Fuel Cells Bulletin
ISSN: 1464-2859

The Game Strategies of Energy-Intensive Enterprises' Participation in the National Carbon Emission Trading Market Considering Regional Characteristics

Lina Hu[1], Hui Li[2]*
1. School of Business Administration, Liaoning Technical University, No.188 Longwan South Street, HuluDao City, Liaoning Province, China
2 Graduate School of Business, SEGi University, Petaling Jaya 47810, Selangor, Malaysia
Corresponding Author's Email: SUKD2101339@segi4u.my

Abstract: Against the backdrop of China's "carbon peaking and carbon neutrality" goal, carbon emissions trading is crucial for regional carbon reduction. The purpose of this study is to analyze the strategic choices of local governments and energy - intensive enterprises in the national carbon emission trading market (ETM). An evolutionary game model is con-structed, with the Kaya identity extended and incorporated to account for regional characteristics. Based on China's regional economic development and ETM operation, parameter values are set and numerical simulation is used. The results show that the participation of energy-intensive enterprises and policy-making of local governments are influenced by multiple factors. It concludes that this model can offer insights for promoting the entry of energy - intensive enterprises into the national ETM and there are directions for further research.

Keywords: emissions trading market; energy-intensive enterprises; local government; evolutionary game model; the kaya identity.

1. Introduction

Under China's "carbon peaking and carbon neutrality" goal, the nation is actively pursuing the implementation of a sustainable emission reduction strategy [1]. Carbon emissions trading (CET), as a potent market-oriented policy tool, plays a pivotal role in driving regional carbon emission reduction. Since 2013, China has established seven pilot carbon emission trading markets, achieving notable emission reduction outcomes. In December 2017, the national construction plan for the carbon emission trading market (ETM) in the power generation industry was unveiled, marking rapid progress toward the establishment of a unified national ETM system. With the inauguration of the national carbon emissions trading market in 2021, it becomes imperative for the government to broaden the scope of covered entities and enhance the liquidity of the carbon market [2]. The 2024 Chinese Government Work Report clearly proposes to expand the coverage of the national carbon market industry. Other regions also need to integrate into the national unified ETM to collectively work towards the objective of reducing regional carbon emissions. Energy-intensive industries stand out as a critical domain for carbon emissions, making it of paramount significance to promote the participation of energy-intensive enterprises in the national ETM across all regions to achieve climate change goals.

In the realm of carbon emission reduction, local governments and energy-intensive enterprises act as two pivotal agents within the ETM [3]. However, during their involvement in the national ETM, regional policy choices exhibit distinctive characteristics due to variations in resource endowments, leading industries, and eco-nomic development among regions. The trade-off between carbon emission reduction and regional economic growth introduces differentiation in the policy choices of regional governments. The allocation of carbon emission reduction responsibility (CERR) presents regional disparities, with significant differences in CERR among participants in different regions at the onset of each trading period [4]. Pilot areas exhibit variations in coverage thresholds and quota allocation methods owing to differences in economic development and industrial structure [5,6]. This discrepancy directly influences the motivation of enterprises to engage in the ETM [7]. The choice of carbon emission rights al-location methods significantly impacts the direct costs of investment, social welfare, and emission reduction [8], necessitating local governments to consider regional conditions when selecting redistribution methods. The achievement of China's emission re-duction targets heavily relies on the judicious allocation of regional emission reductions. Regional differences loom large in the allocation of CERR for China's energy-intensive industries [9]. Regarding carbon pricing, diverse policies exert varying effects on the cost of regional emission reduction, resulting in differences in carbon prices [10]. Furthermore, the coverage thresholds of the seven pilot areas differ, with unified thresholds for industries in Beijing, Chongqing, Guangdong, Hebei, and Tianjin, while Shanghai, Shenzhen, and other areas have distinct thresholds. More developed cities, such as Shenzhen and Beijing, exhibit relatively low coverage thresholds, whereas less developed cities, such as Hubei, have higher thresholds [11].

Simultaneously, various energy-intensive enterprises exhibit differences in low-carbon technologies and production costs, influencing their eagerness to engage in the national ETM. Within the constrained scale of the ETM, the allocation of carbon quotas dissuades enterprises with high carbon emissions and limited operational capabilities from participation. Many Chinese enterprises lack the motivation for CET driven by voluntary commitment. The imperfect carbon quota trading mechanism creates resistance among enterprises to partake in the carbon trading market. The ETM, by differentially impacting the total factor productivity of enterprises [12], raises internal operating costs, alters the external development environment, and affects the market competitiveness and investment opportunities of high-carbon enterprises [13]. Enterprises exhibit varying risk-taking levels, with non-state-owned enterprises being more willing to take risks than state-owned enterprises, and small enterprises more likely to actively respond to ETM uncertainty [14]. Additionally, there are differences in the investment costs of enterprises in carbon emission reduction technologies [15]. The optimal trading price, volume, and partners in emissions trading differ among enterprises [16]. Consequently, enterprises with diverse characteristics respond differently when deciding whether to join the ETM [17].

Hence, it is crucial to analyze the strategic choices of different local governments and energy-intensive enterprises in participating in the national ETM and understand its influence mechanism for the construction of the national ETM. As a typical public good, climate protection requires more effective incentive measures, agreements, and constraint mechanisms. Game theory provides a convenient framework for defining this problem [18]. The evolutionary game model stands at the forefront of studying public goods [19]. Previous studies on evolutionary game methods, such as "spatial evolutionary public goods game" [20] and "evolutionary games with environmental feed-backs" [21], support this paper. Moreover, the evolutionary game method has been widely applied in researching government and enterprise behavior in the ETM [22-24]. However, when using the game method to analyze the strategic choices of each participant, researchers mainly focus on carbon emission reduction in the power industry, and there is insufficient research on other industries that are included in the carbon trading market [25]. Existing research on the evolutionary game between the government and energy-intensive enterprises under the ETM overlooks the influence of regional characteristics, crucial factors restricting actions to mitigate climate change [26]. This paper constructs an evolutionary game model involving local governments and energy-intensive enterprises in the national ETM context. The Kaya identity is extend-ed and incorporated into the game model to decompose the impact of regional characteristics. It effectively elucidates the characteristics and influencing factors of energy-intensive enterprises in various regions of China participating in the national ETM and provides recommendations for promoting the entry of energy-intensive enterpris-es from different regions into the national ETM. The model offers a novel method for studying the participation of energy-intensive enterprises in the unified ETM.

2. Methodology

2.1 Construction of the evolutionary game model

This study develops an evolutionary game model encompassing both local governments and energy-intensive enterprises. In the model, x and y represent any two local governments and energy-intensive enterprises, respectively. The probability that local government x opts to issue policies supporting the participation of energy-intensive enterprises in the national ETM is denoted as p, while the probability that energy-intensive enterprise y chooses to engage in the national ETM is represented by q. The probability that local governments and energy-intensive enterprises select different strategies is a function of time t. Both sides exhibit bounded rationality, making decisions based on limited knowledge and information. Throughout the game, local governments and energy-intensive enterprises adjust their strategies in response to each other's behavioral feedback. Table 1 outlines the parameters of the model.

Table 1 Parameters of the model

Parameters	Meaning	interpretation
G_1	Benefits from green economic growth	The government benefits from the green economic growth driven by the ETM, which encompasses improvements in social welfare, environmental enhancements, and output growth resulting from advancements in low-carbon technological progress.
G_2	Benefits from economic growth	The government benefits from economic growth when enterprises choose not to participate in the national ETM.
M	Total regional carbon emissions	Total regional emissions are influenced by factors such as regional industrial structure, energy composition, technological levels, and other relevant factors.
β	Marginal abatement cost (MAC)	The cost for each additional unit of carbon dioxide emission reduction is known as the Marginal Abatement Cost (MAC). An increase in MAC is associated with a loss of GDP. Therefore, careful consideration of MAC is essential for local governments when making decisions.
γ	social cost of carbon(SCC)	The damage resulting from the increase in the emission of one ton of carbon dioxide is quantified by the Social Cost of Carbon (SCC). This metric is utilized to articulate the economic and social losses incurred due to climate change.
α	Influence coefficient of carbon leakage on green economic growth. $(0 < \alpha < 1)$	When energy-intensive enterprises engage in the national ETM, the effectiveness of the government's management becomes crucial. Simultaneously, if regional energy-intensive enterprises excessively trade emission allowances due to their technical capabilities and carbon reduction capacity, it may lead to the transfer of carbon emissions between regions, consequently impacting green economic growth. The influence coefficient plays a significant role in this context, where a smaller α signifies a greater impact of carbon leakage on green economic growth.
R_1	Operating income of energy-intensive enterprises after joining the national ETM	Upon joining the national ETM, an enterprise not only engages in carbon emission license trading, resulting in revenue or expenditure, but also undergoes a transformation in its production mode and an enhancement of technical capabilities to reduce carbon emissions. These modifications lead to the generation of new operating income for the enterprise.
R_2	Operating income of energy-intensive enterprises when they do not join the national ETM	The operating income under the existing production mode and technology level is the financial outcome for energy-intensive enterprises when they choose not to participate in the national ETM.
P	Price of emission allowances	The transaction price of emission allowances, as specified in the listing agreement within the national ETM.
T_0	Free allocation of emission allowances	The total amount of carbon dioxide permitted to be released into the atmosphere within a specific time frame, acquired by the energy enterprise following verification by the competent government department.
T	Carbon emissions of energy-intensive enterprises	The carbon dioxide emissions originating from the production processes of energy-intensive enterprises.
S	Income of energy-intensive enterprises from policy support	Incorporating subsidies, tax relief, and other benefits directly acquired by energy-intensive enterprises through government policies.

The payment matrix of evolutionary games (Table 2) illustrates several key points. Firstly, when local governments choose to issue policies supporting the participation of energy-intensive enterprises in the national

ETM, and these enterprises indeed join the national ETM, the revenue of local governments G_1 is the benefits from economic growth minus the total cost of carbon reduction βM. This underscores the delicate balance local governments must strike between economic growth objectives and carbon emission reduction goals in climate change governance. Effective policy decisions should seek measures that generate greater synergy and increased welfare. In this scenario, the income of the enterprise comprises three components: the operating income of energy-intensive enterprises after joining the national ETM R_1, income or expenditure from the ETM $P(T_0 - T)$, and benefits from government policy support S. The income or expenditure from the ETM depends on the difference between the free emission allowances allocated to the enterprise and its actual carbon emissions $T_0 - T$. If the carbon emissions are lower than the allocated allowances, the enterprise can sell excess carbon quotas for income. If the emissions exceed the allocated allowances, the enterprise needs to purchase additional emission allowances.

Secondly, when local governments issue policies but energy-intensive enterprises do not participate in the national ETM, local governments fail to achieve green growth and can only obtain revenues from conventional economic growth G_2. The implementation of the policy also necessitates consideration of the cost of carbon emission reduction.

Thirdly, when local governments do not issue policies to support energy-intensive enterprises participating in the national ETM, and these enterprises still join the ETM, the local government, in addition to the revenues from green economic growth, must account for the loss of benefits due to carbon leakage resulting from the absence of policy guidance. In this situation, energy-intensive enterprises cannot obtain revenues from government policies due to the lack of government support.

Fourthly, when local governments do not provide policy support and energy-intensive enterprises do not participate in the national ETM, the government only gains from conventional economic growth. Simultaneously, since neither the government nor energy-intensive enterprises have implemented measures to address climate change, the government incurs economic losses and environmental damage caused by carbon emissions γM, expressed as the product of the social cost of carbon and the total amount of regional carbon emissions.

Table 2 Game payment matrix of the game participants

players		Energy-intensive enterprises	
		Participation (q)	Nonparticipation $(1-q)$
Local governments	Policy support (p)	$G_1 - \beta M, R_1 + P(T_0 - T) + S$	$G_2 - \beta M, R_2$
	No policy support $(1-p)$	$\alpha G_1, R_1 + P(T_0 - T)$	$G_2 - \gamma M, R_2$

Additionally, this paper assumes that the marginal abatement cost β is always less than the social cost of carbon γ. On one hand, according to the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), global climate change has a definite and extensive impact on the environmental, economic, and social systems, exposing humanity to significant climate change risks. On the other hand, when formulating policies to mitigate climate change, it is essential to consider both the benefits and costs of carbon emission reduction. The optimal climate policy often necessitates that the marginal abatement cost β equals the social cost of carbon γ. If the marginal abatement cost exceeds the social cost of carbon, the costs borne by policymakers to mitigate climate change outweigh the benefits, which contradicts the current reality of global climate change governance.

2.2 Incorporation of the kaya identity into the model

The Kaya identity [27] stands as a significant achievement and a primary method for examining the driving factors of greenhouse gases by dissecting the influences on total carbon emissions. Initially proposed by the Japanese scholar Kaya in 1989, the Kaya identity delineates the connection between overarching macro factors such as society, economy, energy, and emissions. It encapsulates four essential drivers of carbon emissions:

energy carbon intensity, energy intensity per unit of GDP, per capita GDP, and population size. These factors can be further expanded and scrutinized from various perspectives through multiple decomposition techniques [28].

In this paper, the total regional carbon emissions are decomposed as follows:

$$M = GDP \frac{IOV}{GDP} \frac{E}{IOV} \frac{FE}{E} \frac{M}{FE} \tag{1}$$

Where, M is emissions, GDP is gross domestic product, E is energy consumption, IOV is output value of high energy consuming industries, and FE is fossil energy consumption. Therefore, the influencing factors of total regional carbon emissions are decomposed into GDP, industrial structure($\frac{IOV}{GDP}$), energy intensity($\frac{E}{IOV}$), energy consumption structure ($\frac{FE}{E}$) and carbon emission intensity($\frac{M}{FE}$). By employing the Kaya identity, the characteristics of different regions can be integrated into the game process. This allows for the analysis of diverse policy choices influenced by disparities in industry, energy, energy consumption, carbon emissions, and other factors. Under the national ETM, decomposing the influencing factors of total regional carbon emissions becomes crucial in identifying the basis for local governments to make policy choices. Consequently, in the payment matrix of the evolutionary game, the total carbon emission reduction cost βM is the product of the Marginal Abatement Cost β and the total regional carbon emission M. Considering the decomposition of total regional carbon emissions M by the Kaya identity, local governments, when making policy choices, should take into account the region's industrial structure, energy structure, technical level, and other factors. These factors determine the emission reduction costs and economic growth losses borne by different regions.

3. Analysis and Discussion of Modeling and Simulation

3.1 Stabilization strategies

The expected return of the policy support chosen by local governments is:

$$Ex_p = q(G_1 - \beta M) + (1-q)(G_2 - \beta M) \tag{2}$$

The expected return of no policy support selected by local governments is:

$$Ex_{1-p} = q\alpha G_1 + (1-q)(G_2 - \gamma M) \tag{3}$$

The average expected return of local governments is:

$$\begin{aligned} \overline{Ex} &= pEx_p + (1-p)Ex_{1-p} \\ &= p[q(G_1 - \beta M) + (1-q)(G_2 - \beta M)] \\ &\quad + (1-p)[q\alpha G_1 + (1-q)(G_2 - \gamma M)] \end{aligned} \tag{4}$$

The replication dynamic equation of local governments is:

$$\begin{aligned} F(p) = \frac{dp}{dt} &= p\left(Ex_p - \overline{Ex}\right) \\ &= p(1-p)\{q[(1-\alpha)G_1 - \gamma M] - (\beta - \gamma)M\} \end{aligned} \tag{5}$$

When $\frac{dp}{dt} = 0$, all stable states of local governments can be obtained: $p^* = 0, p^* = 1$ and $q^* = \frac{(\beta-\gamma)M}{(1-\alpha)G_1 - \gamma M}$.

By the stability theorem of the differential equation, the steady strategy of the local government must satisfy $F(p^*) = 0, F'(p^*) < 0$. When $q^* = \frac{(\beta-\gamma)M}{(1-\alpha)G_1 - \gamma M}$ ($0 \le \frac{(\beta-\gamma)M}{(1-\alpha)G_1 - \gamma M} \le 1$), there is always $F(p) = 0$, that is, for any value of p, it is in a stable state. When energy-intensive enterprises choose the entry strategy with probability $\frac{(\beta-\gamma)M}{(1-\alpha)G_1-\gamma M}$, There is no difference between the benefits of local governments choosing policy support and no policy support. Any strategic choice of local governments is stable. When $q^* > \frac{(\beta-\gamma)M}{(1-\alpha)G_1-\gamma M}$, Two possible stable points are $p^* = 0$ and $p^* = 1$. Since this paper assumes that $\beta < \gamma$, only $p^* = 0$ satisfy condition $F(p=0)=0,\ F'(p=0)<0$, $p^* = 0$ is an evolutionary stability strategy, that is, the evolutionary stability strategy of local governments does not issue policies to support energy-intensive enterprises. When $q^* < \frac{(\beta-\gamma)M}{(1-\alpha)G_1-\gamma M}$, the two possible stable points are $p^* = 0$, $p^* = 1$, and only $p^* = 1$ meets condition $F(p=1)=0, F'(p=1)<0$. Therefore, $p^* = 1$ is the evolutionary stability strategy, that is, the evolutionary stability strategy of local governments is to issue policies to support energy-intensive enterprises.

The preceding analysis indicates that when the probability of energy-intensive enterprises opting to enter the national ETM is low, the government's stabilization strategy involves providing policy support to these enterprises. However, when the probability of energy-intensive enterprises entering the national ETM is high, the government's stabilization strategy shifts to not providing policy support. This suggests that government policy support serves as a crucial incentive for energy-intensive enterprises to participate in the national ETM. As energy-intensive enterprises autonomously engage in the national ETM, government policy support can be gradually scaled back.

The expected return of energy-intensive enterprises choosing to join the national ETM is:

$$Ey_q = p[R_1 + P(T_0 - T) + S] + (1-p)[R_1 + P(T_0 - T)] \tag{6}$$

The expected return of energy-intensive enterprises choosing not to join the national ETM is:

$$Ey_{1-q} = pR_2 + (1-p)R_2 = R_2 \tag{7}$$

The average expected return of energy-intensive enterprises is:

$$\begin{aligned}\overline{Ey} = qEy_q + (1-q)Ey_{1-q} \\ &= q\{p[R_1 + P(T_0 - T) + S] \\ &+ (1-p)[R_1 + P(T_0 - T)]\} + (1-q)R_2\end{aligned} \tag{8}$$

The replication dynamic equation of energy-intensive enterprises is:

$$F(q) = \frac{dq}{dt} = q\left(Ey_q - \overline{Ey}\right) = q(1-q)[pS + R_1 - R_2 + P(T_0 - T)] \tag{9}$$

When $\frac{dq}{dt} = 0$, all stable states of energy-intensive enterprises can be obtained: $q^* = 0, q^* = 1$ and $p^* = \frac{R_2 - R_1 - P(T_0 - T)}{S}$.

By the stability theorem of the differential equation, the steady strategy of the energy-intensive enterprises must satisfy $F(q^*) = 0, F'(q^*) < 0$. When $p^* = \frac{R_2 - R_1 - P(T_0 - T)}{S}$ $(0 \le \frac{R_2 - R_1 - P(T_0 - T)}{S} \le 1)$, there is always $F(q) = 0$, that is, for any value of q, it is in a stable state. When local governments choose the policy support strategy with probability $\frac{R_2 - R_1 - P(T_0 - T)}{S}$, any strategic choice of energy-intensive enterprises is stable. When $p^* > \frac{R_2 - R_1 - P(T_0 - T)}{S}$, Two possible stable points are $q^* = 0$ and $q^* = 1$. Since this paper assumes that $\beta < \gamma$, only $q^* = 1$ satisfy condition $F(q=1) = 0$, $F'(q=1) < 0$. $q^* = 1$ is an evolutionary stability strategy. The evolutionary stability strategy of energy-intensive enterprises is to join the national CTEM. When $p^* < \frac{R_2 - R_1 - P(T_0 - T)}{S}$, the two possible stable points are $q^* = 0$ and $q^* = 1$, and only $q^* = 0$ meets condition

$F(q=0)=0, F'(q=0)<0$. Therefore, $q^*=0$ is the evolutionary stability strategy, that is, the evolutionary stability strategy of energy-intensive enterprises is not to join the national ETM.

The analysis above reveals that when the probability of local governments issuing policies to support energy-intensive enterprises is low, the stability strategy for energy-intensive enterprises is to abstain from joining the national ETM. Conversely, when the probability of local government issuance of policies supporting energy-intensive enterprises is high, the stable strategy for energy-intensive enterprises is to participate in the national ETM. This implies that the likelihood of government policy issuance to support energy-intensive enterprises positively influences their participation in the national ETM.

3.2 Stability analysis of the evolutionary game

Through the aforementioned investigation, we have derived the local stable equilibrium points of the evolutionary game system: $(0,0),(0,1),(1,0),(1,1),(p^*,q^*)$, where $p^*=\frac{R_2-R_1-P(T_0-T)}{S}, q^*=\frac{(\beta-\gamma)M}{(1-\alpha)G_1-\gamma M}$. The stability of the equilibrium points in the system can be ascertained through the local stability analysis of the Jacobian matrix of the system. The Jacobian matrix of the system is:

$$J=\begin{bmatrix}\frac{\partial F(p)}{\partial p} & \frac{\partial F(p)}{\partial q}\\ \frac{\partial F(q)}{\partial p} & \frac{\partial F(q)}{\partial q}\end{bmatrix}$$
$$=\begin{bmatrix}(1-2p)\{q[(1-\alpha)G_1-\gamma M]-(\beta-\gamma)M\} & p(1-p)[(1-\alpha)G_1-\gamma M]\\ q(1-q)S & (1-2q)[pS+R_1-R_2+P(T_0-T)]\end{bmatrix} \tag{10}$$

Considering the model's specified value range for each variable, an analysis of the potential for the five local equilibrium points to become Evolutionary Stable Strategies (ESS) is conducted under various circumstances. Table 3 provides the determinant and trace of the Jacobian matrix at these five equilibrium points.

Table 3. Determinant and trace of Jacobian matrix at local equilibrium points.

	$detJ$	trJ
(0,0)	$-(\beta-\gamma)M[R_1-R_2+P(T_0-T)]$	$-(\beta-\gamma)M+R_1-R_2+P(T_0-T)$
(0,1)	$[\beta M-(1-\alpha)G_1][R_1-R_2+P(T_0-T)]$	$-[\beta M-(1-\alpha)G_1]-[R_1-R_2+P(T_0-T)]$
(1,0)	$(\beta-\gamma)M[R_1-R_2+S+P(T_0-T)]$	$(\beta-\gamma)M+R_1-R_2+S+P(T_0-T)$
(1,1)	$-[\beta M-(1-\alpha)G_1][R_1-R_2+S+P(T_0-T)]$	$\beta M-(1-\alpha)G_1-[R_1-R_2+S+P(T_0-T)]$
(p*,q*)	0	0

The determination of Evolutionary Stable Strategy (ESS) in the system relies on the positive and negative values of the determinant and trace of the Jacobian matrix. The sign of the matrix determinant and trace is contingent on the size relationships within the following parameter groups: MAC (β) and SCC (γ), Operating income of energy-intensive enterprises when they do not join the national ETM (R_2) and the total income after joining the national ETM without subsidies $R_1+P(T_0-T), R_2$ and total income after joining the national ETM with policy support $R_1+S+P(T_0-T)$, total carbon governance cost (βM), and the loss of green economic growth caused by carbon leakage $(1-\alpha)G_1$.

Based on the asymptotic stability of the equilibrium point in the replicated dynamic system illustrated in Table 4, the following conclusions can be drawn.

First, when $R_2>R_1+S+P(T_0-T)$, irrespective of the relationship between βM and $(1-\alpha)G_1$, the evolutionary equilibrium point of the system is (1,0), as depicted in (1) and (2) in Table 4. This indicates that when the conventional income of energy-intensive enterprises, when they do not join the national ETM, exceeds the combined income from joining, revenue from ETM, and income from local government policy support, even with the local government opting for policy support, energy-intensive enterprises refrain from joining the national ETM.

Second, when 2$R_2 < R_1 + P(T_0 - T)$ and $\beta M > (1 - \alpha)G_1$, the evolutionary equilibrium point of the system is (0,1), as illustrated in Table 4(3). In this scenario, when energy-intensive enterprises participate in the national ETM, the total revenue from trading carbon quotas and the operational income of new enterprises surpasses that from non-participation. Moreover, the cost of carbon emission reduction by local governments outweighs the loss of green economic growth due to carbon leakage. Consequently, even in the absence of government policy support due to high carbon emission reduction costs, energy-intensive enterprises spontaneously engage in the national ETM.

Third, when $R_2 < R_1 + P(T_0 - T)$ and $\beta M < (1 - \alpha)G_1$, the evolutionary equilibrium point of the system is (1,1), as depicted in Table 4(4). In this scenario, when the combined income of energy-intensive enterprises after joining the national ETM and the revenue from trading carbon quotas surpasses that of not joining, and the cost of carbon emission reduction by local governments is lower than the loss of green economic growth due to carbon leakage, local governments opt for policy support, and energy-intensive enterprises choose to participate in the national ETM.

Fourth, when $R_1 + P(T_0 - T) < R_2 < R_1 + S + P(T_0 - T)$ and $\beta M < (1 - \alpha)G_1$, the evolutionary equilibrium point of the system is (1,1), as illustrated in Table 4(5). In this situation, when energy-intensive enterprises refrain from joining the national ETM, their operational income exceeds that without government subsidies after joining the national ETM but is less than that with government subsidies. Simultaneously, when the cost of carbon emission reduction by local governments is lower than the loss of green economic growth due to carbon leakage, local governments choose policy support, and energy-intensive enterprises opt to participate in the national ETM.

Fifth, when $R_1 + P(T_0 - T) < R_2 < R_1 + S + P(T_0 - T)$ and $\beta M > (1 - \alpha)G_1$, there is no evolutionary equilibrium point in the system, as depicted in Table 4(6). In this case, local governments and energy-intensive enterprises will continuously alter their strategies in response to each other's behavior, leading to periodic behaviors.

Table 4. Phase diagram of system evolution under various conditions.

		(0,0)	(0,1)	(1,0)	(1,1)
(1). $R_2 > R_1 + S + P(T_0 - T)$ and $\beta M > (1 - \alpha)G_1$	detJ	-	-	+	+
	trJ	uncertain	uncertain	-	+
		saddle point	saddle point	ESS	unstable
(2). $R_2 > R_1 + S + P(T_0 - T)$ and $\beta M < (1 - \alpha)G_1$	detJ	-	+	+	-
	trJ	uncertain	+	-	uncertain
		saddle point	unstable	ESS	saddle point
(3). $R_2 < R_1 + P(T_0 - T)$ and $\beta M > (1 - \alpha)G_1$	detJ	+	+	-	-
	trJ	+	-	uncertain	uncertain
		unstable	ESS	saddle point	saddle point
(4). $R_2 < R_1 + P(T_0 - T)$ and $\beta M < (1 - \alpha)G_1$	detJ	+	-	-	+
	trJ	+	uncertain	uncertain	-
		unstable	saddle point	saddle point	ESS
(5). $R_1 + P(T_0 - T) < R_2 < R_1 + S + P(T_0 - T)$ and $\beta M < (1 - \alpha)G_1$	detJ	-	+	-	+
	trJ	uncertain	+	uncertain	-
		saddle point	unstable	saddle point	ESS
(6).	detJ	-	-	-	-

$R_1 + P(T_0 - T) < R_2 < R_1 + S + P(T_0 - T)$ and $\beta M > (1-\alpha)G_1$	trJ	uncertain saddle point	uncertain saddle point	uncertain saddle point	uncertain saddle point

3.3 Parameter calibration of numerical simulation model

In order to further study the behavior patterns of local governments and energy-intensive enterprises in the national ETM, this part visualizes the dynamic behavior of both parties through numerical simulation. Here, the regional carbon emission M is decomposed based on the assumptions of the previous model, and the parameter values are set in combination with China's actual regional economic pattern and the operation of the national ETM. So as to analyze the impact of regional characteristics such as industrial structure, energy consumption intensity, energy structure, and carbon price, carbon quota, enterprise carbon emissions on the behavior of both parties.

According to the 'statistical bulletin of national economic and social development in 2023' issued by the National Bureau of statistics, it can be calculated that the energy intensity of the industrial sector is about 1.15 tons of standard coal per Ten thousand yuan. This paper sets three scenarios: 1.1, 1.15 and 1.2. According to the data on the website of the National Bureau of statistics, the industrial output value of each province accounts for about 40%. In this paper, the industrial structure is set as 30%, 40% and 50%. The energy structure is set as 0.35, 0.5 and 0.65, which represents the proportion of fossil energy consumption in the total energy consumption.

The carbon emission coefficient of fossil energy follows the current 0.67 ton carbon dioxide per ton standard coal equivalent given by the Energy Research Institute of the National Development and Reform Commission. The MAC and SCC are set at 4000 yuan per ton and 5000 yuan per ton respectively. According to the listing agreement trading price in the national ETM for an average of 30 days, this paper sets the carbon trading price as 50 yuan per ton. The carbon quota allocated by the local government to an energy enterprise is set at 1million tons. See the table 5 for other value settings.

Table 5. Parameter variation of numerical simulation.

Parameters	Unit	Value					
		Base value	Change of Regional characteristics			Change of policy	
			Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
G_1	10k yuan	310	-	-	-	-	-
$\frac{IOV}{GDP}$	-	0.4	0.3/0.4/0.5	-	-	0.3/0.5	0.3/0.5
$\frac{E}{IOV}$	tce / 10k yuan	1.15	-	1.1/1.15/1.2	-	1.1/1.2	1.1/1.2
$\frac{FE}{E}$	-	0.5	-	-	0.35/0.5/0.65	0.35/0.65	0.35/0.65
$\frac{M}{FE}$	tc/tce	0.67	-	-	-	-	-
β	10k yuan / tc	0.4	-	-	-	-	-
γ	10k yuan / tc	0.5	-	-	-	-	-
α	-	0.8	-	-	-	-	-
R_1	10k yuan	1800	-	-	-	-	-
R_2	10k yuan	2100	-	-	-	-	-
P	yuan / tc	50	-	-	-	-	-
T_0	10k tc	100	-	-	-	90/100/110	-
T	10k tc	95	-	-	-	-	-
S	10k yuan	100	-	-	-	-	40/100/160

3.4 The effect of regional characteristics on the evolution result

By substituting the model parameter values based on China's ETM and regional economic development factual data into the replication dynamic equations $F(p)$ and $F(q)$, the simulation results of the evolutionary game between local governments and energy-intensive enterprises under different scenarios are obtained. Scenario 1, Scenario 2, and Scenario 3 represent different regional characteristics.

Firstly, the strategic evolution of local governments and energy-intensive enterprises under different industrial structures is analyzed. The results of the strategic evolution according to the three values of industrial structure (IOV/GDP) set in Scenario 1 are depicted in figure 2. When the proportion of energy-intensive industries in a regional industry is low (IOV/GDP=0.3), local governments gradually shift towards policy support, while energy-intensive enterprises tend to participate in the national ETM. As the proportion of energy-intensive industries in the regional industry structure gradually increases (IOV/GDP=0.4), the pace of strategy evolution slows down. The likelihood of local governments choosing policy support decreases gradually, alongside a decline in the probability of energy-intensive enterprises joining the national ETM. When the proportion of energy-intensive industries in the regional industrial structure is high (IOV/GDP=0.5), the strategies of both local governments and energy-intensive enterprises become unstable, failing to converge to a stable point. This instability results in policies lacking longevity and stability from local governments, while the strategic choices of energy-intensive enterprises struggle to stabilize under repeated policy shifts. Based on the simulation results of the three different industrial structures, it is concluded that the higher the proportion of energy-intensive industries in the regional industrial structure, the more hesitant local governments are to introduce policies supporting energy-intensive enterprises in joining the national ETM. Similarly, energy-intensive enterprises show reluctance to join the national unified carbon market under these circumstances.

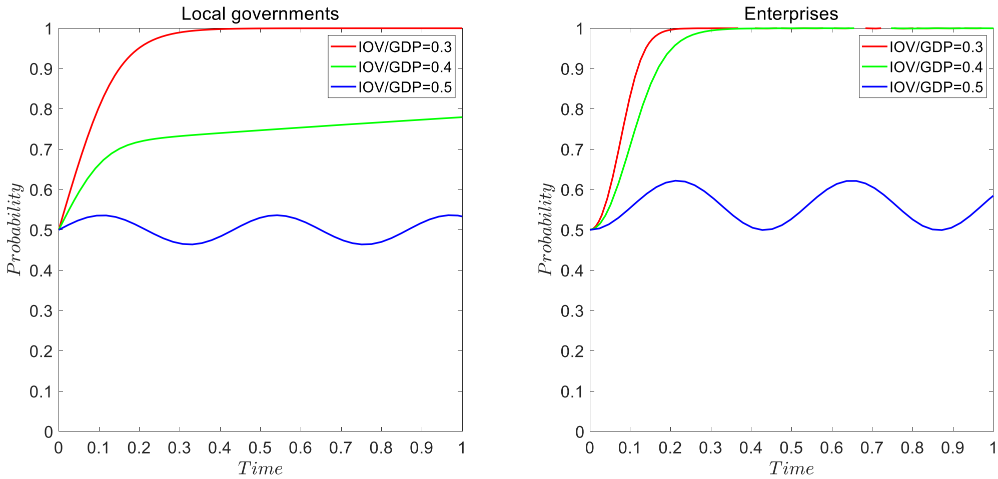

Figure. 1 The effect of the change of industrial structure on the evolution result.

Second, the strategy evolution of local governments and energy-intensive enterprises under different energy intensities is analyzed, and the results based on three values of energy intensity (E/IOV) set in Scenario 2 are illustrated in figure 2. When the energy intensity of a region is low (E/IOV=1.1), local governments gradually shift towards policy support, and energy-intensive enterprises tend to participate in the national ETM. With the increase in energy intensity (E/IOV=1.15), both strategic evolutions slow down. When the region's energy intensity is high (E/IOV=1.2), the strategic choices of local governments become unstable and fail to converge to a stabilization point. Although energy-intensive enterprises choose to participate in the national ETM in the short term, this choice is also unstable, and in the long term, they will still shift to not joining the national ETM. Based on the simulation results of the three different energy intensities, it can be concluded that the higher the energy intensity, the lower the willingness of local governments to introduce policies supporting energy-intensive enterprises to join the national ETM, even in the initial period.

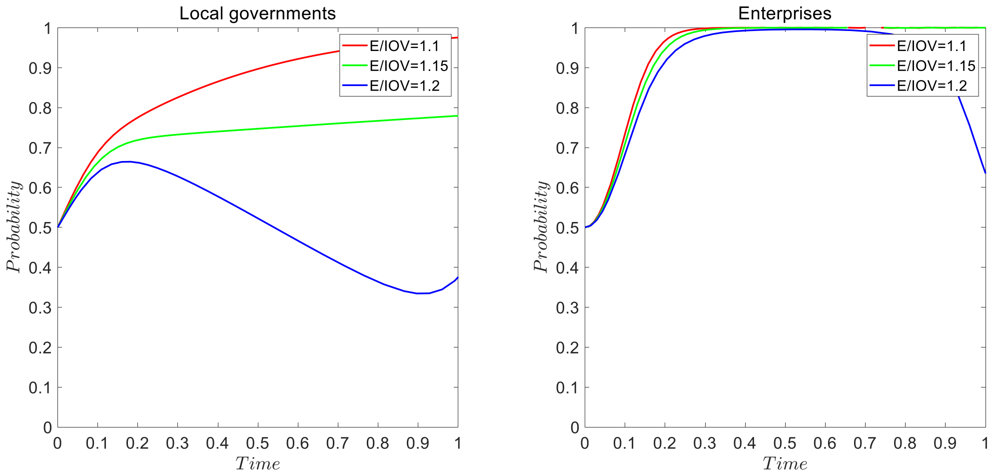

Figure.2 The effect of the change of energy intensity on the evolution result.

Third, the strategic evolution of local governments and energy-intensive enterprises under different energy consumption structures is analyzed, and the results based on three values of energy consumption structure (FE/E) set in Scenario 3 are shown in figure 3. When the proportion of fossil energy consumption in a region's energy consumption structure is low (FE/E=0.35), the strategic choices of local governments gradually evolve into active policy support, and the strategic choices of energy-intensive enterprises gradually evolve into participation in the national ETM. As the proportion of fossil energy consumption in the energy consumption structure increases (FE/E=0.5), the strategic evolution of both slows down. When the proportion of fossil energy consumption in the energy consumption structure of a region is high (FE/E=0.65), the strategies of local governments and energy-intensive enterprises become unstable and fail to converge to a stable point. Based on the simulation results of the three different energy consumption structures, we conclude that differences in the energy consumption structure between regions similarly lead to differences in the strategy evolution of local governments and energy-intensive enterprises. Regions with a lower proportion of fossil energy consumption or with a predominance of renewable energy consumption have local governments that are more inclined to adopt proactive policies to incentivize enterprises to enter the national ETM, and energy-intensive enterprises have a higher willingness to join the national ETM.

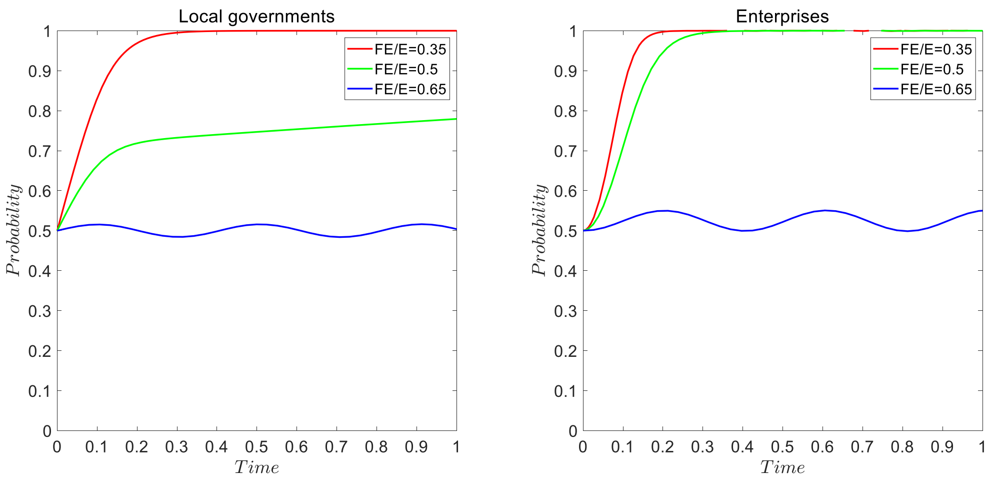

Figure. 3 The effect of the change of energy consumption structure on the evolution result.

3.5 Policy effects under different regional characteristics

This section examines the system evolution results of the game between local governments and energy-intensive enterprises under different free allocations of emission allowances (T_0) as well as different levels of policy support (S), taking into account the characteristics of different regions, such as the values set in Scenario

4 and Scenario 5 in Table 4. Here, T_0 is taken to be 90, 100, and 110, respectively, and S is taken to be 40, 100, and 160, respectively.

Firstly, the policy effects under different industrial structures are analyzed. To make the results more intuitive, two types of industrial structure regions are considered: one with a relatively low share of energy-intensive industries (IOV/GDP=0.3), and the other with a concentration of energy-intensive industries, i.e., a high proportion of energy-intensive industries in the regional industrial structure (IOV/GDP=0.5). The evolution results of the system are shown in figure 4. figure 4(1) demonstrates the effect of the change of T_0 on the system evolution results of the two types of regions. When $T_0 = 90$, the system evolves to the stability point (1,0) regardless of IOV/GDP=0.3 or IOV/GDP=0.5. When $T_0 = 100$, the system evolves to the stable point (1,1) if IOV/GDP=0.3 and fails to evolve to stability if IOV/GDP=0.5. When $T_0 = 110$, if IOV/GDP=0.3, the system evolves to the stable point (1,1), and if IOV/GDP=0.5, the system evolves to the stable point (0,1).

Figure 4(2) demonstrates the effect of the variation of S on the system evolution results for the two types of regions. When S=40, the system evolves to the stability point (1,0) whether IOV/GDP=0.3 or IOV/GDP=0.5. When S=100, the system evolves to the stable point (1,1) if IOV/GDP=0.3 and fails to reach any evolutionary stable point if IOV/GDP=0.5. When S=160, if IOV/GDP=0.3, the system evolves to the stability point (1,1), and if IOV/GDP=0.5, the system's evolution still fails to develop stability.

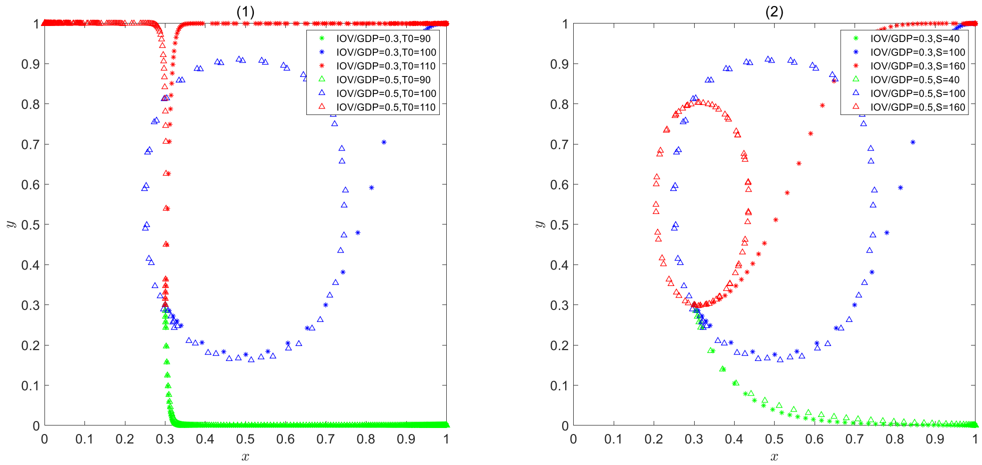

Figure. 4 ESS analysis of policy effects under different industrial structures.

Secondly, the effects of the policy are analyzed under different energy intensities. Given two types of energy intensity regions, one type of region has low energy intensity (E/IOV=1.1), and the other type of region has high energy intensity (E/IOV=1.2). The evolution results of the system are shown in figure 5. In figure 5(1), when $T_0 = 90$, the system evolves to the stability point (1,0) regardless of E/IOV=1.1 or E/IOV=1.2. When $T_0 = 100$, the system evolves to the stable point (1,1) if E/IOV=1.1 and fails to evolve to stability if E/IOV=1.2. When $T_0 = 110$, if E/IOV=1.1, the system evolves to the stable point (1,1), and if E/IOV=1.2, the system evolves to the stable point (0,1). In figure 5(2), when $S = 40$, the system evolves to the stable point (1,0) whether E/IOV=1.1 or E/IOV=1.2. When $S = 100$, if E/IOV=1.1, the system evolves to the stable point (1,1), and if E/IOV=1.2, the system fails to reach any evolutionary stable point. When $= 160$, if E/IOV=1.1, the system evolves to the stability point (1,1), and if E/IOV=1.2, the system's evolution still fails to develop stability.

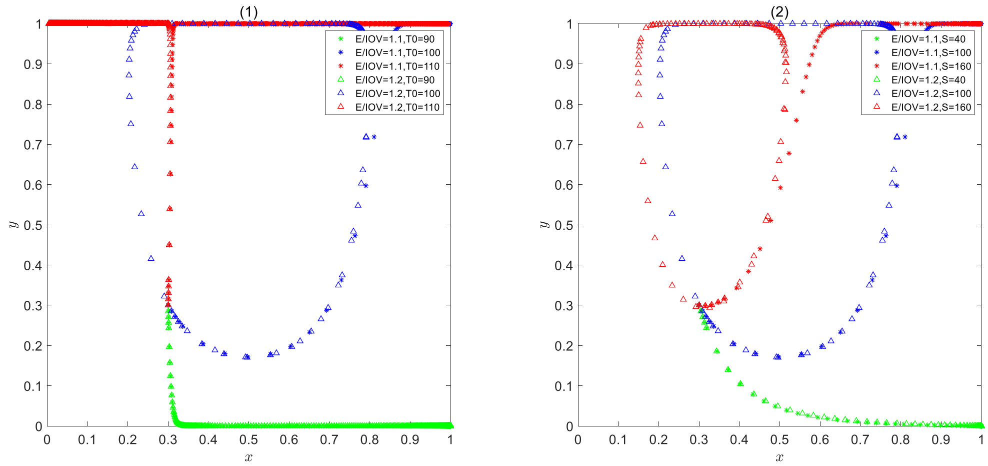

Figure. **5** ESS analysis of policy changes with different energy intensities.

Third, the policy effects under different energy consumption structures are analyzed. Given two types of regions with different energy consumption structures, one type of region is dominated by clean energy consumption (FE/E=0.35), and the other type of region is dominated by fossil energy consumption (FE/E=0.65). The evolution results of the system are shown in figure 6. In figure 6(1), when $T_0 = 90$, the system evolves to the stability point (1,0) regardless of FE/E=0.35 or FE/E=0.65. When $T_0 = 100$, the system evolves to the stable point (1,1) if FE/E=0.35 and fails to evolve to stability if FE/E=0.65. When $T_0 = 110$, if FE/E=0.35, the system evolves to the stable point (1,1), and if FE/E=0.65, the system evolves to the stable point (0,1). In figure 6(2), when $S = 40$, the system evolves to the stable point (1,0) whether FE/E=0.35 or FE/E=0.65. When $S = 100$, if FE/E=0.35, the system evolves to the stable point (1,1), and if FE/E=0.65, the system fails to reach any evolutionary stable point. When $S = 160$, if FE/E=0.35, the system evolves to the stability point (1,1), and if FE/E=0.65, the system's evolution still fails to develop stability.

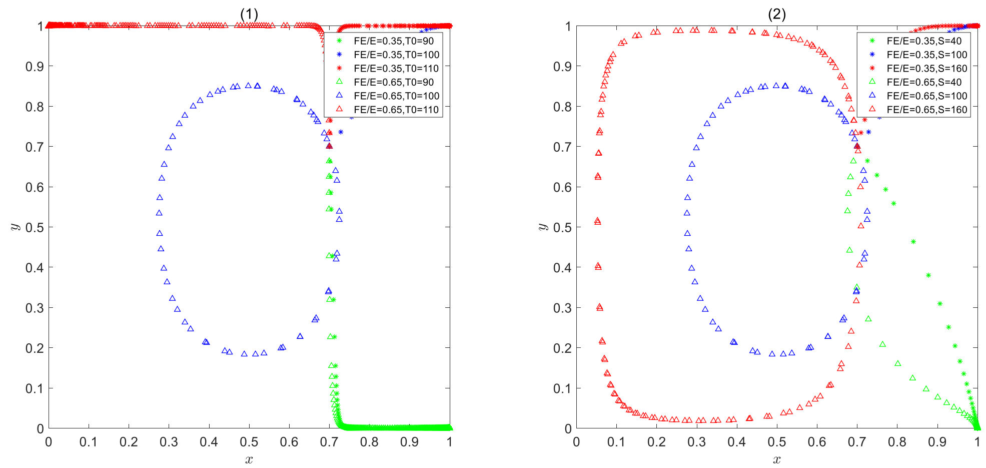

Figure. 6 ESS analysis of policy changes under different energy consumption structures.

3.6 Discussion

(1) How do regional characteristics affect the participation of energy-intensive enterprises in each region in the national unified ETM?

Our results build on the current study of the game relationship between enterprises and governments in the carbon market, and go a step further by discussing the role of regional industrial structure, energy intensity, and energy consumption structure. The differentiated regional characteristics exhibited by different regions will form different states of participation by energy-intensive enterprises in the national unified ETM.

First, the higher the proportion of energy-intensive industries in the regional industrial structure, the more reluctant local governments are to introduce policies to support energy-intensive enterprises to join the national ETM, and the more hesitant energy-intensive enterprises are to participate in the national unified carbon market. In regions where energy-intensive industries dominate, high-emission enterprises are predominant, and strict carbon emission reduction measures will increase the cost of industrial enterprises, resulting in a higher loss of regional economic growth [**Error! Reference source not found.**]. Local governments, in the trade-off between economic growth and environmental governance, are more inclined to maintain the existing production status of carbon-intensive enterprises to ensure that regional economic growth is not affected. At the same time, in the absence of a scientific allocation of emission allowances, energy-intensive enterprises will produce more carbon emissions than other enterprises and need to spend extra money on purchasing emission allowances. Therefore, enterprises choose not to join the national ETM to avoid the increase in enterprise costs.

Second, the higher the energy intensity, the lower the willingness of local governments to introduce policies to support energy-intensive enterprises to join the national ETM, and even if the initial incentives make energy-intensive enterprises join the national ETM, it is not sustainable in the long run. Higher energy intensity in a region means that most of the energy-intensive enterprises in the region depend on energy factor inputs for their production, and the structure of factor inputs is biased towards a low total factor productivity model. These low-technology energy enterprises can hardly earn profits from the national ETM after joining, but on the contrary, they will pay extra costs for purchasing carbon emission allowances, and the local government will also bear the corresponding loss of economic growth due to the decline in the earnings of enterprises in the region. Therefore, local governments will be less willing to choose policy support at this time, and energy companies will lack incentives to join the national ETM.

Third, differences in the structure of energy consumption between regions can similarly lead to differences in the evolution of the strategies of local governments and energy-intensive enterprises. Regions with a lower proportion of fossil energy consumption or with a predominance of renewable energy consumption have local governments that are more inclined to adopt proactive policies to incentivize enterprises to enter the national ETM, and energy-intensive enterprises have a higher willingness to join the national ETM. Regions that have completed the energy transition earlier have a first-mover advantage in participating in the national ETM, and most of the energy-intensive enterprises in the regions are based on renewable energy consumption. They can increase their revenues by selling more emission allowances in the initial stage of the ETM. Local governments actively promoting the entry of energy-intensive enterprises into the national ETM can help achieve the dual goals of regional economic growth and climate change governance.

(2) How to effectively promote the inclusion of local governments and energy-intensive enterprises in the national ETM?

Our results underscore the policy trade-offs local governments face in encouraging energy-intensive enterprises to participate in the national ETM. There is some resistance for energy-intensive enterprises to enter the national ETM independently, influenced by factors such as their own carbon emission levels, emission allowances, and trading prices. Government policy support is crucial for energy-intensive enterprises to enter the national ETM, aligning with previous studies [**Error! Reference source not found.**]. Our study takes a step further by revealing that the effects of policies differ across regional characteristics, emphasizing the need for differentiated policies that consider regional development characteristics [30]. Local governments' policy choices depend on the impacts of enterprises joining the national ETM, requiring trade-offs between economic growth and environmental governance. Therefore, our study provides the following insights for policy formulation.

First, the formulation of carbon emission reduction policies by local governments should fully consider regional characteristics to balance economic development and climate change governance. Policies should promote the transformation of industrial structure, encourage the upgrading of industrial technology to reduce production energy consumption, actively support the shift from fossil energy to renewable energy in the energy consumption structure, and adjust emission reduction costs based on regional conditions [31].

Second, local governments can provide corresponding tax incentives and subsidies to energy-intensive enterprises that join the national ETM. They should actively support energy-intensive enterprises in changing their production modes and improving their technology levels. This will enable energy-intensive enterprises to gain more operating income and reduce carbon emissions through low-carbon transformation, thereby enhancing their willingness to participate in the national ETM.

Third, at the initial stage of the national ETM development, local governments can appropriately increase the carbon quota allocated free of charge to benefit energy-intensive enterprises [32]. As the technology level of carbon reduction improves and the profitability of low-carbon development increases for enterprises, the distribution of free carbon quotas can be gradually adjusted to stabilize the participation of energy-intensive enterprises in the national ETM.

4. Conclusion

This paper presents an evolutionary game model involving local governments and energy-intensive enterprises within the framework of the national ETM. The Kaya identity is extended and incorporated into the game model to decompose the influence of regional characteristics, such as industrial structure, energy consumption intensity, and energy structure, on strategies.

The findings reveal that: Energy-intensive enterprises refrain from joining the national ETM when government subsidies and the income derived from the ETM cannot compensate for the income loss incurred by participation. Even if local governments opt for policy support, energy-intensive enterprises remain reluctant to join. Energy-intensive enterprises may spontaneously participate in the national ETM if their income without government support exceeds the income from not joining, even in the absence of government policies considering high carbon emission reduction costs. Local governments are inclined to issue policies supporting energy-intensive enterprises' participation in the national ETM when the cost of carbon emission reduction is lower than the loss of green eco-nomic growth caused by carbon leakage. The strategic choice of energy-intensive enterprises is influenced by the benefits obtained from government support policies and the cost of carbon emission reduction by local governments, with the latter being lower than the loss of green economic growth due to carbon leakage. The cost of carbon emission reduction by local governments is determined by regional characteristics, with industrial structure, energy consumption intensity, and energy structure negatively impacting the willingness of local governments to issue support policies. Free carbon quotas allocated to energy-intensive enterprises and the benefits from policies positively influence the participation of energy-intensive enterprises in the national ETM. Carbon emissions from energy-intensive enterprises negatively affect their willingness to participate in the national ETM.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, author-ship, and/or publication of this article.

Data Sharing Agreement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

[1] H. Dong and J. Yang (2024) Study on regional carbon quota allocation at provincial level in China from the perspective of carbon peak, J. Environ. Manage., 351: 119720.

[2] J. Yu, P. Liu, X. Shi and X. Ai (2023) China's emissions trading scheme, firms' R&D investment and emissions reduction, Econ. Anal. Policy, 80 :1021‑1037.

[3] D. Ma, Y. Xiao and N. Zhao (2022) Optimization and spatiotemporal differentiation of carbon emission rights allocation in the power industry in the Yangtze River Economic Belt, Sustainability, 14 (9) :5201.

[4] P. Zhou and M. Wang (2016) Carbon dioxide emissions allocation: A review, Ecol. Econ., 125 :47‑59.

[5] Q. Wu (2022) Price and scale effects of China's carbon emission trading system pilots on emission reduction, J. Environ. Manage., 314 :115054.
[6] H.R. Peng, J. Cui and X. Zhang (2022) Does China emission trading scheme reduce marginal abatement cost? A perspective of allowance allocation alternatives, Sustain. Prod. Consum., 32 :690‑699.
[7] C.J. Ji, Y.J. Hu, B.J. Tang et al. (2021) Price drivers in the carbon emissions trading scheme: Evidence from Chinese emissions trading scheme pilots, J. Clean. Prod., 278 :123469.
[8] Y.G. Kim and J.S. Lim (2021) Treatment of indirect emissions from the power sector in Korean emissions trading system, Environ. Econ. Policy Stud., 23 (3) :581‑592.
[9] Y. Wei, T. Zhao, J. Wang et al. (2023) Two-level allocation and its future change of CO2 reduction responsibility in China's power sector, Environ. Impact Assess. Rev., 99 :107031.
[10] C.J. Ji, Y.J. Hu, B.J. Tang and S. Qu (2021) Price drivers in the carbon emissions trading scheme: Evidence from Chinese emissions trading scheme pilots, J. Clean. Prod., 278 :123469.
[11] C.J. Ji, Y.J. Hu, B.J. Tang and S. Qu (2021) Price drivers in the carbon emissions trading scheme: Evidence from Chinese emissions trading scheme pilots, J. Clean. Prod., 278 :123469.
[12] X. Pan, C. Pu, S. Yuan and H. Xu (2022) Effect of Chinese pilots carbon emission trading scheme on enterprises' total factor productivity: The moderating role of government participation and carbon trading market efficiency, J. Environ. Manage., 316 :115228.
[13] W. Wang and Y.J. Zhang (2022) Does China's carbon emissions trading scheme affect the market power of high-carbon enterprises?, Energy Econ., 108 :105906.
[14] B. Lin and N. Wu (2022) Will the China's carbon emissions market increase the risk-taking of its enterprises?, Int. Rev. Econ. Finance, 77 :413‑434.
[15] W. Tong, H. Liu and J. Du (2022) Does the carbon trading mechanism affect social and environmental benefits of the retailer-led supply chain: Strategic decisions of emissions reduction and promotion, Front. Environ. Sci., 10 :971214.
[16] Z. Hong, Z. Peng and L. Zhang (2022) Game analysis on the choice of emission trading among industrial enterprises driven by data, Energy, 239 :122447.
[17] S. Li, J. Liu and D. Shi (2021) The impact of emissions trading system on corporate energy efficiency: Evidence from a quasi-natural experiment in China, Energy, 233 :121129.
[18] Z. Xu, A. Sukumar, V. Jafari-Sadeghi et al. (2021) Local-global design: entrepreneurial ecosystem approach for digital gaming industry, Int. J. Technol. Transfer Commer., 18 (4) :418‑438.
[19] K. Zhou, Q. Wang and J. Tang (2022) Evolutionary game analysis of environmental pollution control under the government regulation, Sci. Rep., 12 (1) :474.
[20] J. Liu, M. Peng, Y. Peng et al. (2021) Effects of inequality on a spatial evolutionary public goods game, Eur. Phys. J. B, 94 :1‑7.
[21] P. Ghasemi, F. Goodarzian, A. Gunasekaran et al. (2023) A bi-level mathematical model for logistic management considering the evolutionary game with environmental feedbacks, Int. J. Logist. Manag., 34 (4) :1077‑1100.
[22] C. Zhang and X. Zhang (2022) Evolutionary game analysis of air pollution co-investment in emission reductions by steel enterprises under carbon quota trading mechanism, J. Environ. Manage., 317 :115376.
[23] X. Song, M. Shen, Y. Lu, L. Shen and H. Zhang (2021) How to effectively guide carbon reduction behavior of building owners under emission trading scheme? An evolutionary game-based study, Environ. Impact Assess. Rev., 90 :106624.
[24] S. Zheng and L. Yu (2022) The government's subsidy strategy of carbon-sink fishery based on evolutionary game, Energy, 254 :124282.
[25] Z. Li and B. Wang (2025) A bibliometric analysis of carbon allowances in the carbon emissions trading market, Energies, 18 :57.
[26] J. Luo, X. Jin and Y. Hu (2024) Top-down or bottom-up? Government policies, public awareness and carbon reduction, Econ. Anal. Policy, 83 :118‑120.
[27] S. Akther, M.R. Sultanuzzaman, Y. Zhang et al. (2024) Exploring the influence of green growth and energy sources on “carbon-dioxide emissions”: implications for climate change mitigation, Front. Environ. Sci., 12 :1443915.

[28] Y. Yang, S. Mou, H. Wang et al. (2024) Global source apportionment of aerosols into major emission regions and sectors over 1850–2017, Atmos. Chem. Phys., 24 (11) :6509–6523.
[29] D. Chen, Y. Huang, N. Tan, T. Hong and T. Ma (2024) Cross-regional economic impact of carbon emission regulations: a quantitative spatial equilibrium model for China, Struct. Change Econ. Dyn., 69 :438–462.
[30] F. Dong, G. Li, Y. Liu, Q. Xu and C. Li (2023) Spatial-temporal evolution and cross-industry synergy of carbon emissions: evidence from key industries in the city in Jiangsu Province, China, Sustainability, 15 (5) :3881.
[31] F. Dong, J. Li, Z. Li, Y. Chen, L. Zheng, B. Lu and Y. Liu (2023) Exploring synergistic decoupling of haze pollution and carbon emissions in emerging economies: fresh evidence from China, Environ. Dev. Sustain., 1-38.
[32] X. Zhai, Y. An, X. Shi and H. Cui (2023) Emissions trading scheme and green development in China: impact of city heterogeneity, Sustain. Dev., 31(4): 2583-2597.