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A Collaborative Policy Study on the Low-Carbon Transition of the Shipping Industry Based on a Tripartite Game Model

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Abstract: The global shipping industry is under urgent pressure to achieve a low-carbon transition. The implementation of the European Union's carbon tax policy, combined with the ambiguity of China's domestic regulations, has placed shipping enterprises under dual pressures of emission reduction compliance and rising operational costs. This study constructs a tripartite dynamic game model involving shipping enterprises, the Chinese government, and the European Union. Using backward induction and Python-based numerical simulation, it quantitatively analyzes the impacts of carbon tax and subsidy policies on enterprises' low-carbon investments, route capacity allocation, and expected returns. The findings reveal that a combination of high carbon taxes and high subsidies can promote an increase in the proportion of low-carbon investments by enterprises, albeit at the cost of a sharp decline in short-term profits. The EU's carbon tax policy transmits regulatory pressure through adjustments in route capacity, forcing enterprises to optimize their global capacity networks. However, technological bottlenecks in emission reduction limit the effectiveness of policy incentives, requiring technological innovation to break through marginal abatement constraints. This study proposes a "dynamic investment–flexible capacity–data-driven" decision-making framework, offering strategic support for enterprises to cope with international carbon regulations and providing a theoretical basis for government policy design.

Keywords: Shipping enterprise decision-making, international carbon tax, tripartite dynamic game, marginal abatement effect, flexible capacity allocation, policy coordination

1. Introduction

The global shipping industry plays a vital role in international trade and transportation, accounting for more than 80% of global cargo volumes. However, its contribution to global carbon emissions cannot be overlooked, representing nearly 3% of total global emissions and growing at an average annual rate of 2.5%. As a result, it has become a core focus in international climate governance. With the European Union taking the lead in implementing shipping carbon tax policies (for example, imposing a 70% carbon tax on vessels exceeding 5,000 deadweight tons starting in 2025), the development of a global carbon pricing system is accelerating. Consequently, shipping enterprises face the dual challenges of emission reduction compliance and cost control [1]. Although China, as the world's largest ship-owning nation, is still exploring its domestic shipping carbon policies, the uncertainty of these regulations, coupled with the restrictive effects of international carbon tax systems, creates a compounded dilemma for shipping enterprises [2]. They must navigate strategic

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choices in the dynamic game between the EU's carbon tax policies and China's potential countermeasures, such as imposing reciprocal carbon taxes or providing subsidies. Balancing low-carbon investment, route planning, and profit maximization within this complex policy landscape has become an urgent issue [3-5].

This study constructs a dynamic game model involving shipping enterprises, the Chinese government, and the European Union. Through backward induction and numerical simulation techniques, it seeks to reveal the transmission mechanisms of carbon tax policies and their impact paths on corporate decision-making [6]. The research focuses on three core issues: (1) How do carbon tax and subsidy policies incentivize shipping enterprises to undertake low-carbon investments and adjust route capacity? (2) In the context of international policy interactions, how should enterprises dynamically adjust their strategies to balance short-term returns with long-term emission reduction goals? (3) How do technological limitations in emission reduction and policy uncertainty affect the scope of corporate decision-making [7-10]? By quantitatively analyzing the evolutionary equilibrium states under different policy scenarios, this study aims to construct a comprehensive decision-making framework that integrates policy responses, technological upgrades, and risk hedging for shipping enterprises [11]. It provides theoretical support for enterprises and serves as a reference for governments in formulating carbon emission regulation policies that balance industrial competitiveness with climate responsibility [12].

2. Research Model and Framework

2.1. Adaptability of the Game Model

In the context of promoting a low-carbon transition in the shipping industry, it is particularly important to construct a research framework based on a tripartite game model. This framework aims to conduct an in-depth analysis of the interactions among shipping enterprises, the Chinese government, and the European Union (EU) regarding carbon tax and subsidy policies, as well as how these policies influence the low-carbon investment decisions, route capacity allocation, and expected returns of shipping companies [13].

The rationale for choosing a tripartite game model lies in its capacity to effectively simulate and reflect the complex and dynamic international policy environment, especially when there are strategic interactions among different stakeholders. In this model, shipping companies act as rational decision-makers whose primary objective is profit maximization. The Chinese government may support the low-carbon transition of domestic shipping companies by implementing subsidy policies, while the EU promotes emission reductions in the global shipping industry through the implementation of carbon tax policies.

To construct this model, it is necessary first to clarify the basic assumptions and the sequence of the game. Regarding assumptions, this study presumes that shipping companies, the Chinese government, and the EU are all fully rational decision-makers, and that all three parties share complete information [14]. This means that each party can accurately assess the strategies and policy directions of the others, enabling them to make optimal decisions. In terms of game sequence, the study adopts the backward induction method to solve for the equilibrium, starting from the final stage of the game and reasoning backward to the initial stage in order to determine the optimal strategy choices of each party. Subsequently, the study constructs expected return functions to quantitatively analyze the gains and losses for each party. These functions include the returns from low-carbon investments and route capacity allocation for shipping companies, as well as the additional benefits or costs arising from policy changes; the subsidy expenditures of the Chinese government and the environmental benefits resulting from the low-carbon transition of shipping companies; and the EU's carbon tax revenues and the climate benefits generated by emission reductions in the global shipping

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industry [15]. Through the construction of these functions, it becomes possible to gain a clearer understanding of the interests and strategic motivations of each party under different policy scenarios.

2.2. Stakeholders in the Game

The tripartite game model in this study involves the following stakeholders:

1) Shipping Companies: As core participants in market operations, their decisions directly affect both the carbon emissions and economic performance of the shipping industry. Their primary objective is to maximize profits while meeting transportation demand. Accordingly, their decision variables can be set as follows:
2) National Policy: Given that China's current policy on the shipping industry remains unclear, it is assumed that, under the premise of international carbon taxes imposed on high-emission ships, China may implement subsidy policies or impose reciprocal carbon taxes to balance the shipping industry's competitiveness with environmental protection objectives. Accordingly, the decision variables can be set as follows:
3) EU Carbon Tax Policy: As an external constraint, it reflects the direct impact of global emission reduction pressures on the shipping industry. Its decision variables can be set as follows:

2.3. Model Assumptions and Game Sequence

2.3.1. Model Assumptions

1) The EU carbon tax policy has already imposed a 700% carbon tax on ships exceeding 5,000 tonnes. Based on the feasibility analysis in the EU policy assessment document (COM(2025)228), it is assumed that in the extended scenario, the carbon tax rate will increase to a maximum of 100% in 2026.
2) It is assumed that national policymakers in China can observe the decisions of shipping companies in real time and dynamically adjust policies. Considering that China has not yet implemented specific carbon policies, it is assumed that China will adopt reciprocal carbon tax measures, imposing a 100% carbon tax on the carbon emissions of ships operated by shipping companies.
3) Shipping companies are rational decision-makers whose sole objective is profit maximization.
4) During the game period, neither the EU nor China will overturn the already announced carbon tax policies; only minor adjustments to parameters (such as the proportion of free allowances) are allowed.
5) The three parties in the game share complete information.

2.3.2. Game Sequence

1) First Stage: The EU, as the policymaker, sets a 50% coverage ratio for carbon taxes on international shipping routes and establishes phased tax rates (70% carbon tax on ships exceeding 5,000 tonnes in 2025 and 100% carbon tax on ships under 3,000 tonnes in 2026).
2) Second Stage: China observes the EU policy and formulates corresponding domestic policies (such as subsidies) and reciprocal measures against the EU carbon tax policy (such as imposing reciprocal carbon taxes) based on the status of its domestic shipping industry and environmental protection goals.
3) Third Stage: Shipping companies comprehensively assess the EU and Chinese national policies and determine their emission reduction investments and operational strategies.
4) Fourth Stage: The three parties continuously adjust their decisions until achieving dynamic equilibrium.

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3. Construction of the Game Model

3.1. Construction of the Expected Payoff Functions

Based on the aforementioned assumptions and the sequence of the game, a tripartite game matrix is established. The game participants and their variables are presented in Table 1.

Table 1: Game Participants and Variables

Game Participant	Variable	Constraints
Shipping Company (S)	Proportion of low-carbon investment in revenue (x)	0.05 ~ 0.15
	Proportion of capacity allocated to EU routes (y)	0 ~ 1
China (N)	Subsidy rate (s)	0 ~ 1
	Reciprocal carbon tax rate (TN)	€50 - €100 / ton
European Union (EU)	Carbon tax rate (TEU)	€50 - €100 / ton
	Carbon emission payment ratio (θ)	0.7 ~ 1

The parameters in the matrix and their corresponding meanings are shown in Table 2.

Table 2: Parameters and Their Meanings

Parameter	Meaning	Parameter	Meaning
c	Actual unit investment cost coefficient	e_0	Initial carbon emission intensity
Q	Total shipping capacity	λ	Carbon leakage loss coefficient
k	Variable adjustment speed	S	Operating expenditure
W	Operating revenue	h	Technical emission reduction efficiency
E	Expected benefit	D	Economic loss caused by each unit of EU route capacity

Expected Payoff of Shipping Companies (S)

$$E_S = W - S - cxW + sxW - T_{EU}yQe(x)\theta - T_N(1-y)Qe(x)$$

Here, $e(x)$ represents the carbon emission intensity of the shipping company's vessels, where ϵ indicates the lower limit of emission intensity achieved through technical reductions. The specific function is defined as:

$$e(x) = \begin{cases} e_0(1-hx), & x \le x_{max} \\ \epsilon, & x > x_{max} \end{cases}$$

Expected Payoff of China (N)

$$E_N = T_N(1-y)Qe(x) - sxW - Dy$$

Expected Payoff of the European Union (EU)

$$E_{EU} = T_{EU}yQe(x)\theta - \lambda T_{EU}(1-y)Qe(x)$$

3.2. Construction of the Multi-Stage Game Model

3.2.1. Relevant Parameters in the Multi-Stage Game Model

Considering that, after the EU makes its decisions, China and shipping companies will not maintain static policies but will instead adjust their decisions according to actual circumstances, a multi-stage

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dynamic game model is adopted to describe this process. In each stage, participants update their strategies based on information from the previous stage and the strategies of other participants. This dynamic adjustment process reflects the decision-making behavior of policymakers and enterprises in the real world when facing complex environments. Assuming the game is divided into T stages, in order to better capture the changes in the expected payoffs of the three parties during the multi-stage game, the expected payoff functions for the three participants at stage t are defined as follows:

$$E_s^{(t)} = W - S - cx^{(t)}W + s^{(x)}x^{(t)}W - T_{EU}^{(t)}y^{(t)}Qe(x^{(t)})\theta^{(t)} - T_N^{(t)}(1-y^{(t)})Qe(x^{(t)})$$

$$E_N^{(t)} = T_N^{(t)}(1-y^{(t)})Qe(x^{(t)}) - s^{(t)}x^{(t)}W - Dy^{(t)}$$

$$E_{EU}^{(t)} = T_{EU}^{(t)}y^{(t)}Qe(x^{(t)})\theta^{(t)} - \lambda T_{EU}^{(t)}(1-y^{(t)})Qe(x^{(t)})$$

At this point, the emission intensity function is:

$$e(x^{(t)}) = \begin{cases} e_0(1-hx^{(t)}), & x^{(t)} \le x_{max} \\ \epsilon, & x^{(t)} > x_{max} \end{cases}。$$

3.2.2. Model Solution

Given the complexity of the model, which involves six variables, this multi-stage dynamic programming problem is solved using a combination of backward induction and gradient ascent methods to determine the optimal decisions for the shipping company. Additionally, numerical optimization methods are employed with Python software to solve complex equations that cannot be expressed analytically. The game model is set to consist of two stages: Stage 1 represents the initial policy formulation and exploratory investment by enterprises, while Stage 2 involves policy reinforcement and a comprehensive enterprise response. The specific computational steps are as follows:

1) Stage 1 (Backward Induction)

In this stage, the expected payoff for the shipping company is given by:

$$E_s^{(1)} = W - S - cx^{(1)}W + s^{(1)}x^{(1)}W - T_{EU}^{(1)}y^{(1)}Qe(x^{(1)})\theta^{(1)} - T_N^{(1)}(1-y^{(1)})Qe(x^{(1)})。$$

At this point, the shipping company's expected payoff can be calculated. Taking the partial derivatives of the expected payoff with respect to x and y respectively yields the optimal solutions:

$$x^{(1)*} = \frac{s^{(1)} - c}{Qe_0h(T_{EU}^{(1)}\theta^{(1)}y^{(1)} + T_N^{(1)}(1-y^{(1)}))}$$

$$y^{(1)*} = \frac{T_N^{(1)}}{T_{EU}^{(1)}\theta^{(1)} + T_N^{(1)}}$$

At this stage, China's expected payoff is:

$$E_N^{(1)} = T_N^{(1)}(1-y^{(1)*})Qe(x^{(1)*}) - s^{(1)}x^{(1)*}W - Dy^{(1)*}$$

Due to the complexity of the equations, the optimal solutions for TN and s require numerical simulation using Python.

By backward induction, the European Union's expected payoff is then obtained as:

$$E_{EU}^{(1)} = T_{EU}^{(1)}y^{(1)*}Qe(x^{(1)*})\theta^{(1)} - \lambda T_{EU}^{(1)}(1-y^{(1)*})Qe(x^{(1)*})$$

The optimal solutions for TEU and θ are derived based on the decisions made by China and the shipping company.

2) Stage 2 (Gradient Ascent Method)

① Strategy Update Rules

In the second stage, during multiple iterations, all three parties in the game adjust their strategies based on the results of the previous stage.

Shipping Company:

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$$x^{(t+1)} = x^{(t)} + k \cdot \frac{\partial E_s^{(t)}}{\partial x^{(t)}}, y^{(t+1)} = y^{(t)} + k \cdot \frac{\partial E_s^{(t)}}{\partial y^{(t)}}.$$

China:

$$T_N^{(t+1)} = T_N^{(t)} + k \cdot \frac{\partial E_N^{(t)}}{\partial T_N^{(t)}}, s^{(t+1)} = s^{(t)} + k \cdot \frac{\partial E_N^{(t)}}{\partial s^{(t)}}.$$

European Union:

$$T_{EU}^{(t+1)} = T_{EU}^{(t)} + k \cdot \frac{\partial E_{EU}^{(t)}}{\partial T_{EU}^{(t)}}, \theta^{(t+1)} = \theta^{(t)} + k \cdot \frac{\partial E_{EU}^{(t)}}{\partial \theta^{(t)}}.$$

② Dynamic Equilibrium Conditions

The iteration process terminates when the adjustments of all parameters satisfy the following conditions: $|\triangle x|, |\triangle y|, |\triangle s|, |\triangle \theta|, |\triangle T_{EU}|, |\triangle T_N| \lessdot 0.1$.

4. Empirical Analysis

4.1. Simulation Analysis

Based on the theoretical framework, this study employs Python software to conduct numerical simulation analyses of the evolutionary paths of the interaction strategies among shipping companies, China, and the European Union, according to the replicator dynamic equations and corresponding constraints. The effects of parameter variations on the evolutionary outcomes are also examined. Parameter values for different scenarios are assigned by integrating expert interviews, actual circumstances, and reasonable assumptions derived from previous studies, as shown in Table 3 and Table 4.

Table 3: Parameter Values of Constants under Different Scenarios

c	Q	W	k	e0	ϵ	S	h	D	λ	x_{max}
0.1	1e7	1e8	0.01	0.5	0.2	5e7	0.3	1e4	0.2	0.15

Table 4: Initial Values of Variables under Different Scenarios

	s	TN	TEU	θ
High Carbon Tax & High Subsidy	0.2	100	70	0.7
Low Carbon Tax & High Subsidy	0.2	50	70	0.7
High Carbon Tax & Low Subsidy	0.05	100	70	0.7
Low Carbon Tax & Low Subsidy	0.05	50	70	0.7

After running the simulations in Python, the final evolutionary results of the strategies adopted by the three parties—shipping companies, China, and the European Union—under different scenarios are obtained, as shown in Table 5.

Table 5: Final Variable Values under Different Scenarios

	s	TN	TEU	θ	X(%)	Y(%)	E_S
High Carbon Tax & High Subsidy	0.12	92.3	96.7	0.73	13.8	28.4	44.2

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Table 5: (continued).

Low Carbon Tax & High Subsidy	0.18	62.4	88.9	0.76	15	12.1	55.7
High Carbon Tax & Low Subsidy	0.01	98.5	99.8	0.71	7.5	52.6	36.9
Low Carbon Tax & Low Subsidy	0.01	68.2	100	0.70	5	78.3	39.4

To visualize the simulation analysis results, the evolutionary paths of strategies under different scenarios are graphically presented. Figure 1 illustrates the strategy evolution paths of shipping companies, China, and the European Union in the high carbon tax and high subsidy scenario. It can be observed that the low-carbon investment ratio (X) of shipping companies stabilizes after initial fluctuations, indicating that, in the policy environment characterized by high carbon taxes and high subsidies, shipping companies gradually adjust their low-carbon investment strategies to reach an optimal state. Meanwhile, China's subsidy rate (s) and its corresponding carbon tax rate (TN) also show convergence trends, reflecting the policymakers' dynamic adjustments based on the responses of shipping companies and the policy actions of the European Union. Similarly, the carbon tax rate of the European Union (TEU) gradually stabilizes in the game process, demonstrating the constraining effect of the international policy environment on carbon emissions in the shipping industry.

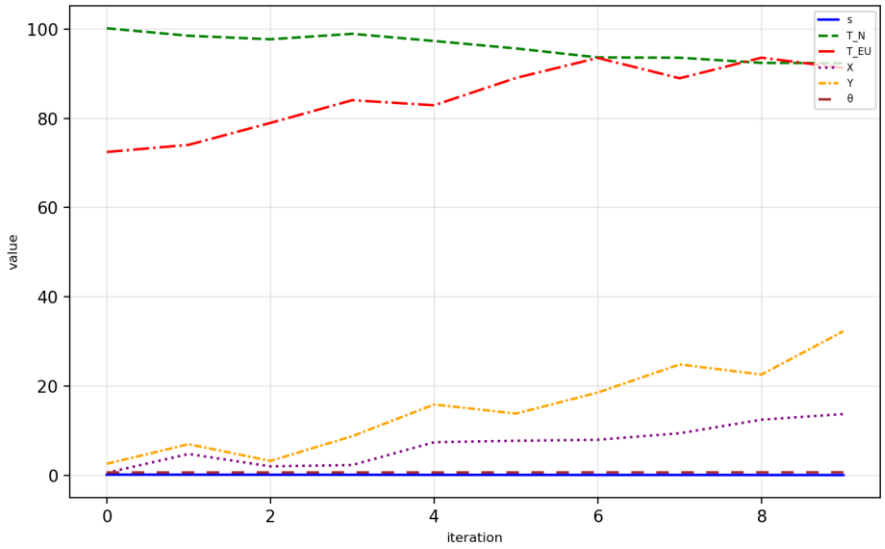

Figure 1: Evolutionary Path under Scenario 1

Figures 2 to 4 display the evolutionary paths of strategies under the scenarios of low carbon tax & high subsidy, high carbon tax & low subsidy, and low carbon tax & low subsidy, respectively. By comparing the evolutionary paths under different scenarios, it is evident that variations in carbon tax and subsidy policies have significant impacts on the low-carbon investment strategies of shipping companies, China's policy responses, and the European Union's carbon tax policy. Under a high carbon tax scenario, shipping companies tend to increase low-carbon investments to cope with the pressure of carbon taxes. In contrast, under a high subsidy scenario, they may reduce low-carbon investments as the subsidy policy lowers their operating costs. Furthermore, China's policy responses show a certain regularity: in a high carbon tax scenario, there is a tendency to reduce the subsidy rate,

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whereas in a high subsidy scenario, the subsidy rate may be increased to balance the competitiveness of the shipping industry with environmental protection goals.

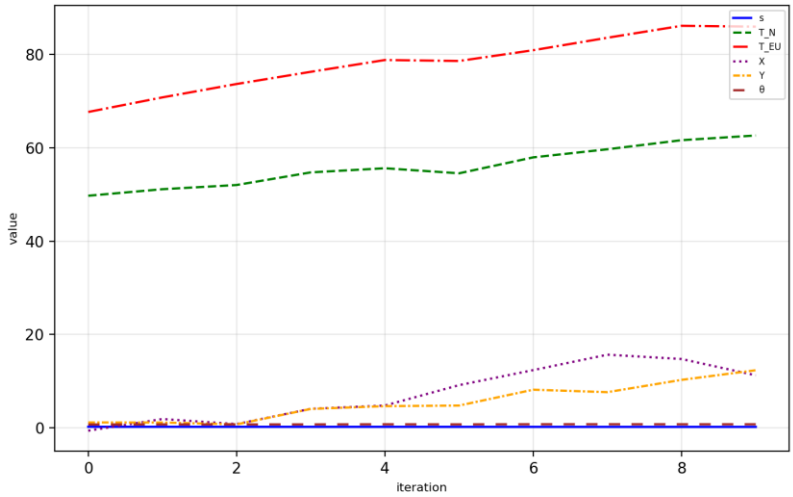

Figure 2: Evolutionary Path under Scenario 2

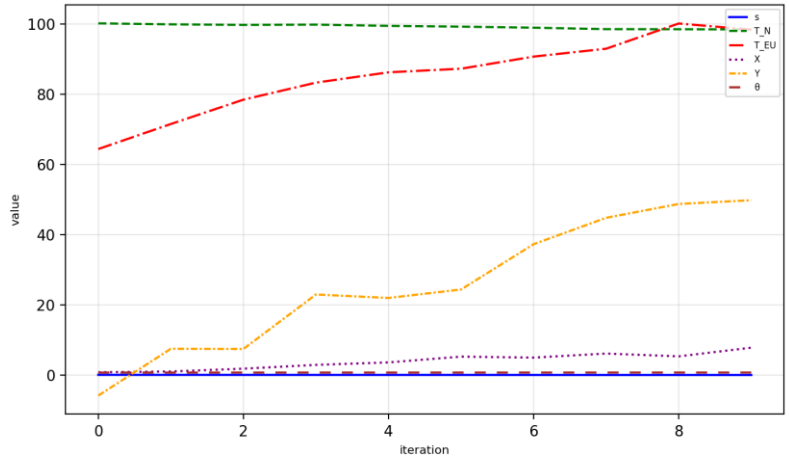

Figure 3: Evolutionary Path under Scenario 3

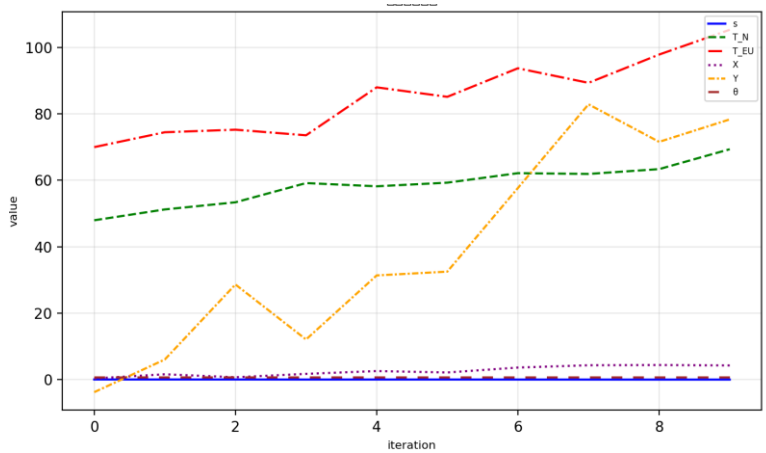

Figure 4: Evolutionary Path under Scenario 4

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Additionally, the expected returns under different scenarios are calculated and analyzed. The results indicate that the expected returns of shipping companies, China, and the European Union vary across scenarios. In the high carbon tax and high subsidy scenario, although the low-carbon investment costs of shipping companies increase, the presence of subsidy policies ensures that their expected returns remain relatively high. Conversely, in the low carbon tax and low subsidy scenario, the expected returns of shipping companies are relatively lower. For China and the European Union, their expected returns are also influenced by carbon tax and subsidy policies, though the degree of impact varies depending on the specific scenario.

In conclusion, the simulation analysis not only provides an intuitive presentation of the evolutionary paths of strategies adopted by shipping companies, China, and the European Union under different scenarios but also calculates and analyzes their respective expected returns. These findings offer valuable insights into understanding the impacts of carbon emission policies on the shipping industry and serve as a reference for policymakers in decision-making.

5. Conclusions and Recommendations

5.1. Research Conclusions

This study employs a tripartite dynamic game model to reveal the mechanisms through which carbon tax and subsidy policies influence low-carbon decision-making by shipping enterprises [16]. The main conclusions are as follows:

① Trade-off Between Low-Carbon Investment and Revenue: The proportion of low-carbon investment by shipping enterprises is driven by both carbon taxes and subsidies. Under scenarios of high carbon tax and high subsidy, companies are required to allocate 13.8% of their revenue to low-carbon technologies in order to avoid excessive tax burdens; however, this significantly reduces short-term profits.

② Dynamic Adjustment of Shipping Capacity: The EU's carbon tax directly affects the proportion of shipping capacity allocated to EU routes. Under high carbon tax scenarios, companies need to divert 52.6% of their capacity to non-EU routes, although this results in economic losses due to China's imposition of reciprocal carbon taxes.

③ Marginal Effects of Technological Emission Reductions: Low-carbon investments encounter technological bottlenecks. Once the investment proportion exceeds a certain threshold, carbon emission intensity approaches its lower limit, indicating that relying solely on policy incentives makes it difficult to achieve deep decarbonization.

④ Strategic Interactions Under Complete Information: Enterprises can quickly optimize decision-making by monitoring policy adjustments in real time. However, policy uncertainties—such as fluctuating tax rates—increase the difficulty of long-term strategic planning.

5.2. Recommendations

Based on the research conclusions, the following enterprise-level strategic recommendations are proposed:

① Optimization of Low-Carbon Investment Portfolios

Short-Term Strategy: Establish carbon tax sensitivity analysis models to dynamically adjust the proportion of low-carbon investment (x). For example, when the EU carbon tax exceeds €70 per ton, increase x to between 10% and 15%, prioritizing the retrofitting of high-emission vessels. Long-Term Planning: Allocate dedicated budgets for R&D to overcome emission reduction technology bottlenecks (e.g., hydrogen fuel propulsion systems), lower the marginal cost of emission reductions (h value), and extend the linear reduction interval of e(x).

② Resilient Management of Shipping Networks

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Develop a "policy-capacity" response mechanism that continuously monitors international carbon tax policies and dynamically allocates capacity between EU and non-EU routes. Simultaneously, explore emerging markets (e.g., RCEP regions) to diversify policy risks and reduce dependency on single shipping routes.

③ Enhancement of Policy Game Participation

Actively participate in the formulation of international carbon tax regulations (e.g., IMO meetings) to secure free allowances or transitional provisions and alleviate compliance pressures. Collaborate with the Chinese government to promote subsidy policies that favor technologically advanced enterprises, linking the proportion of low-carbon investment with subsidy rates.

④ Data-Driven Decision Support

Develop intelligent carbon emission management platforms that integrate real-time vessel emission data, carbon tax costs, and operational revenue, allowing simulations of expected returns under different policy scenarios to support rapid decision-making. Apply reinforcement learning algorithms to train multi-stage dynamic game strategies, optimizing iterative paths and reducing trial-and-error costs.

⑤ Risk Management and Capital Reserves

Establish dedicated carbon tax reserve funds to address the risks of sudden tax hikes (e.g., the EU's tax rate increase to 100% in 2026). Additionally, explore carbon finance instruments (e.g., green bonds, carbon futures) to transform carbon tax costs into capital market financing advantages [17].

6. Conclusion

The low-carbon transformation of the shipping industry urgently requires the integrated support of policies, technologies, and international cooperation. The strategies proposed in this study aim to balance short-term economic pressures with long-term climate objectives, offering theoretical references for achieving carbon neutrality in China's shipping industry and beyond. Future research can further incorporate other stakeholders—such as ports and cargo owners—into the analysis, constructing a more comprehensive industry chain game model to enhance the practical value of policy recommendations.

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