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A Game-Theoretic Study on the Evolution of Carbon Emission Reduction Strategies among Chemical Companies under a Carbon Trading Mechanism

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Abstract

With the national carbon market set to expand coverage to the chemical industry, chemical enterprises face strategic divergence and interaction between two options: achieving emissions reductions through proprietary technologies, or purchasing carbon allowances to meet compliance obligations. This paper incorporates key parameters including carbon price, the severity of government penalties, differences in emission reduction costs, and low-carbon subsidies to construct an evolutionary game model of the interaction between local governments and chemical enterprises under the carbon trading mechanism. Based on this model, this paper employs numerical simulation methods to systematically analyze the evolutionary paths and steady-state conditions of group strategies under different parameter combinations. The results indicate that the system exhibits four evolutionary equilibrium states, and periodic fluctuations are the most common transitional state in carbon emission reduction governance. This phenomenon essentially stems from a "regulation–relaxation" cycle caused by asymmetric incentive structures between the government and enterprises. The ideal equilibrium can be achieved through two pathways: market-driven and policy-guided. Among these, the policy-guided equilibrium combines endogenous dynamics with regulatory safeguards, and delivers greater stability and sustainability. Finally, based on the research findings, this paper proposes targeted recommendations from the perspectives of both the government and chemical enterprises.

Keywords

Carbon Trading; Evolutionary Game; Chemical Enterprises.

1. Introduction

Global warming has become a major challenge to sustainable human development. Against this backdrop, the international consensus on advancing green low-carbon transitions and curbing greenhouse gas emissions has continued to strengthen. According to data from the *World Energy Outlook 2025* published by the International Energy Agency (IEA), global energy-related carbon dioxide emissions reached 38 billion metric tons in 2024, and emissions are expected to stay at a high level in 2025. This means the pressure on global climate governance and carbon reduction will keep intensifying.To tackle the crisis brought by climate change, China formally put forward two phased emission reduction targets at the 75th session of the United Nations General Assembly in 2020: "reaching carbon peak by 2030 and achieving carbon neutrality by 2060". Among the policy arrangements for meeting these targets, the National Carbon Emission Trading Market is the core market-based institutional arrangement for implementing this strategic goal.With carbon emission allowances as its trading product, this market internalizes the external cost of carbon emissions through a combination of total

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emission caps, market-based pricing, allowance trading and compliance mechanisms. It guides high-emission market entities to cut emissions voluntarily, thus providing crucial institutional support for achieving the carbon peak and carbon neutrality goals on schedule.

The chemical industry is a foundational, pillar, and strategic sector that underpins the stable operation of the national economy and the sound development of the industrial system. It covers key areas such as petroleum refining, synthetic materials, and fine chemicals, and its products are extensively used in core sectors of the national economy, including new energy, high-end equipment, and electronic information. It serves as a vital material foundation for ensuring the autonomy and controllability of industrial and supply chains and for promoting high-quality development in the manufacturing sector.As a typical industry characterized by highly concentrated energy consumption and carbon emissions, China’s chemical sector accounts for a large share of the country’s total fossil fuel use: total fossil fuel consumption in the sector is projected to reach approximately 4.83 billion metric tons of standard coal in 2025, with annual CO_2 emissions across the sector estimated at about 1.6 billion metric tons-accounting for 12.7% of the nation’s total carbon emissions and ranking among the highest of all industrial sectors.At the same time, the chemical industry faces widespread practical constraints, including lengthy production processes, complex technological pathways, and high costs associated with low-carbon retrofitting. Enterprises must navigate multiple trade-offs between emissions reduction investments, production efficiency, market competition, and policy compliance, making emissions reduction significantly more challenging than in general manufacturing.Against the dual backdrop of the “Dual Carbon” goals and the accelerated expansion of the national carbon market, the chemical industry will soon be fully incorporated into mandatory carbon emissions trading compliance management. How to use market-based mechanisms to overcome emission reduction constraints, balance development with carbon reduction, and guide enterprises to proactively implement low-carbon transformation has become a major practical issue concerning the industry’s sustainable development and the timely achievement of the nation’s “Dual Carbon” goals.

Currently, academic circles have conducted in-depth research on emissions reduction in chemical enterprises from perspectives such as strategic transformation, technological innovation, the application of management tools, and the interaction between policy and the market.Dai Houliang et al. (2024) systematically analyzed the internal and external development dynamics and core challenges facing the green and low-carbon transition of China’s petrochemical and chemical industries. From multiple perspectives-including technological innovation, industrial structure, energy consumption, and production processes-they proposed a comprehensive transition plan comprising eight major projects, providing a roadmap for the industry’s high-quality, low-carbon development[1].Chen Lujun et al. (2024) systematically established a technical implementation pathway for synergistic pollution reduction and carbon reduction in chemical industrial parks, based on three dimensions: enterprise production, supporting infrastructure, and industrial symbiosis[2].Ding Shufang et al. (2025) employed spatial analysis methods to investigate the spatiotemporal distribution characteristics and driving factors of carbon emission efficiency in China’s chemical industry; the study indicates that energy structure adjustment is a key measure for improving carbon emission efficiency[3]. Wang Lei et al. (2025) conducted an in-depth analysis of the synergy mechanisms and practical pathways for the low-carbon transition of chemical enterprises from three dimensions: policy guidance, financial support, and corporate technological innovation[4]. However, existing research largely focuses on the technical level or the evaluation of individual policy effects, with few studies revealing the dynamic game-theoretic process between the government and chemical enterprises under the carbon trading mechanism. Although previous studies have constructed game models, they have not fully

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considered key parameters such as carbon allowances and carbon prices, making it difficult to accurately guide emission reduction practices and policy optimization in the chemical industry. Accordingly, against the backdrop of the full-scale rollout of the national carbon market and the imminent inclusion of the chemical industry in the compliance system, this paper constructs a dynamic evolutionary game model of the government and chemical enterprises under the carbon trading mechanism. It systematically analyzes the utility functions, replicator dynamics equations, and evolutionarily stable strategies of the two agents under different scenarios. Based on this, numerical simulations are conducted using MATLAB to ultimately reveal the intrinsic mechanisms by which carbon trading drives emissions reductions in chemical enterprises, clarify the constraints for achieving an ideal equilibrium, and propose optimized carbon reduction strategies and policy recommendations tailored to the chemical industry.

2. Model Assumptions and Construction

2.1. Problem Description

Under the rigid constraints of the "Dual Carbon" strategic goals, the national carbon emissions trading market has entered a phase of deepening cross-industry expansion and normalized operation. The carbon trading mechanism provides a market-based incentive framework for carbon emissions reduction by chemical enterprises through market-driven quota pricing and compliance constraints. However, in the practical implementation of policies, it still faces widespread information asymmetry and principal-agent dilemmas: local governments must balance regulatory costs against the effectiveness of environmental governance, while chemical enterprises, constrained by high emissions reduction costs, encounter moral hazards such as passive emissions reduction and data falsification.As bounded-rational decision-makers, the strategic choices of these two parties involve a dynamic balance of interests, forming a typical non-cooperative evolutionary game relationship. To clarify the logic of strategic interaction and the pathways of interest transmission between the two parties under the synergistic mechanism of carbon trading and carbon taxes, this paper constructs an evolutionary game analysis framework that includes local governments and chemical enterprises. The interactive game relationships among all parties are illustrated in Figure 1.

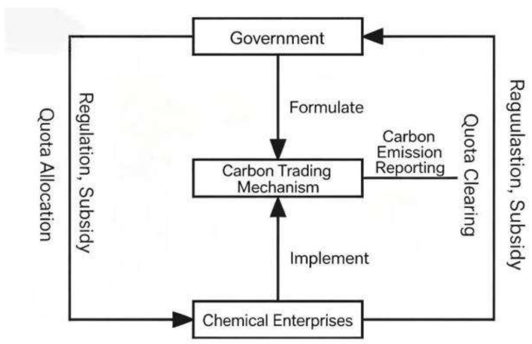

Figure 1. Diagram of the Game Relationship Between the Government and Chemical Companies

2.2. Model Assumptions

By analyzing the game-theoretic relationship between the government and chemical enterprises and drawing on relevant literature, this paper proposes the following assumptions:

Assumption 1: Both local governments and chemical companies are bounded-rational decision-makers; they cannot choose optimal strategies based on complete information at the initial stage of the game. Instead, they gradually optimize their strategies through continuous learning, trial and error, and adjustments, ultimately reaching an evolutionarily stable equilibrium.

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Assumption 2: The government's strategy set is {active regulation, passive regulation}, with a probability of x of choosing active regulation and a probability of $1-x$ of choosing passive regulation; the chemical company's strategy set is {active emissions reduction, passive emissions reduction}, with a probability of y of choosing active emissions reduction and a probability of $1-y$ of choosing passive emissions reduction.

Assumption 3: The government allocates initial carbon allowances Q_0 to firms for a single compliance period based on industry benchmarks, such that $Q_1 < Q_0 < Q_2$ (i.e., firms generate a surplus of allowances when they prioritize emissions reduction and exceed their allowances when they do not), and sets a unit carbon tax rate t, levied on the basis of the firm's total actual emissions.Active government regulation incurs regulatory costs C_g, while passive regulation incurs no additional costs. When a firm neglects emissions reduction and the government engages in passive regulation, the government must bear environmental governance costs $L_g$and suffers reputational losses D_g due to regulatory failure.Under active government regulation, if a firm's excessive emissions resulting from a lack of emphasis on emission reduction are verified, the government imposes a fine F; firms that prioritize emission reduction receive a subsidy b per unit of emission reduction, with the total subsidy amount S being positively correlated with the firm's emission reduction relative to its quota, where $S = b(Q_0 - Q_1)$. Under passive government regulation, no carbon tax is levied, no fines are imposed, and no subsidies are provided.

Table 1. Symbols and Definitions of Parameters

Parameter Name	Parameter Symbol	Parameter Definition
Government Regulatory Cost	C_g	Total process costs under strict government regulation
Government Fines Imposed on Firms	F	Fines imposed by the government on companies after detecting excessive emissions
Reputational damage resulting from government inaction	D_g	Reputational damage resulting from the government's failure to regulate a company's excessive emissions
Environmental governance costs	L_g	Environmental remediation costs borne by the government due to corporate excess emissions
Subsidy rate per unit of emissions reduction	b	Government-prescribed subsidy amount per metric ton of emission reduction
Revenue from the enterprise's proactive emission reductions	A_1	Production revenue when the enterprise actively reduces emissions
Revenue generated when the enterprise passively reduces emissions	A_2	Production revenue when a company passively reduces emissions
Carbon emissions when the firm actively reduces emissions	Q_1	Actual Carbon Emissions When a Firm Engages in Active Emissions Reduction
Carbon Emissions When a Firm Passively Reduces Emissions	Q_2	Actual carbon emissions when the company actively reduces emissions
Carbon tax rate	t	Government-mandated carbon tax rate
Carbon price	P	The trading price of carbon allowances in the carbon market
Carbon tax amount	T	Carbon tax payable by enterprises for exceeding emission allowances
Initial Carbon Allowances	Q_0	Government-approved upper limit on a company's compliant emissions
Enterprise Emission Reduction Costs	C_f	Costs incurred by enterprises for proactive emissions reductions

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Assumption 4: When firms actively reduce emissions, they earn a base production revenue of A1and incur a uniform abatement cost of C_f; at this point, actual carbon emissions are Q_1, resulting in a surplus of allowances. When firms passively reduce emissions, they earn a base production revenue of A_2 without incurring any abatement costs, satisfying $A_2 > A_1 > 0$; at this point, actual carbon emissions are Q_2, resulting in a permit deficit. The trading price per unit of carbon permit in the carbon market is P, an exogenously given parameter; the behavior of individual firms does not affect the market carbon price. When the government actively regulates, firms that actively reduce emissions can sell their surplus permits on the carbon market to earn a profit of $P(Q_0 - Q_1)$, while also receiving a special emissions reduction subsidy of $b(Q_0 - Q_1)$, and pay a carbon tax of tQ_1 ; when firms passively reduce emissions, they must purchase allowances to cover the shortfall at a cost of $P(Q_2 - Q_0)$, while also paying a carbon tax of tQ_2 and a penalty of F. Under passive government regulation, firms have no obligation to settle allowances, engage in no carbon trading, and are not required to pay carbon taxes, penalties, or receive subsidies.

2.3. Model Construction

Based on the above assumptions, variable settings, and an analysis of the relationship between the government and chemical companies, the payoff matrix for both parties under different strategies is shown in the table below.

Table 2. Payoff Matrix for the Government and Chemical Companies

Strategy Set	Government	Chemical Company
Proactive Regulation,Proactive Emissions Reduction	$tQ_1-C_g-b(Q_0-Q_1)$	$A_1-C_f+P(Q_0-Q_1)+b(Q_0-Q_1)-tQ_1$
Proactive Regulation,Passive Emissions Reduction	$F-C_g+tQ_2$	$A_2-P(Q_2-Q_0)-tQ_2-F$
Passive Regulation,Proactive Emissions Reduction	0	A_1-C_f
Passive Regulation,Passive Emissions Reduction	$-L_g-D_g$	A_2

(1) The government's expected revenue

When the government chooses the "active regulation" strategy, its expected revenue isE_{G1} . Therefore,

$$E_{G1}=y\left[tQ_1-C_g-b\left(Q_0-Q_1\right)\right]+(1-y)\left(F-C_g+tQ_2\right)$$

When the government chooses the "passive regulation" strategy, its expected revenue isE_{G2} ; therefore,

$$E_{G2}=y\cdot 0+(1-y)(-L_g-D_g)=(y-1)(L_g+D_g)$$

The government's average expected revenue is:

$$E_G=xE_{G1}+(1-x)E_{G2}$$

(2) Expected Revenue of the Chemical Company

When the chemical company chooses the "active emissions reduction" strategy, its expected revenue isE_{Q1} ; therefore,

$$E_{Q1}=x\left[A_1-C_f+P(Q_0-Q_1)+b(Q_0-Q_1)-tQ_1\right]+(1-x)(A_1-C_f)$$

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When the chemical company chooses the "passive emissions reduction" strategy, its expected payoff isE_{Q2} , so

$$E_{Q2}=x\left[A_2-P(Q_2-Q_0)-tQ_2-F\right]+(1-x)A_2$$

The chemical company's average expected revenue is:

$$E_Q=yE_{Q1}+(1-y)E_{Q2}$$

Based on the above formula and the principles of replicating dynamic equations, the replicating dynamic equations for the government and the chemical company are as follows:

$$F(x)=\frac{dx}{dt}=x(E_{G1}-E_G)=x(1-x)(E_{G1}-E_{G2})$$
$$=x(1-x)\left\{y\left[t(Q_1-Q_2)-b(Q_0-Q_1)-F-L_g-D_g\right]+F+tQ_2+L_g+D_g-C_g\right\}$$
$$F(y)=\frac{dy}{dt}=x(E_{Q1}-E_Q)=y(1-y)(E_{Q1}-E_{Q2})$$
$$=y(1-y)\left\{x\left[(P+t)(Q_2-Q_1)+b(Q_0-Q_1)+F\right]+A_1-A_2-C_f\right\}$$

3. Model Solution and Stability Analysis

3.1. Solving for the System Equilibrium Point

An equilibrium point in an evolutionary game system refers to a state in which the proportions of strategy choices made by both parties no longer change over time. At this point, the derivatives of the replicating dynamic equations are zero.By solving the system of replicating dynamic equations for the government and the chemical company simultaneously and setting them both equal to zero, we obtain four pure-strategy equilibria: $E_1(0,0)$,$E_2(1,0)$,$E_3(0,1)$, and $E_4(1,1)$, as well as one mixed-strategy equilibrium: $E_5(x^*,y^*)$, where $x^*=\frac{A_2-A_1+C_f}{(P+t)(Q_2-Q_1)+b(Q_0-Q_1)+F}$,$y^*=\frac{tQ_2+F-C_g+L_g+D_g}{t(Q_2-Q_1)+b(Q_0-Q_1)+F+L_g+D_g}$, and $0\leq x^*,y^*\leq 1$ hold if and only if.

3.2. Stability Analysis and Determination of Equilibrium Points

The Jacobian matrix describes the dynamic characteristics of the system near the equilibrium points. To analyze the local stability of each equilibrium point, we calculate the partial derivatives of the replicating dynamic equations for the government and the chemical company with respect tox andy , respectively, and construct the system's Jacobian matrix as shown below. Here,x is the probability that the local government chooses an active regulatory strategy, andy is the probability that the chemical company chooses an active emission-reduction strategy.

$$J=\begin{pmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y}\\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y}\end{pmatrix}=$$

ISSN: 2692-7608 DOI: 10.6981/FEM.202607_7(7).0013

$$\begin{pmatrix} (1\text{-}2x)\begin{Bmatrix} y\left[t\left(Q_1\text{-}Q_2\right)\text{-}b\left(Q_0\text{-}Q_1\right)\text{-}F\text{-}L_g\text{-}D_g\right] \\ +F+tQ_2+L_g+D_g\text{-}C_g \end{Bmatrix} & x(1\text{-}x)\begin{bmatrix} t\left(Q_1\text{-}Q_2\right)\text{-}b\left(Q_0\text{-}Q_1\right) \\ \text{-}F\text{-}L_g\text{-}D_g \end{bmatrix} \\ y(1\text{-}y)\left[(P+t)\left(Q_2\text{-}Q_1\right)+b\left(Q_0\text{-}Q_1\right)+F\right] & (1\text{-}2y)\begin{Bmatrix} x\left[(P+t)\left(Q_2\text{-}Q_1\right)+b\left(Q_0\text{-}Q_1\right)+F\right] \\ +A_1+A_2\text{-}C_f \end{Bmatrix} \end{pmatrix}$$

According to Friedman's criterion, for a two-dimensional dynamical system, the local stability of an equilibrium point is determined jointly by the determinant det(J) and the trace tr(J) of its Jacobian matrix: if $\det(J)>0$ and $tr(J)<0$, then the point is an evolutionarily stable strategy (ESS) that is asymptotically stable; if $\det(J)>0$ and $tr(J)>0$, then it is an unstable node; if $\det(J)<0$, then it is a saddle point.Since the evolutionary game stability criterion applies to pure strategy equilibrium points, this paper calculates only the determinants and traces of the Jacobian matrices for the four pure strategy equilibrium points to determine their stability. By substituting the equilibrium points into the Jacobian matrices, we obtained the values of det(J) and tr(J) for each equilibrium point, as shown in Figure 2.

Equilibrium Point	det(J)	tr(J)
$E_1(0,0)$	$(tQ_2+F-C_g+L_g+D_g)(A_1-A_2-C_f)$	$(tQ_2+F-C_g+L_g+D_g)+(A_1-A_2-C_f)$
$E_2(1,0)$	$-(tQ_2+F-C_g+L_g+D_g)[A_1-A_2-C_f+(P+t)(Q_2-Q_1)+b(Q_0-Q_1)+F]$	$-(tQ_2+F-C_g+L_g+D_g)+[A_1-A_2-C_f+(P+t)(Q_2-Q_1)+b(Q_0-Q_1)+F]$
$E_3(0,1)$	$-(tQ_1-b(Q_0-Q_1)-C_g)(A_1-A_2-C_f)$	$(tQ_1-b(Q_0-Q_1)-C_g)-(A_1-A_2-C_f)$
$E_4(1,1)$	$(tQ_1-b(Q_0-Q_1)-C_g)[A_1-A_2-C_f+(P+t)(Q_2-Q_1)+b(Q_0-Q_1)+F]$	$-(tQ_1-b(Q_0-Q_1)-C_g)-[A_1-A_2-C_f+(P+t)(Q_2-Q_1)+b(Q_0-Q_1)+F]$

Figure 2. det(J) and tr(J)

For ease of analysis, let $M_1=tQ_2+F\text{-}C_g+L_g+D_g$, $M_2=A_1\text{-}A_2\text{-}C_f$, $M_3=tQ_1\text{-}b(Q_0\text{-}Q_1)\text{-}C_g$, and $M_4=A_1\text{-}A_2\text{-}C_f+(P+t)(Q_2\text{-}Q_1)+b(Q_0\text{-}Q_1)+F$. Based on the fundamental premises of carbon emission reduction policy research, this paper fixes two parameter relationships of broad practical significance: $M_3<0$, indicating that when firms engage in comprehensive and proactive emission reductions, the government must pay subsidies but incurs no fines or excess carbon tax revenue; at this point, the net benefit of government regulation is negative, which is the fundamental cause of the cyclical nature of the strategic interaction between the government and firms; $M_4>0$ indicates that when the government actively regulates, the benefits of enterprises actively reducing emissions exceed those of passively reducing emissions; that is, the policy instrument itself imposes emission reduction constraints, thereby ruling out the extreme case of complete policy failure. On this basis, the system is divided into four theoretical scenarios based on the combination of positive and negative signs of the government's regulatory incentive indicator M_1 and the enterprise's endogenous emission reduction incentive indicator M_2 , and the stability and evolutionary characteristics of their equilibrium points are analyzed one by one.

Scenario 1: When $M_1<0$ and $M_2<0$, the system's evolution-stable strategy is $E_1(0,0)$, meaning the government adopts a "passive regulation" strategy, while chemical companies adopt a "passive emissions reduction" strategy. In this scenario, the sum of the companies' costs for technological upgrades and R&D investments to actively reduce emissions exceeds the sum of the revenue from selling carbon allowances and the premium on green products.As rational "economic agents," if the investment costs of low-carbon transition exceed the economic benefits it brings, this is inconsistent with the firms' goal of maximizing profits. This situation leads to a lack of intrinsic motivation for firms to proactively reduce emissions, causing them to opt instead for a passive production model that shifts the environmental costs of carbon emissions onto society.At the same time, because enterprises generally adopt a passive approach to emissions reduction, the combined direct and indirect costs of proactive regulation

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by local governments exceed the total of fines, carbon tax revenue, and the benefits gained from avoiding environmental damage. Consequently, local governments tend to adopt lax regulatory strategies, allocating their limited fiscal resources to more immediate performance goals, such as economic growth.These passive strategies on the part of both the government and enterprises create a mutually reinforcing vicious cycle, ultimately resulting in persistently high carbon emission intensity within the industry, continued deterioration of environmental quality, and obstacles to the chemical industry's green transition and high-quality development.

Scenario 2: When $M_1>0$ and $M_2<0$, the system lacks a pure strategy evolutionarily stable solution, and the strategies of the government and enterprises will exhibit cyclical fluctuations around the mixed-strategy equilibrium point $E_5(x^*,y^*)$. At this point, the sum of the enterprise's costs for technical upgrades and R&D investments aimed at active emissions reduction remains higher than the total of revenue from the sale of carbon allowances and the premium on green products. As rational "economic agents," enterprises lack the intrinsic motivation to proactively reduce emissions; without external policy constraints, they will inevitably choose a passive emissions reduction strategy.At the same time, however, the total benefits to local governments from proactive regulation when firms adopt passive emission reduction strategies—including fines for violations, revenue from excess carbon taxes, and the avoided costs of environmental remediation and reputational damage-already exceed the direct and indirect costs of regulation. Consequently, local governments have a strong incentive to engage in proactive regulation.This asymmetry in incentive structures leads to a dynamic strategic game between the government and enterprises: when the proportion of enterprises adopting passive emission reduction strategies within an industry rises, the government will intensify regulatory efforts, increase the frequency of enforcement, and raise the severity of penalties to compel enterprises to shift toward active emission reduction;as the proportion of companies actively reducing emissions continues to rise, the marginal benefits of government regulation gradually decline while regulatory costs rise relatively, prompting the government to gradually ease regulatory intensity; however, once regulatory intensity falls below a certain threshold, the expected benefits of passive emission reduction for companies once again exceed the costs of reducing emissions, causing the proportion of passive emission reduction within the industry to rise again, and so the cycle repeats.

Scenario 3: When $M_1>0$ and $M_2>0$, the system's evolutionarily stable strategy is $E_1(0,1)$, meaning the government adopts a "passive regulation" strategy, while chemical companies adopt a "proactive emissions reduction" strategy.At this point, the combined revenue from the sale of carbon allowances generated by enterprises' active emissions reductions, the market premium for green products, and the cost advantages of green financing has stably covered the costs of low-carbon technology R&D and production process upgrades. As rational "economic agents", enterprises find that low-carbon transition fully aligns with their goal of profit maximization, so they will proactively intensify green technological innovation and continuously optimize production processes to reduce carbon emission intensity.At the same time, the total benefits to local governments from proactive regulation targeting enterprises' passive emissions reduction-including violation fines, excess carbon tax revenue, and avoided environmental remediation costs and reputational damage-remain higher than the direct and indirect costs of regulation. Consequently, local governments retain full regulatory capacity and potential incentives for enforcement.This dual-driven dynamic structure, powered by both government and enterprises, creates a robust systemic equilibrium: since the vast majority of enterprises in the industry have developed endogenous incentives for emissions reduction, the government does not need to maintain high-intensity daily oversight. The marginal benefits of regulation are significantly lower than its costs; therefore, the government will naturally opt for a passive regulatory strategy and allocate more administrative resources to the public service sector.However, the potential threat of government regulation serves as an effective

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deterrent against the few enterprises that attempt to violate regulations. Should any passive emissions-reduction behavior occur, the government will immediately initiate regulatory procedures to impose penalties, ensuring that the system does not deviate from its emissions-reduction trajectory. This scenario represents a transitional phase in the development of the carbon emissions-reduction system, during which market mechanisms have already assumed a leading role in emissions reduction, while the government has shifted from a direct regulator to a guardian of the bottom line, providing stable institutional safeguards for the industry's green transition.

Scenario 4: When $M_1<0$ and $M_2>0$, the system's evolutionarily stable strategy is $E_1(0,1)$, meaning the government adopts a "passive regulation" strategy, while chemical enterprises adopt an "active emissions reduction" strategy. At this point, the combined revenue from the sale of carbon allowances generated by enterprises' active emissions reductions, the market premium for green products, and the cost advantages of green financing are sufficient to cover the costs of low-carbon technology R&D and production process upgrades.As rational "economic agents," if the overall benefits of low-carbon transition exceed the associated costs, this is fully consistent with enterprises' goal of maximizing profits. This situation will continuously incentivize enterprises to intensify innovation in low-carbon technologies, proactively advance the green transformation of production processes, and continuously enhance their carbon emission reduction capabilities and market competitiveness.At the same time, since enterprises have developed a stable, endogenous drive for emissions reduction, local governments no longer need to maintain a high-intensity regulatory system-the combined direct and indirect costs of regulation significantly exceed its potential benefits. Consequently, local governments will naturally opt for a passive regulatory strategy. Under these circumstances, the government can redirect the fiscal funds and administrative resources originally allocated to regulation toward areas of greater public value, such as infrastructure development, improvements in public services, and comprehensive ecological and environmental management, thereby achieving comprehensive and coordinated local economic and social development.This represents the ideal state after the maturation of the carbon emission reduction system, where market mechanisms are fully operational and effectively control carbon emissions through self-regulation, while the government transitions from a direct regulator to a guardian of market order and a provider of public services.

4. Numerical Simulation Analysis

To verify the validity of the evolutionary equilibrium conclusions derived from the theoretical analysis above and to intuitively analyze the dynamic evolution of strategy selection by local governments and enterprises under different scenarios, this paper employs MATLAB software to conduct numerical simulation analysis.Parameter settings strictly adhere to the following principles and constraints: First, all parameters take positive values; second, they satisfy the model's core assumption constraints, namely, that the short-term production returns from active emission reduction by firms are lower than those from passive emission reduction ($A_1< A_2$), and that the carbon emissions resulting from active reduction are lower than the government's initial carbon quota and lower than those from passive reduction ($Q_1< Q_0< Q_2$);third, the control variable method is strictly applied; except for parameters that must be adjusted to generate specific scenarios, all other parameters remain completely consistent across different simulation experiments. On this basis, four scenarios are generated by adjusting core parameters, and the system's evolution and stability under different conditions are analyzed sequentially to investigate the effects and mechanisms of various policy instruments.Furthermore, assuming initial conditions where the probability of active regulation by local governments is x = 0.4 and x = 0.6, and the probability of active emissions

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reduction by chemical enterprises is y = 0.4 and y = 0.6, it can be seen from Figures 2–5 that regardless of the levels of these probabilities at the initial state, the final outcome of the evolutionary game remains unchanged, indicating that the equilibrium result is not affected by the initial strategy choices of either party.

(1) Under the conditions of Scenario 1, let A_1= 70, A_2= 80, C_f= 20, Q_1= 2, Q_0= 3, Q_2 =4, P = 30, t = 10, b = 10, F = 10, C_g= 95, L_g = 30, and D_g= 10. The simulation results are shown in Figure 3.

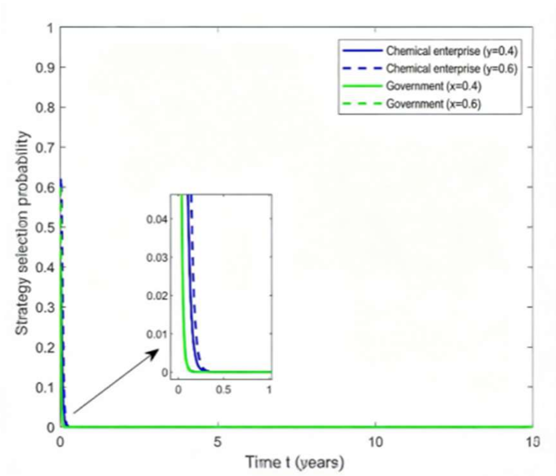

Figure 3. Numerical Simulation Results for Scenario 1

As shown in Figure 3, during the evolutionary game process, the probability that local governments adopt active regulation rapidly decreases from the initial values of 0.4 and 0.6, while the probability that chemical companies adopt active emission reduction also rapidly decreases from the initial values of 0.4 and 0.6. Both probabilities converge to 0, thus forming the system equilibrium point (0,0), where local governments choose the "passive regulation" strategy and chemical companies choose the "passive emission reduction" strategy.

At this point, the combined cost of technological upgrades and R&D investments required for chemical companies to implement active emission reduction far exceeds the total sum of revenue generated from selling carbon allowances and the premium earned from green products. Regardless of whether local governments enforce strict regulations, the benefits that chemical companies obtain from passive emission reduction-after deducting non-compliance fines and excess carbon taxes-still exceed the benefits gained from active emission reduction. Over the course of the continuous evolutionary game process, chemical companies will gradually develop a tendency toward passive emission reduction.At the same time, the total sum of revenue from violation fines and excess carbon taxes collected by local governments through strict regulation, when combined with the avoided costs of environmental remediation and reputational damage, is still insufficient to cover the human, material, and organizational coordination costs incurred by regulation. Regardless of whether enterprises implement emission reduction measures, the benefits local governments gain from non-enforcement exceed those gained from enforcement. To cut down on regulatory costs, local governments will also gradually develop a tendency toward lax regulation.Under these circumstances, the equilibrium outcome of the evolutionary game is that local governments fail to enforce regulation, and chemical companies do not voluntarily reduce carbon emissions. This ultimately results in a vicious cycle of “regulatory failure and worsening pollution,” making it difficult for the system to spontaneously evolve toward a low-carbon transition.

(2) Under the conditions of Scenario 2, let A_1 = 95, A_2 = 80, C_f = 5, Q_1 = 2, Q_0= 3, Q_2 =4, P = 30, t = 10, b = 10, F = 10, C_g = 95, L_g = 30, and D_g= 10. The simulation results are shown in Figure 4.

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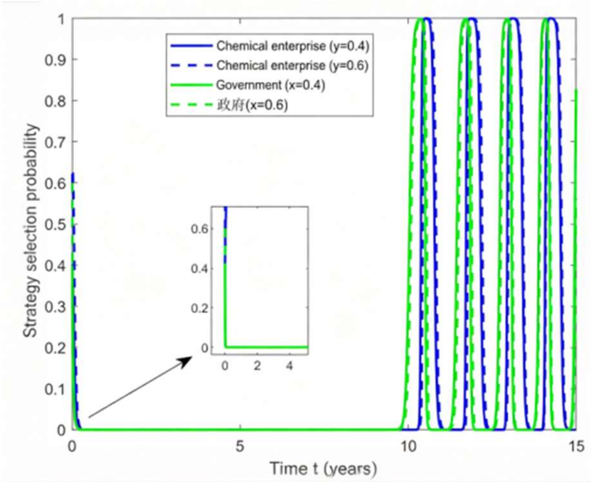

Figure 4. Numerical Simulation Results for Scenario 2

As shown in Figure 4, during the evolutionary game process, neither the probability of chemical companies actively reducing emissions nor the probability of local governments actively regulating converges to a fixed value. Instead, both exhibit regular periodic fluctuations with stable amplitude and period, showing no trend of attenuation or amplification. At the same time, it can be observed that fluctuations in the probability of government regulation consistently lead fluctuations in the probability of corporate emission reduction, which reflects the sequential transmission relationship in the strategic interaction between the government and the enterprise.

At this point, the sum of revenue from selling carbon allowances generated by the chemical company’s active emissions reduction and the premium on green products is still insufficient to cover the costs of low-carbon technology upgrades and R&D investments. In the absence of external policy constraints, the company, acting as a rational economic agent, will inevitably choose a passive emissions reduction strategy.However, when the proportion of firms adopting passive emission reduction strategies within the industry is high, the sum of violation fines, excess carbon tax payments, and the avoided costs of environmental remediation and reputational damage—all generated by local governments through strict regulation—exceeds the direct and indirect costs of regulation. Consequently, local governments have a strong incentive to proactively enforce regulations.This asymmetry in incentive structures leads to a dynamic cycle of strategic interaction between the government and enterprises: when the proportion of firms adopting passive emission reduction strategies within the industry rises, the government will intensify regulatory efforts, increase enforcement frequency, and raise penalty severity to compel firms to adopt active emission reduction strategies; as the proportion of firms adopting active emission reduction strategies continues to rise, the marginal benefits of government regulation gradually decline while regulatory costs rise relatively, prompting the government to gradually ease regulatory intensity. However, once regulatory intensity falls below a certain threshold, the expected benefits of passive emissions reduction for firms once again exceed the costs of abatement, causing the proportion of passive emitters within the industry to rise again, and the cycle repeats.This equilibrium avoids the double-negative dilemma of "regulatory failure–worsening pollution" but also fails to establish a long-term mechanism for voluntary corporate emissions reduction; it is the most common transitional state in the process of carbon emissions governance.

(3) Under the conditions of Scenario 3, let A_1 = 95, A_2 = 80, C_f = 5, Q_1 = 2, Q_0 = 3, Q_2 = 4, P = 30, t = 10, b = 10, F = 10, C_g= 70, L_g = 30, and D_g = 10. The simulation results are shown in Figure 5.

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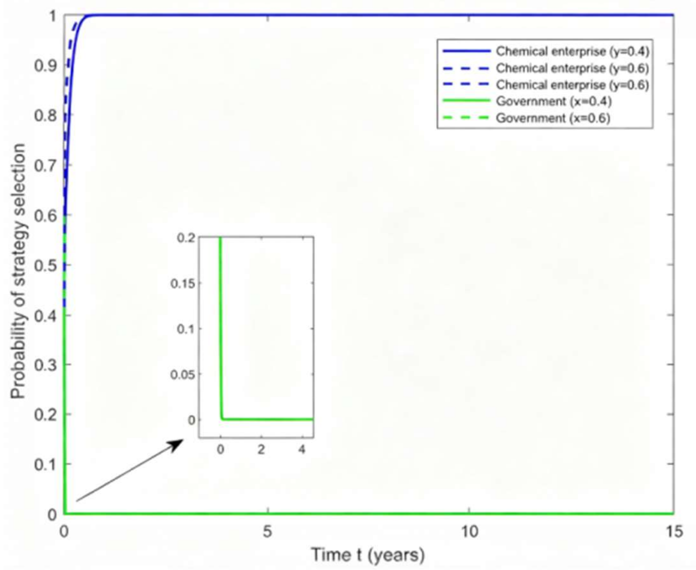

Figure 5. Numerical Simulation Results for Scenario 3

As shown in Figure 5, during the evolutionary game process, the probability that the chemical company will actively reduce emissions rises rapidly from its initial value and stabilizes at 1, while the probability that the local government will actively regulate falls rapidly in tandem and stabilizes at 0. This ultimately leads to a system equilibrium point (1, 0), meaning that the chemical company fully implements an "active emission reduction" strategy, and the local government fully shifts to a "passive regulation" strategy.

At this point, the sum of revenue from carbon quota trading, the market premium for green products, and government subsidies generated by chemical enterprises' active emission reduction is significantly higher than their costs for low-carbon technology upgrades and R&D investments. Even without government regulatory constraints, the net benefits of active emission reduction for chemical enterprises are clearly superior to those of passive emission reduction, leading to the spontaneous formation of a consensus on emission reduction during the group evolution process.At the same time, under this scenario, government regulatory costs remain within a reasonable range. When the proportion of firms practicing passive emission reduction within the industry is high, the sum of violation fines, excess carbon tax revenue, and the avoided environmental losses and reputational damage resulting from strict regulation by local governments can fully cover regulatory costs, providing the government with sufficient incentive to regulate.

However, as chemical companies generally shift toward proactive emission reduction, the number of entities subject to regulation decreases significantly, and the marginal benefits of regulation rapidly approach zero. To optimize the allocation of fiscal resources, local governments will gradually phase out intensive regulation and adopt a more lenient regulatory strategy.This equilibrium state is the result of the synergistic interaction between policy guidance and market mechanisms. It not only fosters stable, endogenous incentives for enterprises to reduce emissions but also preserves the government's role as a safety net. It represents the most sustainable and ideal state in carbon emission governance—namely, the policy-guided ideal equilibrium..

(4) Under the conditions of Scenario 4, let $A_1 = 70$, $A_2 = 80$, $C_f = 20$, $Q_1 = 2$, $Q_0 = 3$, $Q_2 = 4$, $P = 30$, $t = 10$, $b = 10$, $F = 10$, $C_g = 70$, $L_g = 30$, and $D_g = 10$. The simulation results are shown in Figure 6.

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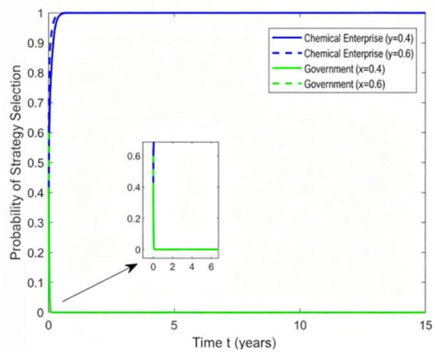

Figure 6. Numerical Simulation Results for Scenario 4

As shown in Figure 6, during the evolutionary game process, the probability that the chemical company will choose active emission reduction rises rapidly from the initial values of 0.4 and 0.6, while the probability that the local government will choose active regulation declines rapidly from the initial values of 0.4 and 0.6. Both probabilities gradually converge to stable values, ultimately forming the system equilibrium point (0, 1), where the local government chooses the "passive regulation" strategy and the chemical company chooses the "active emission reduction" strategy.

Currently, the combined total of revenue from carbon credit sales generated by proactive emissions reductions, price premiums for green products, and government low-carbon subsidies is already sufficient to fully cover the costs of technological upgrades and R&D investments. Regardless of whether local governments enforce regulations, the benefits that chemical enterprises obtain from proactive emissions reductions exceed those from passive emissions reductions. Over the course of this continuous evolutionary game, chemical enterprises will gradually converge toward the strategy of proactive emissions reductions.At the same time, the sum of violation fines, revenue from excess carbon taxes, and avoided costs of environmental remediation and reputational damage-all generated by local governments' strict regulation-is insufficient to cover the human, material, and organizational coordination costs required for regulation enforcement. Furthermore, given that enterprises have already formed internal incentives for voluntary emissions reductions, local governments gain more from not enforcing regulations than from enforcing them, regardless of whether enterprises actually implement emissions reductions. To reduce regulatory costs, local governments will gradually tend to adopt more lenient regulation.Under this dynamic, chemical enterprises form a stable, self-driven emissions reduction mechanism, while local governments, no longer needing to maintain high-intensity oversight, can allocate more fiscal resources to supporting low-carbon technology R&D and guiding industrial development. This constitutes a relatively ideal equilibrium in carbon emissions governance, known as the market-driven ideal equilibrium.

5. Research Conclusion and Recommendations

5.1. Research Conclusion

Based on the assumption of bounded rationality, this paper constructs an evolutionary game model of the interaction between the government and chemical enterprises under a carbon trading mechanism. Through theoretical derivation and numerical simulation, it analyzes the evolutionary stability characteristics of the system and the logic behind agents' strategy choices under different scenarios, and ultimately draws the following conclusions:

(1) The government-enterprise carbon emission reduction game system has four equilibrium points. Their evolutionary stability is determined by the sign combination of the government's

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net regulatory revenue (M_1) and the enterprise's net emission reduction revenue (M_2), resulting in four distinct scenarios. When $M_1 < 0$ and $M_2 < 0$, the unique evolutionarily stable strategy of the system is (passive regulation, passive emission reduction). In this case, the government lacks incentives to regulate due to excessively high regulatory costs or insufficient environmental and reputational losses, while firms incur losses from emission reduction in the absence of effective policy intervention. The strategies of both parties reinforce each other negatively, ultimately leading to a double-deficit dilemma. When $M_1 < 0$ and $M_2 > 0$, (passive regulation, active emission reduction) becomes the unique evolutionarily stable strategy. Although the government still lacks incentives to regulate, firms have the economic rationality to reduce emissions voluntarily based on their green technology advantages or market premiums. The government shares the environmental benefits generated by corporate self-regulation without incurring regulatory costs, forming a firm-led emission reduction framework. When $M_1 > 0$ and $M_2 < 0$, all pure-strategy equilibrium points are saddle points or unstable nodes; the system has no evolutionarily stable strategy, and strategy evolution presents continuous cyclic oscillation around the internal equilibrium point. In this scenario, the government tends to take proactive measures because regulating excessive emissions is profitable, while firms tend to choose passive emission reduction due to losses from baseline emission reduction. However, once the government implements strict regulation, firms will shift to active emission reduction under policy incentives; then the government relaxes enforcement because regulation no longer brings profits, and firms rebound back to passive emission reduction, forming a closed loop characterized by "alternating strict and lax regulation and fluctuating emission reduction willingness." When $M_1 > 0$ and $M_2 > 0$, the strategy of "passive regulation, active emission reduction" also becomes an evolutionarily stable strategy, but its evolutionary path differs from the previous scenario: the government may actively intervene in the initial stage; as firms' emission reduction levels improve, regulatory revenue declines rapidly due to reduced carbon taxes and increased subsidies; eventually the government withdraws, and firms stabilize in an active emission reduction state driven by both policy support and market forces.

(2) The strategic choices of the government and enterprises are essentially a dynamic evolutionary process based on cost-benefit analysis, and their core decision-making logics are relatively independent of each other. A firm's strategic choice ultimately depends on whether the net benefit of emission reduction is positive or negative: when the sum of carbon allowance sales revenue, green product premiums and government subsidies obtained through active emission reduction is sufficient to cover the costs of low-carbon technology upgrading and R&D investment, the corporate sector will eventually tend toward active emission reduction through learning and imitation, regardless of the intensity of government regulation; when the net benefit of emission reduction is negative, firms lack the intrinsic motivation for voluntary emission reduction, and their strategic choices depend entirely on the intensity of government regulatory constraints. In turn, the government's strategic choice depends on whether the net benefit of regulation is positive or negative: when the sum of violation fines, excess carbon tax revenue, and avoided environmental remediation and reputational damage costs brought by strict regulation is sufficient to cover the direct and indirect costs of regulation, the government has sufficient economic incentives to implement regulation; when the net benefit of regulation is negative, the government will choose a loose regulatory strategy based on the consideration of optimizing fiscal resource allocation. This net-benefit-oriented decision-making logic fundamentally determines the evolution direction of the government-enterprise game; any policy intervention that deviates from the benefit structure of both parties is difficult to achieve long-term stable governance outcomes.

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5.2. Policy Recommendations

Based on the findings of this paper regarding the patterns of the government-enterprise evolutionary game under the carbon trading mechanism, and to break the “regulation-relaxation” cycle dilemma in carbon emission reduction governance and promote the system’s evolution toward a sustainable, ideal equilibrium state, the following targeted policy recommendations are proposed for both the government and chemical enterprises.

5.2.1. Government Level

(1) Establish a policy framework that “balances penalties with incentives.” For local governments, the core policy objective should be to fundamentally alter the benefit structures of both the government and enterprises through systematic institutional design and policy adjustments, thereby breaking the cyclic dynamic caused by asymmetric incentives. Relying solely on increasing fines for violations can only shorten the system’s fluctuation cycle and amplify the amplitude of fluctuations; it cannot fundamentally resolve the issue. The government should shift its policy focus from “post-event penalties” to “pre-event incentives.” Through various measures-such as reasonably raising the carbon trading price benchmark, implementing differentiated emission reduction subsidies, and improving the green finance support system-it should ensure that policy intensity exceeds a critical threshold. This will enable the comprehensive benefits of proactive emission reductions to consistently cover enterprises’ costs of technological upgrades and R&D investments, thereby gradually fostering endogenous motivation for emission reductions among enterprises.

((2) Optimize regulatory mechanisms, reduce regulatory costs, and enhance regulatory efficiency. The government should focus on optimizing regulatory mechanisms by leveraging modern information technologies such as big data and the Internet of Things (IoT) to build a real-time monitoring platform for corporate carbon emissions. It should implement third-party verification and information disclosure systems to effectively reduce regulatory costs arising from information asymmetry. Furthermore, through interdepartmental joint law enforcement and the “double random, one public” regulatory model, the government should improve regulatory precision and avoid inefficient allocation of regulatory resources.

(3) Maintain an appropriate level of regulatory deterrence. Policy-guided ideal equilibria are more stable and sustainable than purely market-driven equilibria. Therefore, the government should not completely withdraw from the regulatory sphere once enterprises have developed a willingness to reduce emissions; rather, it should maintain a moderate level of routine regulatory deterrence and establish a collaborative governance model characterized by “market-led with government as a safety net.” When market mechanisms experience short-term failures, the government should intervene promptly to prevent the system from deviating from the ideal equilibrium and ensure the stable achievement of carbon emission reduction targets.

5.2.2. At the Chemical Enterprise Level

(1) Increase investment in low-carbon technology R&D to foster endogenous motivation for emissions reduction. As the primary entities responsible for carbon emissions reduction, chemical enterprises should proactively align with the trend toward green and low-carbon development, transforming carbon emissions reduction from an external constraint into an endogenous development need and a core competitive advantage for the enterprise.Enterprises should incorporate low-carbon development into their long-term strategic planning, establish stable special funds for low-carbon technology R&D, increase investment in core technologies such as carbon capture, utilization, and storage (CCUS), energy conservation and consumption reduction, and clean energy substitution, strengthen in-depth industry-academia-research collaboration with universities and research institutes, and accelerate the industrial application of advanced low-carbon technologies. By reducing carbon

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emission intensity and emission reduction costs at the source of production, enterprises can break free from dependence on government regulation and achieve sustainable development.

(2) Actively participate in carbon market trading and fully leverage policy benefits. Chemical enterprises should establish a professional carbon asset management system, conduct in-depth research into the operational mechanisms of the carbon market, strategically plan the timing of carbon allowance holding and trading, actively develop Verified Voluntary Emission Reduction (VVER) projects, fully tap into the economic value of carbon assets, and transform carbon costs into carbon revenues.

(3) Strengthen communication and collaboration with the government to foster a favorable development environment. Chemical companies should enhance regular communication and exchange with government departments, promptly report practical difficulties and policy requests encountered during the emissions reduction process, actively participate in the formulation of industry carbon emissions standards and policies, promote the establishment of a fair and reasonable carbon emissions reduction market order, and achieve the synergistic improvement of both corporate economic and environmental benefits.

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