penalties for a coal power firm's ECEs per unit
$1 - y$		The initial probability of passive implementation by the local government
L		The negative environmental benefits per unit brought by a coal power firm's ECEs to the local government
R		The environmental benefits from a coal power firm's CER per unit
z	Coal power firm	The initial probability of a coal power firm implementing GTI
C		The cost from CER per unit
C_1		Initial net income of a coal power firm when it does not implement GTI
P		The revenue from CER per unit
ΔH_1		Carbon emissions reduced by a coal power firm when it implements GTI
$1 - z$		The initial probability of a coal power firm that does not implement GTI
ΔH_2		ECE of a coal power firms when it does not implement GTI

3.3. Income Matrix Construction

The benefits of the three parties are summarized in Table 2 under different conditions.

Table 2. Income matrix of game players.

Symbol	Behavioral Strategy (Central Government, Local Government, and Coal Power Firm)	Benefits of Tripartite Behavior Strategy (Central Government, Local Government, and Coal Power Firm)
I	(Actively supervises, actively implements, implements GTI)	$\{-S_1 - D_2 + R\Delta H_1,$ $-C_3 - V\Delta H_1 + R\Delta H_1 + D_2,$ $C_1 + (P - C + V)\Delta H_1\}$
II	(Actively supervises, actively implements, does not implement GTI)	$\{-S_1 - D_2 - \beta L\Delta H_2,$ $-C_3 + U\Delta H_2 + D_2 - L\Delta H_2,$ $C_1 - U\Delta H_2\}$
III	(Actively supervises, passively implements, implements GTI)	$\{-S_1 + S_2 + \alpha R\Delta H_1,$ $R\Delta H_1 - S_2,$ $C_1 + (P - C)\Delta H_1\}$
IV	(Passively supervises, actively implements, implements GTI)	$\{\alpha R\Delta H_1,$ $-C_3 + R\Delta H_1 - V\Delta H_1,$ $C_1 - (P - C + V)\Delta H_1\}$
V	(Passively supervises, actively implements, does not implement GTI)	$\{-\Delta H_2\beta L,$ $-C_3 + U\Delta H_2 - L\Delta H_2,$ $C_1 - U\Delta H_2\}$
VI	(Passively supervises, passively implements, implements GTI)	$\{\alpha R\Delta H_1,$ $R\Delta H_1,$ $C_1 + \Delta H_1(P - C)\}$
VII	(Actively supervises, passively implements, does not implement GTI)	$\{-S_1 + S_2 - \beta L\Delta H_2,$ $-S_2 - L\Delta H_2,$ $C_1\}$
VIII	(Passively supervises, passively implements, does not implement GTI)	$\{-L\Delta H_2$ $-L\Delta H_2,$ $C_1\}$

4. Model Analysis

4.1. Analysis of the Evolution and Stability Strategy of Central Government

According to Table 2, when the central government actively supervises, the expected revenue is

$$G1 = yz(-S_1 - D_2 + R\Delta H_1) + y(1 - z)(-S_1 - D_2 - \beta L\Delta H_2) + (1 - y)z(-S_1 + S_2 + R\Delta H_1) + (1 - y)(1 - z)(-S_1 + S_2 - \beta L\Delta H_2) = -yD_2 + zR\Delta H_1 - S_1 + S_2 - \beta L\Delta H_2 - yS_2 + z\beta L\Delta H_2 \quad (1)$$

When the central government negatively supervises, the expected revenue is

$$G2 = yz\alpha R\Delta H_1 - y(1 - z)\beta L\Delta H_2 + (1 - y)z\alpha R\Delta H_1 - (1 - y)(1 - z)L\Delta H_2 = -y\beta L\Delta H_2 + yz\beta L\Delta H_2 + z\alpha R\Delta H_1 - L\Delta H_2 + yL\Delta H_2 + zL\Delta H_2 - yzL\Delta H_2 \quad (2)$$

The average expected revenue of the central government is

$$G = xG1 + (1 - x)G2 = -xyD_2 + xzR\Delta H_1 - xS_1 + xS_2 - x\beta L\Delta H_2 - xyS_2 + xz\beta L\Delta H_2 - y\beta L\Delta H_2 + yz\beta L\Delta H_2 + z\alpha R\Delta H_1 - L\Delta H_2 + yL\Delta H_2 + zL\Delta H_2 - yzL\Delta H_2 + xy\beta L\Delta H_2 - xyz\beta L\Delta H_2 - xz\alpha R\Delta H_1 + xL\Delta H_2 - xyL\Delta H_2 - xzL\Delta H_2 + xyzL\Delta H_2 \quad (3)$$

The dynamic equation of the central government for active supervision is

$$F(x) = \frac{dx}{dt} = x(G1 - G) = x(1 - x)(-yD_2 + zR\Delta H_1 - S_1 + S_2 - \beta L\Delta H_2 - yS_2 + z\beta L\Delta H_2 + y\beta L\Delta H_2 - yz\beta L\Delta H_2 - z\alpha R\Delta H_1 + L\Delta H_2 - yL\Delta H_2 - zL\Delta H_2 + yzL\Delta H_2) \quad (4)$$

According to the stability theorem of differential equations and the properties of evolutionary stability strategy (ESS), when $F'(u) < 0$, u^* is an ESS. To analyze the evolutionary stabilization strategies of the central government, let $F(x) = 0$, and we can obtain

$$x_1 = 0, x_2 = 1, y_a = \frac{-zR\Delta H_1 + S_1 - S_2 + \beta L\Delta H_2 - z\beta L\Delta H_2 + z\alpha R\Delta H_1 - L\Delta H_2 + zL\Delta H_2}{-D_2 + \beta L\Delta H_2 - z\beta L\Delta H_2 - L\Delta H_2 + zL\Delta H_2 - S_2} \quad (5)$$

When $y = y_a$, then $F(x) \equiv 0$. The central government's strategic choices are stable in this case. When $y \neq y_a$, let $F(x) = 0$, then $x_1 = 0, x_2 = 1$ are two stable points. Taking the derivative of $F(x)$, we can obtain $\frac{dF(x)}{dt} = (1 - 2x)(-yD_2 + zR\Delta H_1 - S_1 + S_2 - \beta L\Delta H_2 - yS_2 + z\beta L\Delta H_2 + y\beta L\Delta H_2 - yz\beta L\Delta H_2 - z\alpha R\Delta H_1 + L\Delta H_2 - yL\Delta H_2 - zL\Delta H_2 + yzL\Delta H_2)$. When $y > y_a$, $\frac{dF(x)}{dt}\bigg|_{x=0} < 0$, $\frac{dF(x)}{dt}\bigg|_{x=1} > 0$. $x_1 = 0$ is the evolutionary equilibrium point, and the strategy of the central government is "passively supervise". When $y < y_a$, $\frac{dF(x)}{dt}\bigg|_{x=0} > 0$, $\frac{dF(x)}{dt}\bigg|_{x=1} < 0$. $x_2 = 1$ is the evolutionary equilibrium point, and the strategy of the central government is "actively supervise".

4.2. Analysis on the Evolution and Stability Strategy of Local Government

When the local government actively implements, the expected revenue is as follows:

$$L1 = xz(-C_3 - V\Delta H_1 + R\Delta H_1 + D_2) + x(1 - z)(-C_3 + (U - L)\Delta H_2 + D_2) + (1 - x)z(-C_3 + (R - V)\Delta H_1) + (1 - x)(1 - z)(-C_3 + (U - L)\Delta H_2) = xD_2 + zR\Delta H_1 - zV\Delta H_1 - C_3 + U\Delta H_2 - L\Delta H_2 - zU\Delta H_2 + zL\Delta H_2 \quad (6)$$

When the local government passively implements, the expected revenue is

$$L2 = xz(R\Delta H_1 - S_2) + x(1 - z)(-S_2 - L\Delta H_2) + (1 - x)z(R\Delta H_1) + (1 - x)(1 - z)(-L\Delta H_2) = -xS_2 + zR\Delta H_1 - L\Delta H_2 + zL\Delta H_2 \quad (7)$$

The average expected revenue of the local government is

$$L = yL1 + (1 - y)L2 = yxD_2 - yzV\Delta H_1 - yC_3 + yU\Delta H_2 - yzU\Delta H_2 - xS_2 + zR\Delta H_1 - L\Delta H_2 + zL\Delta H_2 + yxS_2 \quad (8)$$

The dynamic equation of local government for active supervision is

$$F(y) = \frac{dy}{dt} = y(L1 - L) = y(1 - y)(xD_2 - zV\Delta H_1 - C_3 + U\Delta H_2 - zU\Delta H_2 + xS_2) \quad (9)$$

Similarly, to analyze the ESS of local government, let $F(y) = 0$, and we can obtain

$$y_1 = 0, y_2 = 1, x_a = \frac{zV\Delta H_1 + C_3 - U\Delta H_2 + zU\Delta H_2}{S_2 + D_2} \quad (10)$$

If $x = x_a$, then $F(y) \equiv 0$. The local government's strategic choices are stable in this case. If $x \neq x_a$, let $F(y) = 0$, then $y_1 = 0, y_2 = 1$ are two stable points. Taking the derivative of $F(y)$, we can obtain $\frac{dF(y)}{dt} = (1 - 2y)(xD_2 - zV\Delta H_1 - C_3 + U\Delta H_2 - zU\Delta H_2 + xS_2)$. When $x > x_a$, $\frac{dF(y)}{dt}\bigg|_{y=0} > 0$, $\frac{dF(y)}{dt}\bigg|_{y=1} < 0$. $y_2 = 1$ is the evolutionary equilibrium point, and the local government's strategy choice is "actively implement". When $x < x_a$, $\frac{dF(y)}{dt}\bigg|_{y=0} < 0$, $\frac{dF(y)}{dt}\bigg|_{y=1} > 0$. $y_1 = 0$ is the evolutionary equilibrium point, and the local government's strategy choice is "passively implement".

4.3. Analysis on Evolution and Stability Strategy of Coal Power Firm

According to Table 2, when a coal power firm implements GTI, the expected revenue is

$$E1 = xy(C_1 + (P - C + V)\Delta H_1) + x(1 - y)(C_1 + (P - C)\Delta H_1) + (1 - x)y(C_1 + (P - C + V)\Delta H_1) + (1 - x)(1 - y)(C_1 + \Delta H_1(P - C)) = C_1 + \Delta H_1P - \Delta H_1C + yV\Delta H_1 \quad (11)$$

When a coal power firm does not implement GTI, the expected revenue is

$$E2 = xy(C_1 - U\Delta H_2) + x(1 - y)(C_1) + (1 - x)y(C_1 - U\Delta H_2) + (1 - x)(1 - y)C_1 = -yU\Delta H_2 + C_1 \quad (12)$$

The average expected revenue of the coal power firm is

$$E = zE1 + (1 - z)E2 = C_1 - z\Delta H_1C + z\Delta H_1P - yU\Delta H_2 + yzU\Delta H_2 + zyV\Delta H_1 \quad (13)$$

The replicated dynamic equation of the coal power firm for implementing GTI is

$$F(z) = \frac{dz}{dt} = z(E1 - E) = z(1 - z)(\Delta H_1P - \Delta H_1C + yV\Delta H_1 + yU\Delta H_2) \quad (14)$$

Similarly, to analyze the ESS of a coal power firm, let $F(z) = 0$, and we can obtain

$$z_1 = 0, z_2 = 1, x_b = \frac{-\Delta H_1P + \Delta H_1C - yV\Delta H_1}{U\Delta H_2} \quad (15)$$

If $x = x_b$, then $F(z) \equiv 0$. The coal power firm's strategic choices are stable in this case. If $x \neq x_b$, let $F(z) = 0$, then $z_1 = 0, z_2 = 1$ are two stable points. Taking the derivative of $F(z)$, we can obtain $\frac{dF(z)}{dz} = (1 - 2z)(\Delta H_1P - \Delta H_1C + yV\Delta H_1 + xU\Delta H_2)$. When $x > x_b$, $\frac{dF(z)}{dz}\big|_{z=0} > 0$, $\frac{dF(z)}{dz}\big|_{z=1} < 0$. $z_2 = 1$ is the evolutionary equilibrium point, and the strategy of the coal power firm is "implement GTI". When $x < x_b$, then $\frac{dF(z)}{dz}\big|_{z=0} < 0$, $\frac{dF(z)}{dz}\big|_{z=1} > 0$. $z_1 = 0$ is the evolutionary equilibrium point, and the strategy of the coal power firm is "do not implement GTI".

4.4. Analysis of the Stability Strategy of System Evolution

According to EGT, the game player is regarded as being bounded rationality by the replication dynamic equation, which will select dynamic strategies through constant imitation and learning [43]. The following tripartite evolutionary game replication dynamic system (16) is composed of the three single population replication dynamic equations of the central government, local government, and coal power firm.

$$\begin{aligned} \frac{dF(x)}{dt} &= x(1 - x)(-S_1 + S_2 + L\Delta H_2 - yD_2 - yS_2 - \beta L\Delta H_2 - yL\Delta H_2 - zL\Delta H_2 + zR\Delta H_1 + y\beta L\Delta H_2 \\ &\quad + z\beta L\Delta H_2 - z\alpha R\Delta H_1 - yz\beta L\Delta H_2 + yzL\Delta H_2) \\ \frac{dF(y)}{dt} &= y(1 - y)(xD_2 - zV\Delta H_1 - C_3 + U\Delta H_2 - zU\Delta H_2 + xS_2) \\ \frac{dF(z)}{dt} &= z(1 - z)(\Delta H_1P - \Delta H_1C + yV\Delta H_1 + yU\Delta H_2) \end{aligned} \quad (16)$$

The Jacobian matrix (17) of the system is shown as follows:

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \quad (17)$$

The parameters in the Jacobian matrix (17) are described as follows:

$$\begin{aligned}
R_{11} &= (1-2x)(-S_1 + S_2 + L\Delta H_2 - yD_2 - yS_2 - \beta L\Delta H_2 - yL\Delta H_2 - zL\Delta H_2 + zR\Delta H_1 + y\beta L\Delta H_2 + z\beta L\Delta H_2 - \\
&\quad z\alpha R\Delta H_1 - yz\beta L\Delta H_2 + yzL\Delta H_2) \\
R_{12} &= x(1-x)(-D_2 - S_2 + \beta L\Delta H_2 - z\beta L\Delta H_2 - L\Delta H_2 + zL\Delta H_2) \\
R_{13} &= x(1-x)(R\Delta H_1 + \beta L\Delta H_2 - y\beta L\Delta H_2 - \alpha R\Delta H_1 - L\Delta H_2 + yL\Delta H_2) \\
R_{21} &= y(1-y)(D_2 + S_2) \\
R_{22} &= (1-2y)(xD_2 - zV\Delta H_1 - C_3 + U\Delta H_2 - zU\Delta H_2 + xS_2) \\
R_{23} &= y(1-y)(-V\Delta H_1 - U\Delta H_2) \\
R_{31} &= 0 \\
R_{32} &= z(1-z)(V\Delta H_1 + U\Delta H_2) \\
R_{33} &= (1-2z)(\Delta H_1 P - \Delta H_1 C + yV\Delta H_1 + yU\Delta H_2)
\end{aligned} \tag{18}$$

According to the local stability analysis method of the Jacobian matrix, let $\frac{dF(x)}{dt} = 0, \frac{dF(y)}{dt} = 0, \frac{dF(z)}{dt} = 0$. The pure strategic equilibrium points of three populations can be obtained: (0,0,0), (0,0,1), (0,1,0), (1,0,0), (1,1,0), (1,0,1), (0,1,1), and (1,1,1). The pure strategic equilibrium points are denoted as $E_1 \sim E_8$. According to the Lyapunov stability theory, it is an equilibrium point if all eigenvalues of the Jacobian matrix of the replicated dynamic system have negative real components [44]. Table 3 displays the eigenvalues of the pure strategy equilibrium point of the game tripartite population as well as the asymptotic stability conditions. As shown in Table 3, the evolutionary game system has seven potential evolutionary stable strategies.

Table 3. Three-dimensional dynamic system (16) asymptotic stability conditions of the equilibrium point.

Equilibrium Point (x,y,z)	Asymptotic Stability Condition
$E_1(0,0,0)$	$-S_1 + S_2 - \beta L\Delta H_2 + L\Delta H_2 < 0,$ $-C_3 + U\Delta H_2 < 0,$ $\Delta H_1 P - \Delta H_1 C < 0$
$E_2(0,0,1)$	$(1-\alpha)R\Delta H_1 - S_1 + S_2 < 0,$ $-V\Delta H_1 - C_3 < 0,$ $\Delta H_1 C - \Delta H_1 P < 0$
$E_3(0,1,0)$	$-D_2 - S_1 < 0,$ $C_3 - U\Delta H_2 < 0,$ $V\Delta H_1 + \Delta H_1 P - \Delta H_1 C + U\Delta H_2 < 0$
$E_4(1,0,0)$	$S_1 - S_2 - (1-\beta)L\Delta H_2 < 0,$ $D_2 - C_3 + U\Delta H_2 + S_2 < 0,$ $\Delta H_1 P - \Delta H_1 C < 0$
$E_5(1,1,0)$	$D_2 + S_1 < 0,$ $-D_2 + C_3 - U\Delta H_2 - S_2 < 0,$ $V\Delta H_1 + \Delta H_1 P - \Delta H_1 C + U\Delta H_2 < 0$
$E_6(1,0,1)$	$-(1-\alpha)R\Delta H_1 + S_1 - S_2 < 0,$ $D_2 - V\Delta H_1 - C_3 + S_2 < 0,$ $-\Delta H_1 P + \Delta H_1 C < 0$
$E_7(0,1,1)$	Unstable
$E_8(1,1,1)$	$D_2 + S_1 - (1-\alpha)R\Delta H_1 < 0,$ $V\Delta H_1 + C_3 - D_2 - S_2 < 0,$ $-V\Delta H_1 - \Delta H_1 P + \Delta H_1 C - U\Delta H_2 < 0$

5. Numerical Simulations

To analyze the influencing factors of the various behavior strategies of the central government, the local government, and coal power firms under the dual-carbon target, this section will use numerical simulations performed using the MATLAB 2021b software,

focusing on the analysis of the changes in the central and local governmental S&P, the impact on the evolution strategy, and the evolutionary trajectory of the relevant game players. The optimal state $E_8(1, 1, 1)$ was selected for the simulation analysis of the initial state. Equation (19) illustrates the conditions that must be met by the numerical value under the original circumstances. The parameters in the initial circumstance are shown in Table 4.

$$D_2 + S_1 - (1 - \alpha)R\Delta H_1 < 0, V\Delta H_1 + C_3 - D_2 - S_2 < 0, -V\Delta H_1 - \Delta H_1P + \Delta H_1C - U\Delta H_2 < 0 \quad (19)$$

Table 4. Initial assignment table.

Parameter	S_1	D_2	S_2	C_3	V	U	L	R
Assignment	7	7.5	12	10	0.3	0.35	0.5	0.75
Parameter	C	P	C_1	ΔH_1	ΔH_2	a	b	
Assignment	0.6	0.42	4	30	20	0.3	0.3	

5.1. Sensitivity Analyses of Initial Probabilities

We set x_0 , y_0 , and z_0 to be the initial probability of the central government, the local government, and coal power firms, that is, the values of x , y , and z when $t = 0$. To explore how their initial willingness affected evolutionary process, x_0 , y_0 , and z_0 were changed from 0.3 to 0.9 simultaneously, and the evolutionary path of the system is shown in Figure 1.

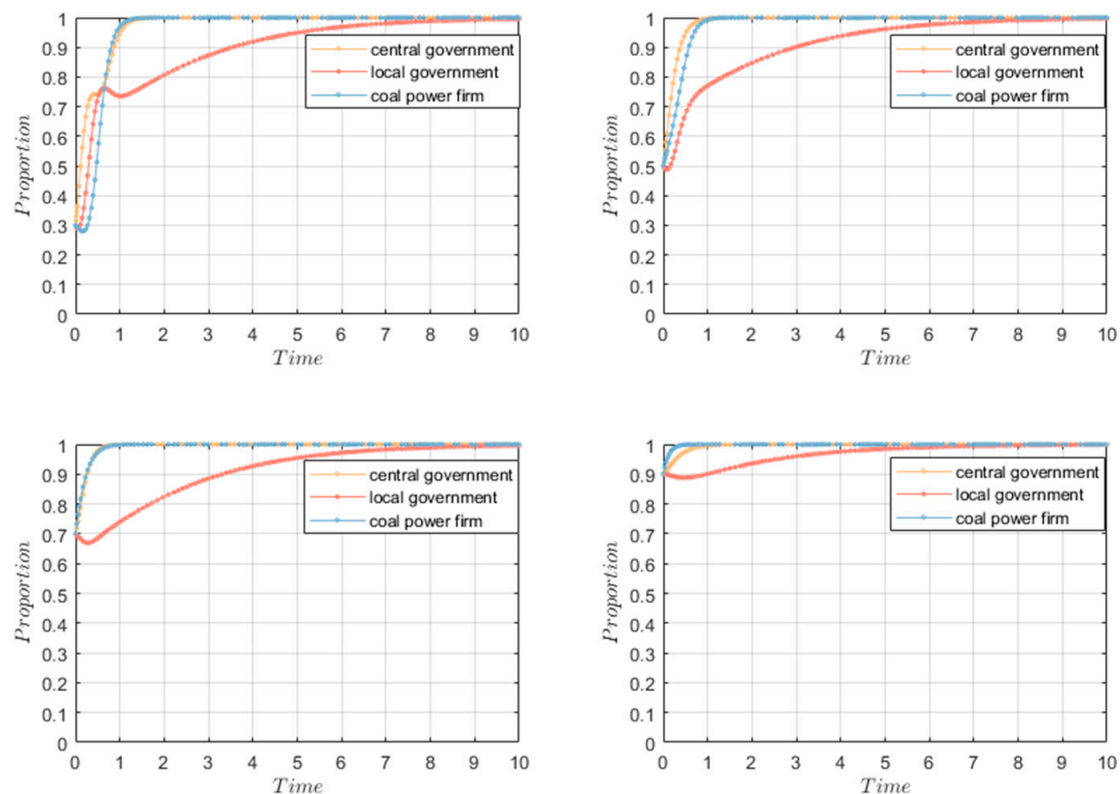


Figure 1. The evolutionary process under different initial probabilities.

First, an increase in the initial willingness facilitated the system's evolution toward a positive state. As shown in Figure 1, the higher initial willingness led to a faster evolutionary process, highlighting the significance of enhancing the overall initial willingness. Second, both the central government and the coal power firm stabilized simultaneously, while the local government acted the slowest. According to Figure 1, the time taken for the willingness of the central government and the coal power firm to stabilize at 1 was nearly

the same and always before $t = 1.5$. The local government evolved toward a stable state around $t = 5$ or $t = 10$ under different circumstances. This could be attributed to the proactive role of the central government in implementing regulatory measures as a proponent of CER. Furthermore, when the system reached the optimal state, the central government's benefits derived from GTI outweighed the regulatory costs ($D_2 + S_1 < R\Delta H_1$), thereby facilitating the quicker evolution of the central government.

Moreover, the implementation of S&P by the local government allowed enterprises to attain positive returns from GTI compared with non-innovative approaches. The regulatory actions by the central government sent a clear signal to coal power firms, prompting them to implement GTI. On the other hand, the local government faced higher regulatory costs, and positive returns were only feasible when both the central government and the coal power firm actively participated. When the central government actively supervises and the enterprise implements GTI, the benefits for the local government is $-C_3 - V\Delta H_1 + R\Delta H_1 + D_2 = -10 - 0.3 \times 30 + 0.75 \times 30 + 7.5 > 0$; when the central government actively supervises while the firm does not implement GTI, the benefits for the local government is $-C_3 - L\Delta H_2 + D_2 = -7.5 - 0.5 \times 20 + 10 < 0$; and when both the central government and the firm are in a negative state, the benefits for the local government is $-C_3 < 0$. Consequently, the local government required more time to evaluate its options and make preparations.

To explore the impact of changes in the initial willingness of the central government, x_0 was set to four values with a gradient of 0.2, meaning that x_0 varied between 0.2 and 0.8. The evolution of the local government and the coal power firm is shown in Figure 2. Figure 2 shows the evolution of the willingness of the local government and the coal power firm (y-axis) over time (x-axis) under the influence of changes in the central government's initial willingness.

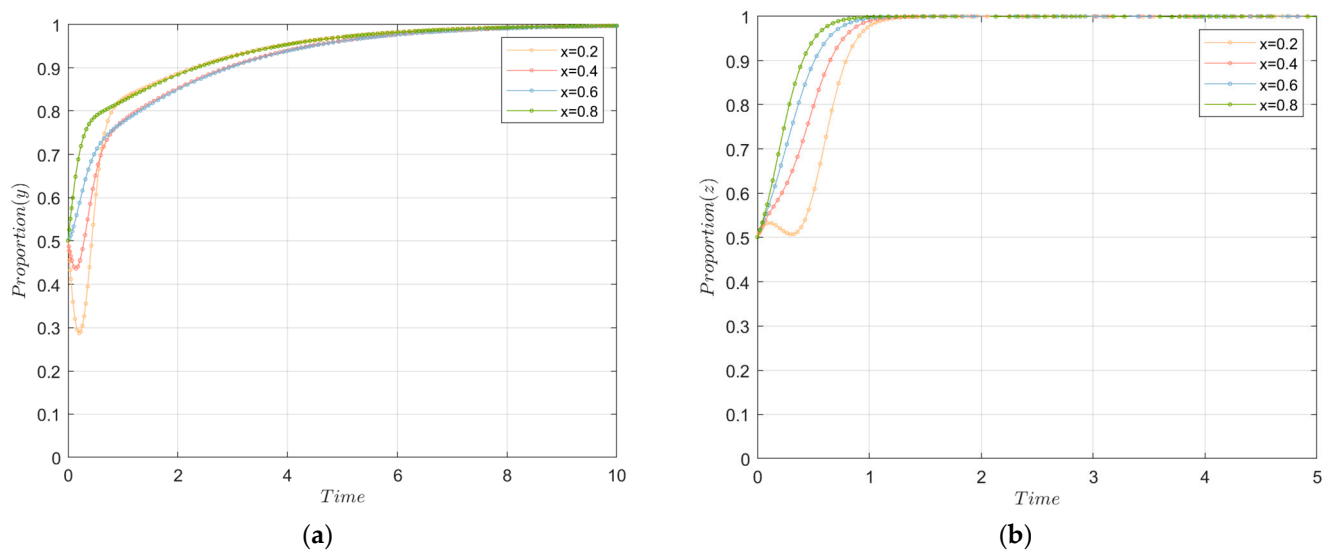


Figure 2. Influence of changes in the initial willingness of the central government: (a) the evolution of the local government and (b) the evolution of the coal power firm.

Similarly, y_0 was also changed from 0.2 to 0.8 to explore the impacts of changes in the initial willingness of the local government. Figure 3 shows the evolution of the willingness of the local government and the coal power firm (y-axis) over time (x-axis) under the influence of changes in the local government's initial willingness.

First, the increase in the initial willingness of the central government facilitated the promotion of the coal power firm's GTI, but it had little impact on the local government. As shown in Figure 2a, increasing x_0 did not significantly affect the time it took for y to stabilize at 1, which always occurred around $t = 10$. However, the increase in x_0 resulted in a shorter time for z to stabilize at 1 (as shown in Figure 2b). This was because the local government faced higher regulatory costs, and it required more time to evaluate its options

and make preparations. Therefore, under established central government S&P conditions, the evolution of the local government was largely independent of the central government's initial willingness. For coal power firms, the intentions of the central government often serve as an important indicator of market trends, causing enterprises to be more sensitive to market changes and respond more actively.

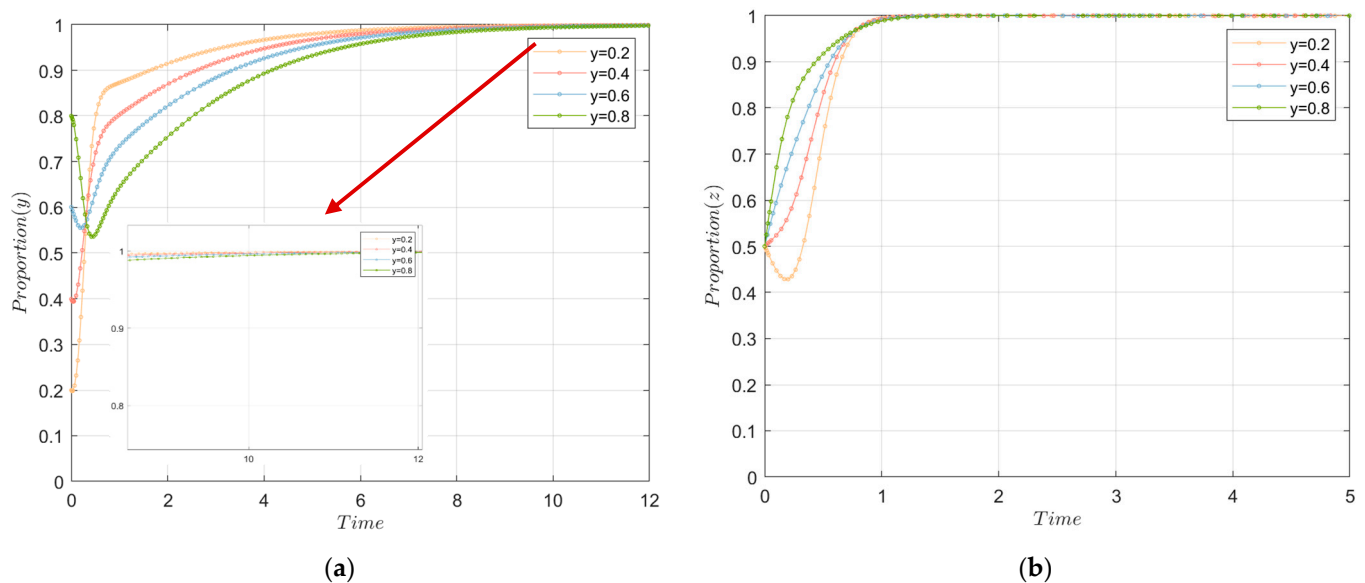


Figure 3. Influence of changes in the initial willingness of the local government: (a) the evolution of the local government and (b) the evolution of the coal power firm.

Second, the changes of the local government's initial willingness had little impact on the evolution of the coal power firm. As shown in Figure 3b, an increase in y hardly affected the time it took for z to stabilize at 1, which remained around $t = 1.2$. This phenomenon can be explained by Figure 3a. As shown in Figure 3a, increasing the initial intention (y) of the local government did not accelerate its evolution, and it stabilized at a positive state around $t = 10$ for different cases. Therefore, the increase in the initial willingness of local governments did not necessarily imply a stronger long-term implementation willingness or intensity, thus having a relatively small impact on coal power firms.

Third, we can further observe from Figure 3a that a higher initial willingness of the local government could not be sustained. Instead, it decreased and remained lower than the case with a lower initial willingness for a period. As shown in Figure 3a, when $y_0 = 0.6$ and 0.8 (the initial willingness of the local government), y decreased rapidly and then increased with time. However, for cases where $y_0 \geq 0.6$, the value of y was lower than where $y_0 < 0.6$ when $t > 0.33$. This is because the local government required more preparation in the early stages, and the initially higher implementation intent may have certain implications for the subsequent sustained development. The local government may need to lower their willingness and provide a certain buffer.

5.2. The Influence of the Change of the Central Governmental S&P on the Evolution of the System

To explore the effect of the central government S&P, D_2 and S_2 were set to six values with 0.5 gradient. That is, D_2 varied from 6.5 to 9, and S_2 varied from 11 to 13.5. The evolution of the local government is shown in Figure 4. Figure 4 shows the evolution of the local government's willingness (y -axis) over time (x -axis) under the influence of the central government S&P. Comparing Figure 4 with Figure 2a, it can be seen that the change in the central government's S&P intensity had a greater impact on the local government than the change in the central government's initial willingness.

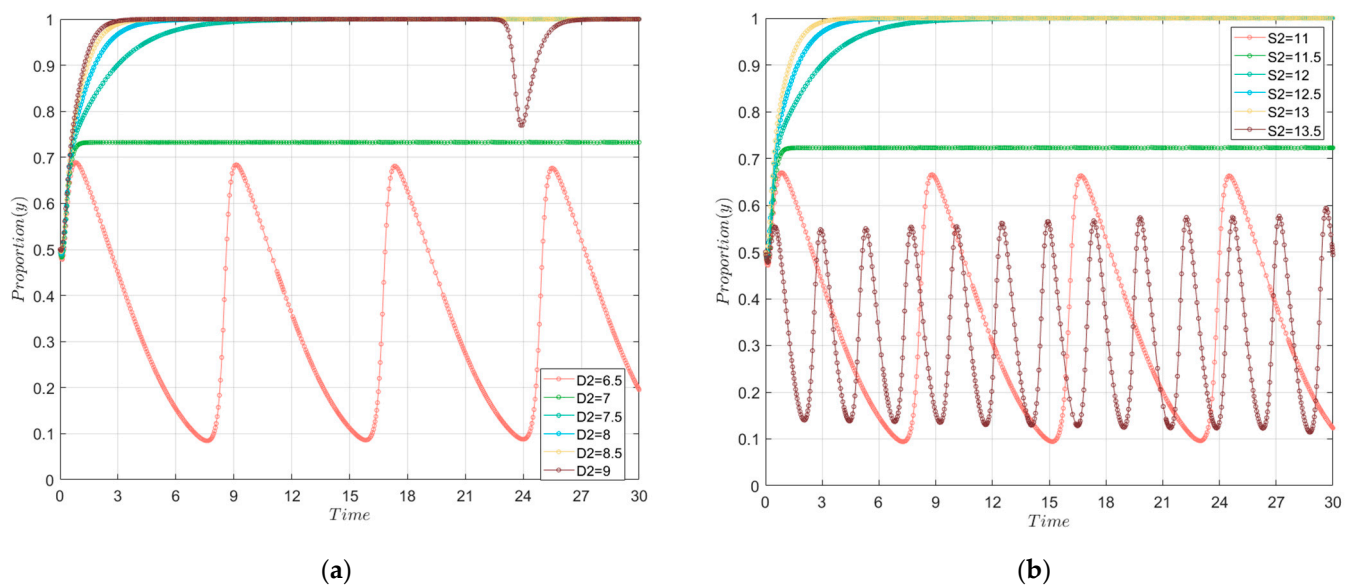


Figure 4. Influence of changes in the intensity of the central government S&P on the evolution of the local government: (a) the influence of central government subsidies and (b) the influence of central government penalties.

First, Figure 4 illustrates the ineffectiveness of low S&P in promoting active implementation by the local government. The willingness of local governments to actively implement showed a fluctuating state, that is, when $D_2 = 6.5$ or $S_2 = 11$, the lines in Figure 4 showed periodic fluctuations. This was due to the high costs associated with the active implementation by the local government, coupled with the strong positive externalities of GTI. The struggle to strike a balance between socio-economic development and environmental protection was evident as local governments faced financial pressures when subsidies were low [45]. Furthermore, the insufficient level of penalties failed to compel them to take action. This is also consistent with the view that environmental decentralization often leads local governments to adopt more relaxed environmental policies, resulting in a “race to the bottom” [46].

Second, the central government S&P only could be effective within a certain range, and the impact was positively correlated with its intensity but with diminishing marginal returns. From Figure 4, we can find that only when $D_2 \geq 7.5$ or $13 \geq S_2 \geq 12$ could S&P effectively promote local government implementation. The willingness of the local government ultimately equaled 1, achieving a stable positive state. The local government lacked the drive to enforce environmental regulations, which could only be effectively executed through appropriate S&P. This aligns with the belief of neo-institutional theorists that organizational behavior is influenced by the institutional environment [47]. Additionally, the effect of S&P was positively correlated with the intensity, but the marginal benefits decreased. With the continuous increase in D_2 and S_2 , the time for the local government’s willingness to evolve to 1 continued to shorten, but the degree of shortening decreased. This is consistent with the view of Xu et al. (2023) [48] that increasing the S&P for local government will shorten the time of system equilibrium.

Moreover, we find that a moderate level of S&P can stabilize the willingness of the local government to a certain level rather than a positive state. When $D_2 = 7$ or $S_2 = 11.5$, the willingness of the local government remained stable at around 0.72. This demonstrated the trade-off of the local government in terms of implementation efficiency. The effectiveness of S&P was relatively limited and could only promote the local government to carry out a certain degree of implementation at this time.

However, high-level central government S&P can lead to a sudden decrease or even instability in the willingness of local government. From Figure 4a, we further found that

when $D_2 = 9$, the willingness of the local government decreased for a period and continued to rise steadily to 1 when $t = 23$ to $t = 27$. High subsidies can lead to a brief “sudden drop” in local government implementation willingness. This is because offering excessive subsidies may lead to a situation where local governments receive more funding even if they make little effort to implement measures, which reduces their willingness to implement. Additionally, high central government penalties are ineffective. From Figure 4b, we can observe that when $S_2 = 13.5$, the willingness of the local government showed periodic fluctuations. This was due to the need for a certain buffer period for local government regulation, as excessive penalties were likely to heavily deplete their resources in the initial stage. However, high penalties force the local government to strive for proactive regulation, yet prolonged high penalties make it difficult for them to maintain such proactive oversight due to resource constraints. Therefore, it is not necessarily better for the central government to impose harsher punishments.

Moreover, we set $D_2 = 0$ and $S_2 = 0$ to explore the interactions between the central government S&P mechanisms, as depicted in Figure 5. First, we can see from Figure 5 that in the absence of a parallel system of S&P from the central government, the behavior of the local government always fluctuated or became passive. From Figure 5a, the willingness of the local government quickly stabilized at 0, which was a negative state. From Figure 5b, we can observe that the willingness of the local government was in a fluctuating state. The parallel implementation of S&P is a crucial safeguard to ensure the proactive actions of local government. Additionally, the effect of punitive measures seems to be more effective than the effect of subsidies. As shown in Figure 5b, the willingness of local government was fluctuating at this time but within a certain range of ups and downs, rather than being entirely negative as depicted in Figure 5a.

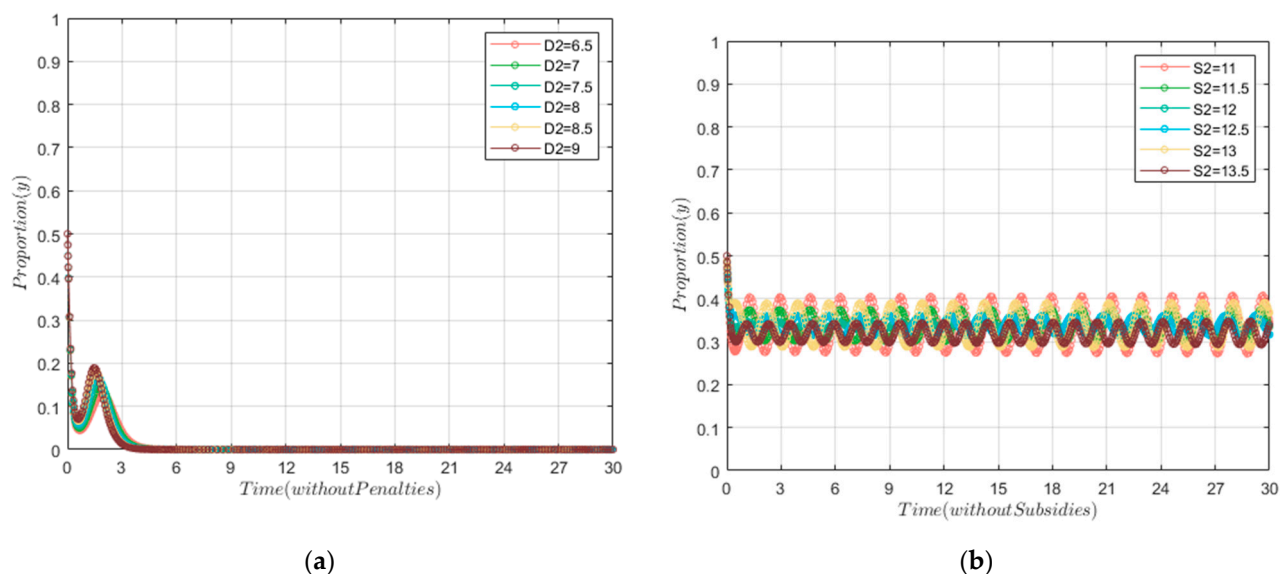


Figure 5. Influence of changes in the intensity of the central government S&P on the evolution of local government for the scenario without subsidies or penalties: (a) the influence of central government subsidies and (b) the influence of central government penalties.

5.3. The Influence of the Change of Local Government S&P on the Evolution of the System

To explore the effect of local governmental S&P, U and V were set to six values with 10% gradient. That is, V varied from 0.1 to 0.5, and U varied from 0.15 to 0.55. The evolution of the local government is shown in Figure 6. Figure 6 shows the evolution of a coal power firm’s willingness to implement GTI (y-axis) over time (x-axis) under the influence of the local government S&P.

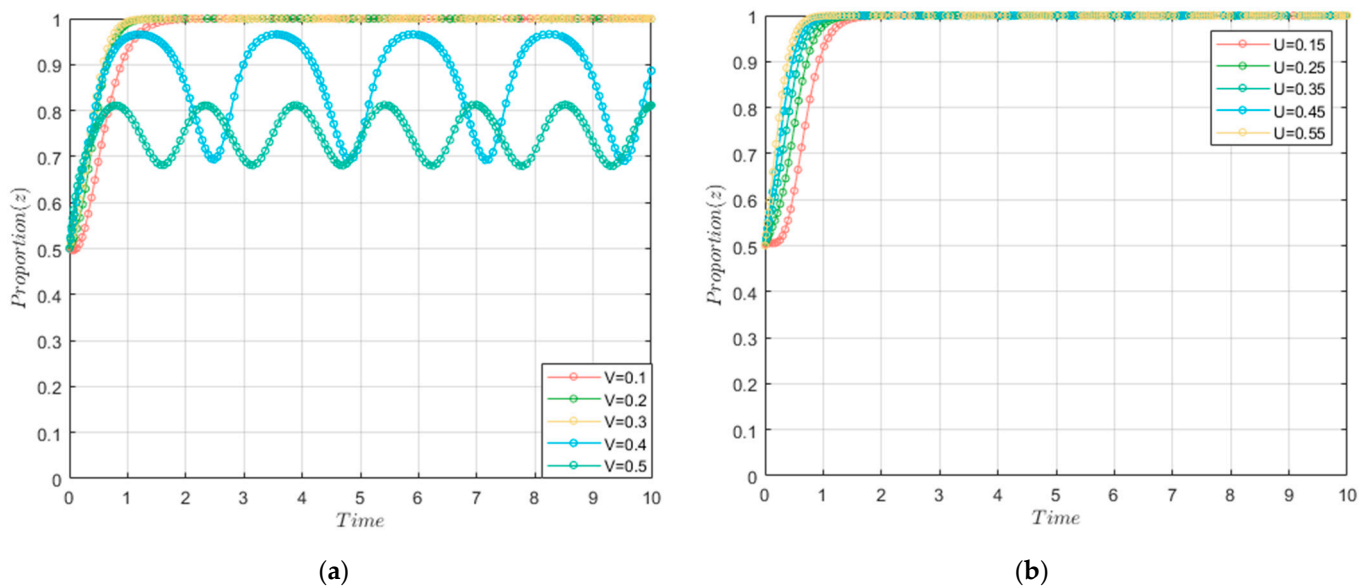


Figure 6. Influence of changes in the intensity of the local government S&P on the evolution of a coal power firm: (a) the influence of local government subsidies and (b) the influence of local government penalties.

First, increasing the intensity of the local government S&P will accelerate the coal power firm's evolution. As shown in Figure 6, when V increased from 0.1 to 0.3, the decision-making time of the coal power firm was shortened. Additionally, we can also notice that the evolution time of the coal power firm shortened with the increase in U . This was because subsidies alleviated the financial burden on firms engaging in GTI, while penalties intensified the repercussions of excessive ECE. Yin et al. (2020) [49] also had a similar conclusion.

However, when there are more local governmental subsidies ($V \geq 0.4$), the behavior of the coal power firm fluctuated. The ideal subsidy point for the coal power firm was $V = 0.3$. This was because excessive government investment in independent innovation activities led enterprises to deviate from market efficiency principles in financing, diminishing the incentive effect of financial support [50]. Excessive subsidies may also lead to moral hazard behavior of firms [51], which greatly reduces the effectiveness of allowance incentives. This is also consistent with the conclusion of many studies that government subsidies have a "threshold effect" [32,52], that is, there is an optimal range of governmental subsidies.

Furthermore, we set $V = 0$ and $U = 0$ to examine the interaction between the local government's S&P mechanisms, as depicted in Figure 7. We noticed that lower-intensity S&Ps still required integration, while higher-intensity S&Ps may also yield certain effectiveness. We can see that the willingness of coal fired power firms rapidly stabilized at 0 and remained in a negative state when $V \leq 0.2$ or $U \leq 0.35$. The results demonstrated that without a parallel system of S&P implemented by the local government, the behavior of the coal power firm fluctuated or became passive when subsidies or penalties were low. Moreover, the willingness of the coal-fired power firm eventually stabilized to 1 when $V = 0.3$ or $U \geq 0.45$. Only when there was a high intensity of S&P did enterprises exhibit positive behavior. This was different from the performance of the local government, indicating that coal power firms had a stronger willingness.

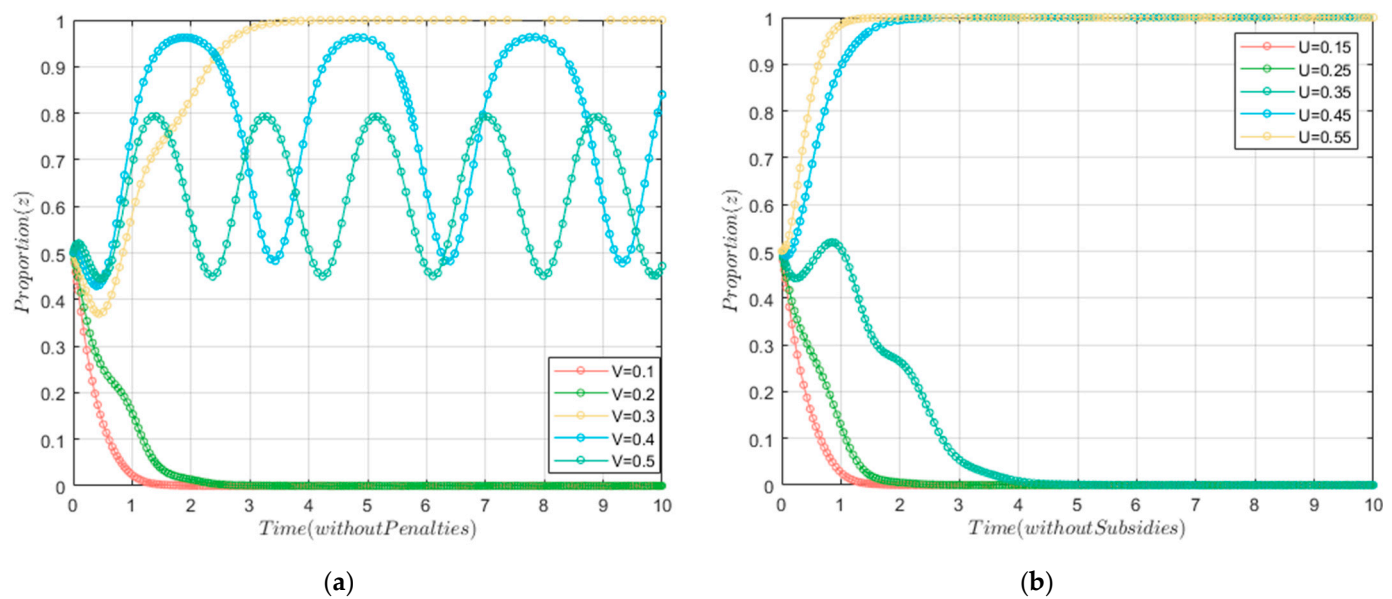


Figure 7. Influence of changes in the intensity of the local government S&P on the evolution of coal power firms, for the scenario without subsidies or penalties: (a) the influence of local government subsidies and (b) the influence of local government penalties.

6. Conclusions and Implications

To examine the interaction among the central government, local government, and coal power firms under the dual-carbon target, this study conducted a novel tripartite EGM. This paper calculated the replication dynamic equations of the three parties and subsequently identified seven potential ESSs. Through numerical simulations, the sensitivity analyses of the main parameters were carried out based on the ideal potential stable equilibrium point $E_8(1, 1, 1)$. Specifically, we conducted sensitivity analyses on the impacts of changes in the initial willingness of the three parties, as well as changes in S&P measures imposed by the central and local governments, on the evolution of the three parties. Finally, the scenarios where the central government and local government only implemented either subsidy or penalty measures were also analyzed. The results showed the following: (1) Enhancing the initial willingness can accelerate the system's attainment of an optimal state. The local government exhibits a slower pace of evolution. Coal power firms are more sensitive to changes in the initial willingness of the central government. (2) The local government is more sensitive to changes in the central government's S&P intensity rather than changes in the central government's initial willingness. Low levels of central government S&P and high penalties are ineffective, while high subsidies can lead to a sudden decrease in the local government's willingness. (3) Local government penalties have a positive correlation with their effectiveness in promoting GTI, whereas high subsidies are ineffective. (4) The separate implementation of subsidies or penalties by either the central or local government is detrimental to achieving the optimal state. Such an approach renders the fluctuant or negative behavior of the local government and coal power firms.

Based on the results, the following implications are obtained:

- (1) During the initial phase of policy implementation, it is advisable to intensify promotional efforts, promptly establish reasonable S&P measures, and provide local government with appropriate preparation time. The initial signals of the central government's strong intention are helpful for the implementation of coal power firms' GTI, which can be achieved through activities such as enterprise exchanges or policy advocacy campaigns. Moreover, in the early stages, reasonable S&P measures are more important than strict regulation in driving the local government to actively implement. The central government should conduct advance research to prepare for

promptly designating appropriate S&P measures and grant the local government a certain period of implementation preparation.

- (2) The central government should adopt a scientifically reasonable evaluation mechanism to implement appropriate S&Ps for the local government. By establishing a comprehensive system of evaluation indicators, the central government can provide rewards to outstanding local governments, such as financial support and special subsidies, while also ensuring transparent fund allocation to prevent misuse. For underperforming local governments, the central government can impose punishments, such as reducing financial allocations and limiting resource distribution, to encourage improvement in energy transition efforts.
- (3) The local government should adopt proper S&P values to promote coal power firms' GTI. Local governments should implement measures such as tax reductions and subsidies to incentivize coal power firms' GTI. Stricter penalties should be given to firms that violate environmental laws or surpass emission limits to achieve environmental protection goals effectively. Additionally, the government should strengthen supervision by closely examining and monitoring how subsidies given to coal-fired power enterprises are used, thus preventing subsidy misuse.
- (4) The concurrent implementation of S&P by the central and local governments is a critical imperative. It necessitates the establishment of clear guidelines and policies for subsidy allocation, robust monitoring and evaluation mechanisms, and enhanced communication and coordination. Additionally, it is crucial for the local government to acknowledge the significance of simultaneous S&P implementation, especially when the intensity of these measures is comparatively low.

In summary, this study expands existing research theoretically and provides a theoretical model for analysis. In practice, it provides insights for policy-making to promote the active implementation and GTI of management and enterprises within a dual-regulatory system.

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Abbreviations

CC, carbon capture; ECE, excess carbon emissions; CER, carbon emission reduction; CTPP, coal-fired power plants; ESS, evolutionary stability strategy; EGM, evolutionary game model; EGT, evolutionary game theory; GTI, green technology innovation; GHG, greenhouse gas; IGCC, integrated gasification combined cycle technology; PVPP, solar photovoltaic power plants; SPP, solar power plants; S&P, subsidies and penalties; TPP, coal-fired thermal power plants.

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