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Carbon emissions reduction in shipping based on four-party evolutionary game

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In order to realize a win-win situation between economic development and environmental benefits, this paper constructs a four-party evolutionary game model including the government, two homogeneous ports and shipping companies based on evolutionary game theory. By calculating the payoff matrices of the four parties and replicating the dynamic equations, according to the Jacobi matrix, we study and discuss the possible stabilization points of the model under five different scenarios. The game is simulated using MATLAB and the relevant parameters are selected for sensitivity analysis. The results show that the environmental benefits are maximized when the government does not implement the policy and the port and shipping companies use the shore electricty system (i.e., the stability point E12 (0,1,1,1)). Meanwhile, by analyzing the port size sensitivity, when t=1.116, the large-scale port evolution tends to 0, while the small-scale port fluctuates up and down, which leads to the conclusion that the small-scale ports have more potential to implement shore electricty and are able to gain benefits faster. This study provides theoretical support for the implementation of shore electricty systems, while pointing out the key role of the government in promoting the development of shore electricty. It provides a reference for effectively promoting the use of shore electricty in the context of carbon emission reduction, which is especially important for the implementation of shore electricty in small-scale ports and helps to maximize the environmental benefits of port operations.

KEYWORDS

four-party evolutionary game model, shore electricity system, subsidy, strategies choice, shipping

1 Introduction

Ports serve as vital transit hubs for international trade and transportation as well as the primary means of international trade in goods (Zhao et al., 2021). However, the growth in port production and trade has resulted in high energy consumption and pollution, and large amounts of greenhouse gases, including carbon dioxide, sulfur dioxide, and nitrogen oxides, are produced by port operations. The emission of these gases can have considerable adverse effects on both the environment and human beings. These hazards have given rise to a wide range of concerns about the impacts on air quality (Shu et al., 2023). A greenhouse gas study published by the IMO states that two to three percent of the carbon dioxide (CO2) released into the atmosphere worldwide is caused by pollution from shipping (Shang et al., 2024). And a large number of studies have shown that ships produce 1.2-1.6 tonnes of particulate matter, 4.7-6.5 tonnes of sulphur oxides and 5-6.9 tonnes of nitrogen oxides per year, respectively. International trade will cause a considerable increase in air pollution released by ships during the next 10 to 40 years (Shu et al., 2023). Therefore, more and more researchers have begun to study how to take the effect of lowering emissions on port services to reduce the air pollution from shipping.

Several scholars have already proposed measures to mitigate the pollution problem in harbours. Use hybrid or electrified machinery, including AGV and E-RTG, to cut down on port gas emissions. Explore how to equip power and deploy smart technologies to further reduce energy and lower carbon emissions through the use of LNG, dual-fuel, and hydrogen fuel cells (Wang and Li, 2023). To create a carbon-neutral environment, use the SSSR technique to optimize the order in which ships reach ports and slow down high-speed vessels (Xia et al., 2021). Air quality is enhanced and pollutants are decreased when ships generate power using shore electricity as a substitute technology when they are berthed. Nowadays, using shore electricity has proven to be a successful way of lowering emissions in ports (Zhao et al., 2021). Ports around the world are realising the importance of shore electricity deployment, and increasingly more nations and areas are implementing shore electricity with more urgency. However, high costs hinder the development of shore electricity. The adoption of shore electricity is not particularly motivated by port and shipping firms. Government needs to measure to encourage the growth of shore electricity. Shore electricity development is directly impacted by the decision-making practices of ports and shipping companies, both as suppliers and consumers of shore electricity (Sheng et al., 2023). In the real market, due to the ports' competitive connection, the adjustment of their strategies to attract shipping corporations to use shore electricity. Additionally, their competition with each other plays a crucial role in promoting shore electricity throughout the sector.

Therefore, the main objective of this paper is to analyse how different strategies evolve over time among the various players by modelling the dynamic interactions between the government, port and shipping companies in the choice of shore electricity strategies. By constructing a four-party evolutionary game model with the government, two homogeneous ports and shipping corporation, and to investigate the impact of the four parties' behaviour on the implementation of shore electricity. The government is the supervising party in this situation, and it has two options: a motivational strategy or a non-motivational strategy. There are two options available to port corporations A1 and A2: implementing shore electricity or not. The shipping corporation can choose to retorfit or not to retorfit the shore electricity receiving equipments. The following are the questions we hope to address with this study:

(1) In the four-party evolutionary game model, how can the shore electricity usage benefit matrix be constructed for various interested parties? What is the equation for the determinant?

(2) How are the equilibrium points in the model calculated? How to find evolutionary stabilization strategies? How can these strategies be implemented to maximize benefits for shore electricity stakeholders?

(3) How can changes in parameters impact the way governments, ports, and shipping companies choose their shore electricity methods over time?

In order to solve the above problems, this paper establishes a four-party evolutionary game model between the government, two homogeneous ports, and shipping companies, using a model that is relatively rare in previous shore electricity studies. By constructing this model, the benefit matrix was established. And the four-party replication dynamics equations were calculated, and the evolutionary stability point and the corresponding stability conditions were found through the Jacobi matrix. Finally, numerical modeling is performed to analyze the effects of each parameter on the evolution. These studies reveal the dynamic competition and cooperation mechanisms of each participant under different strategies. In addition, simulations and parameter sensitivity analyses were conducted using MATLAB to further verify the practicality of the model and the applicability of the theory.

The results of this study not only provide theoretical support for the implementation of shore electricity systems, but also point out the key role of the government in promoting the development of shore electricity. By analyzing the stabilization points under different scenarios, the study suggests how to effectively promote the use of shore electricity in the context of carbon emission reduction. Especially, small-scale ports that have more potential to reap faster benefits from the implementation of shore electricity. These findings are important for maximizing the environmental benefits of port operations.

Therefore, this study not only theoretically expands the application of evolutionary game theory in the field of carbon emission reduction in shipping, but also provides a scientific basis for the formulation and implementation of actual policies, which has high archival value and practical application value.

Here is the remainder of the paper. Section 2 analyzes and arranges the relevant literature. Section 3 establishes and examines a four-party evolutionary game model. Section 4 performs simulations and parameter sensitivity analyses using MATLAB. Finally, Section 5 concludes with a summary and recommendations for more research.

2 Literature review

2.1 Literature on carbon emissions reduction

The Green Economy Initiative seeks to require that all sectors of the economy shift to one that lowers carbon emissions without raising them (Hu and He, 2024); Wu and Xu (Wu et al., 2018) believes that businesses urgently need to undergo a low-carbon

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Abbreviations: IMO, International Maritime Organization; CO2, Carbondioxide; AGV, Automated Guided Vehicle; E-RTG, Electric drive rubber-tyred container gantry crane; LNG, Liquefied natural gas; DTA, Digital Terrain Analysis; FDI, Foreign Direct Investment; MGO, Marine gas oil; CFL, Countdown Fuzzy Logic; TFL, Timed Fuzzy Logic; SD, System dynamics.

transition due to society's desire to conserve energy and the environment. Promoting this transition can be achieved by combining the market for low-carbon energy adjustments with the policy for low-consumption adjustments. Throught studying the DTA technology, Hu and He (2024) conclude that, the government can enact a number of tax and transfer payment-based fiscal policies that will speed the establishment of a low-carbon economy. A key tool for promoting the global energy transition and the reduction of carbon emissions is the carbon emissions trading policy. A sound carbon emissions trading policy and moderately strengthened environmental regulation can alleviate the conflict between the environment and FDI (Shao et al., 2022). Many firms have begun to redesign their products to reduce their carbon footprint by modifying them or replacing them with recycled or renewable materials (Lewandowski and Ullrich, 2023). In the shipping industry, stricter regulations have been enacted to control emissions reductions, and large marine diesel engines have begun to use common rail fuel injection to reduce PM and NOx emissions (Ni et al., 2020). Many shipping corporations have also taken action. The pashore electricitynger ship Stena Germanica is powered by Wärtsilä's four-stroke medium-speed marine enginesa, medium-speed, which uses direct injection of methanol and marine gas oil (MGO) as pilotfuels to reduce consumption. In addition, Seaside shipping corporation's tankers use low-speed, two-stroke MAN engines, also with separate direct injection of methanol and pilot fuel (MGO) (Harmsen, 2021). Hsu and Tzu (Hsu et al., 2024) believes that the use of shore-side power in harbours would be a more effective measure to achieve cleaner harbours and to reduce emissions to achieve sustainable development.

In summary, carbon emissions reduction has become an urgent task. Papers related to low-carbon emission reduction have been widely applied in many fields such as the supply chain. This paper will organically combine the concept of low-carbon emission reduction with the shipping industry to thoroughly explore the dynamic interaction among the government, two homogeneous port companies, and shipping companies in the process of choosing shore electricity strategies.

2.2 Literature on reduction of carbon emissions in shipping

Meng and Wang (Meng et al., 2022b) selected the government, ports and shipping corporations as incentive objects and decision-making ways, and constructed a differential game model with four scenarios to analyse the emission reduction strategies of port and shipping corporations. Xue and Lai (2023) imposed hard constraints on carbon emissions, and constructed a game model of CFL and TFL as a means to study a green shipping operation system, which confirms that CFL is more effective for decarbonisation. Li and Kuang (Li et al., 2020) studied a two-tier maritime supply chain made up of ports and shipping corporations under the government's green subsidy. By using game theory and system dynamics (SD) methods they determined the optimal subsidy intensity and subsidy reduction point of the government. It presents the government with ideas to shape subsidy policies that will benefit the maritime supply chain.

With the continuous development of shore electricity, more and more scholars are now studying shore electricity to reduce carbon emission in shipping. Wang and Guo (Wang et al., 2022) proposed a Stackelberg game model for optimising the government's shore electricity adoption subsidy scheme considering the interactions between the government, ports and ships. Song and Tang (Song et al., 2022) established a Nash game of two shipping corporations' decisions on shore electricity, and studied the impact between different government intervention methods and the effect of government subsidies on shipping corporations' strategies to use shore electricity in port.

In conclusion, most papers usually utilize general game methods such as Nash equilibrium and differential game to study the interaction mechanisms among the subjects. However, this paper utilizes four-party evolutionary game theory, which will be a novel and powerful tool. It is able to simulate how different strategies evolve over time and propagate among participants, thus revealing the dynamic evolution of carbon reduction strategies in the shipping industry and potential cooperation mechanisms.

2.3 Literature on evolutionary game theory

Evolutionary game theory is frequently employed in the analysis of intricate environmental systems (Chen et al., 2021), including the fields of computer technology (Cheng S. et al., 2020), medicine (Jiang et al., 2023), agriculture and forestry (Han et al., 2020), and shipping (Ye et al., 2024). In order to help governments create efficient waste management regulations, Long and Yang (Long et al., 2019) developed a three-party evolutionary game model of government, consumers, and businesses. This model was designed in response to the significant environmental pollution and resource waste that take-out garbage creates. Based on evolutionary game theory, Cheng et al (Cheng L. et al., 2020). study the long-term bidding problem on the generation side. By analyzing a general N-group multi-strategy evolutionary game model, defining the relative net benefit parameter, exploring the characteristics of long-term equilibrium, and applying it as an example of competitive bidding in the power generation market, they provide a reference for the decision-making in related fields, and look forward to the direction of the future research of EGT. Based on multi-group evolutionary game dynamics, Cheng et al (Cheng et al., 2021) studied the behavioral decision-making in power demand side response management, elaborated relevant evolutionary game models, developed power DRM models and algorithms, and verified the effectiveness of the models through case studies, showing that tariff incentives play an important role in user participation. In the second year, Cheng, Chen, and Liu (Cheng et al., 2022) focused on the long-term bidding problem of power generators in the electricity market, and constructed a general two-population n-strategy evolutionary game model (2PnS - EG) using evolutionary game theory, analyzed the equilibrium characteristics under different market clearing mechanisms in depth, and provided decision-making references to the power generating enterprises and government departments. Recent studies have also made extensive use of evolutionary games, and Cheng et al (Cheng et al., 2024). used a multi-subject complex network evolutionary game model to set up a scenario simulation considering a variety of factors to study the diffusion of flexibility retrofit technology in thermal power enterprises. Evolutionary game theory is also widely used in the shipping industry for related research. In order to investigate the dynamic interactions between shipping corporations and freight forwarders in the shipping supply chain channel selection mechanism, Peng and Wang (2023) integrated evolutionary game theory into a pricing model. Zhang, Wang, and Yu (Zhang et al., 2019) constructed an evolutionary game model between the government and manufacturers, and found that adopting a dynamic carbon trading pricing policy is effective in accelerating carbon emission reduction. In order to study the interaction mechanism among the government, port corporations and liner companies in the strategic choice of shore electricity system, Xu and Di (Xu et al., 2021) constructed an evolutionary game model.

In conclusion, the research findings show that most papers use the three-party evolutionary game model to study shore electricity. However, this paper comprehensively takes into account various stakeholders by establishing a four-party evolutionary game model and reveals the dynamic evolution process and potential cooperation mechanisms of carbon emission reduction strategies in the shipping industry. Thus, it provides decision-making support for policymakers and enterprises to promote the implementation of the shore electricty system and the achievement of environmental protection goals.

3 Construction of the four-party evolutionary game model

3.1 Problem description and model constructions

All participants in the evolutionary game make decisions under the premise of limited rationality. in the early stages of evolution, the participants don't maximize their profits, and by imitating their experiences and communicating with others, they continuously modify their tactics to optimize their profits in the process of evolution. Therefore, the final strategy of the evolutionary game is to maximize the profits of all participants. This paper describes the four-party game relationship between the government, two homogeneous port corporations, and shipping corporation, and investigates the effect of the government's shore electricity implementation policy on the strategies of port and shipping corporations. The four-party game model is constructed for port and shipping corporation to choose shore electricity with the participation of the government, and the logical relationship diagram of the four parties is shown in Figure 1.

3.2 Basic assumptions and model parameters

To construct a game model between the stakeholders of shore electricity and to study the strategic choices of individual stakeholders, the following basic assumptions are made:

Assumption 1 In this study, the government, two homogeneous port corporations, and shipping corporation are chosen as the game subjects, and all four subjects have limited rationality. The government's strategy choice is {promote shore electricity implementation policy G1, don't promote shore electricity implementation policy G2}, respectively, with the corresponding choice probability {y, 1-y}; the port company A1's strategy choice is {implement shore electricity UP1, don't implement shore electricity UP2}, respectively, with the corresponding choice probability {x1, 1-x1}; the port company A2's strategy choice is {implement shore electricity DP1, don't implement shore electricity DP2}, respectively, with the corresponding choice probability {x2,1-x2}.And the shipping corporation's strategy choice is {performing shore electricity use facility modification S1, don't performing shore electricity use facility modification S2}, with corresponding choice probabilities {z, 1-z}, respectively.

Assumption 2 The two port companies are homogeneous ports, i.e., the two port companies have the same characteristics in terms of costs and benefits of implementing shore electricty. In the early stage of the model, this simplification helps to focus on the basic interaction between government policies, ports and shipping companies, avoiding the complexity brought by individual differences in ports and enabling the study to focus on the core game mechanism. The direct impacts of government policies, penalties, and subsidies on port decision-making, as well as the cooperative and competitive relationships between ports and shipping companies in the use of shore electricty, can be more clearly observed. If the two port corporations implement shore electricity at the same time, it is regarded as a joint implementation, then they share the cost of shore electricity.At this time, the two port corporations are in a cooperative relationship, and their share of the cost is proportional to the size of the port.

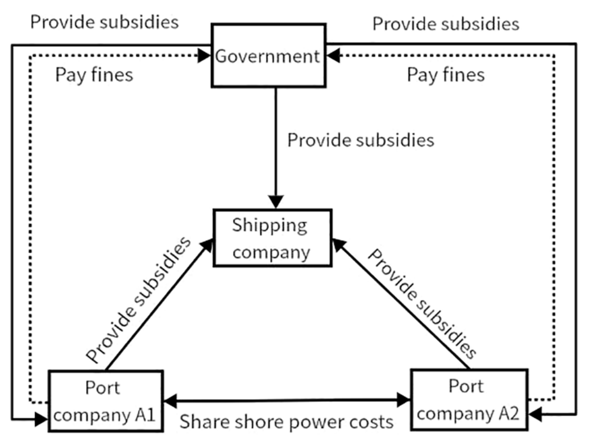

FIGURE 1
The logical diagram of the four parties.

Assumption 3 To reduce emission and become green shipping, port and shipping corporation are strongly encouraged to use shore electricity, and a reward and punishment system for port and shipping corporation is formulated through "behavioral incentives". In order to encourage the adoption of the shore electricity policy, the government will provide financial assistance to the shipping company in order to alter the ship's shore electricity infrastructure. Port corporations that don't implement shore electricity are subject to fines, and where there is only one port company that implements shore electricity, the government subsidises the port company that implements shore electricity, and the port that doesn't implement shore electricity subsidises the cost of the shore electricity to the port that does implement shore electricity.If both port corporations implement shore electricity at the same time, the government believes that the implementation of shore electricity in ports has become the industry standard and the norm, and in order to maximize its own profits, it doesn't give subsidies to ports.

Assumption 4 Only when the shipping corporation and the port company have the conditions for using shore electricity at the same time, i.e., when the port company implements shore electricity and the shipping corporation modifies the ship's facilities for using shore electricity, can it succeed in using shore electricity and obtain additional revenue from using shore electricity. If it is not possible to succeed in using shore electricity, the ship will call at the port and use auxiliary engines to supply electricity.

Assumption 5 As long as there is a port to use shore electricity, the shipping corporation to carry out the shore electricity facilities transformation, it is bound to use shore electricity, and is 100%. If both ports are implemented, the shipping corporation will have a certain probability of choosing one of the two ports to call port, when the two ports are in a competitive relationship. In order to reduce the operating costs of ports, especially the extra expenses caused by fines, ports will encourage or require shipping corporation which they cooperate with to use shore electricity. The shipping corporation are incentivized to use shore electricity by giving them a certain amount of subsidy. As the two ports are now in competition, the selected port company has to subsidizes the ship.By selecting one port for call port, the other port has no additional benefit from the use of shore electricity, but still shares in the cost of implementing shore electricity.

There are some limitations in the above assumptions, for example, the port homogeneity assumption ignores the individual differences of ports in terms of size, technology level, financial status, etc., which may lead to different behaviors of ports in the selection of shore electricty strategies. In practice, the competition among ports is not only reflected in the provision of shore electricty facilities, but also involves a number of aspects, such as the quality of port services, route resources, and logistics efficiency. It may make the model underestimate the decision-making diversity of ports in a complex competitive environment and cannot fully reflect the real competitive situation among ports. Therefore, in the later simulation, we will analyze the sensitivity of the port's size to maximize and narrow down the limitations. These assumptions also have a potential impact on the model results. Since the assumptions do not fully take into account the full extent of the real market, the results derived from the model regarding port strategy choices and evolutionary paths may partially deviate from the actual situation. If policy makers formulate shore electricty promotion policies based entirely on the assumptions in the model, it is possible that the effect of adapting to the actual needs of different types of ports will not be significant enough. Therefore, we will analyze the results through simulation and propose policy recommendations that can be implemented in the context of reality.

The relevant symbols and definitions are described in Table 1, under these assumptions.

3.3 Evolutionary game analysis of replicated dynamic equation

The article computes and presents the Benefit matrix of the four-party evolutionary game in which the government supports shore electricity use policy and does not support shore electricity use policy. The functions in Appendix A represent the gains of the government, port company A1, port company A2 and shipping corporation, respectively.

The replicated dynamic equations for each of the four strategies were calculated by combining the above mentioned Benefit matrix.

$$\begin{aligned} F(y) = \tfrac{dy}{dt} &= y(E_y - \overline{E_y}) = y(1-y)(E_y - E_{1-y}) \\ &= y(y-1)[C_g - P_{E_{A1}} - P_{E_{A2}} + (P_{E_{A1}} + C_{P_1}\omega_1)x_1 \\ &+ (P_{E_{A2}} + C_{P_2}\omega_2)x_2 + C_{S_1}\gamma z + (R'_{g_{A2}} - R_{g_{A1}})x_1 z \\ &+ (R'_{g_{A2}} - R_{g_{A2}})x_2 z - (C_{P_1}\omega_1 + C_{P_2}\omega_2)x_1x_2 + (R_{g_{A1}} \\ &+ R_{g_{A2}} - R_{g_{A12}} - 2R'_{g_{A2}} + R'_{g_{A12}})x_1x_2\mathrm{z}] \end{aligned} \tag{1}$$

$$\begin{aligned} \mathrm{F}(\mathrm{x}_1) = \mathrm{x}_1(x_1 - 1)[\mathrm{C}_{\mathrm{p}_1} - n + (E_{A1} + n - \mathrm{C}_{\mathrm{p}_1} - m)x_2 \\ - ((P_{E_{A1}} + \mathrm{C}_{\mathrm{p}_1}\omega_1)y - R'_{P_{A1}}z + \mathrm{C}_{\mathrm{p}_1}\omega_1 x_2 y \\ + (R'_{P_{A1}} + F_{S_1}a\alpha - Ra)x_2 z] \end{aligned} \tag{2}$$

$$\begin{aligned} \mathrm{F}(\mathrm{x}_2) = \mathrm{x}_2(x_2 - 1)[\mathrm{C}_{\mathrm{p}_2} - m + (E_{A2} + m - \mathrm{C}_{\mathrm{p}_2} - n)x_1 \\ - ((P_{E_{A2}} + \mathrm{C}_{\mathrm{p}_2}\omega_2)y - R'_{P_{A2}}z + \mathrm{C}_{\mathrm{p}_2}\omega_2 x_1 y \\ + (R'_{P_{A2}} - R + Ra + F_{S_1}\beta - F_{S_1}a\beta)x_1 z] \end{aligned} \tag{3}$$

$$\begin{aligned} \mathrm{F}(\mathrm{z}) = \mathrm{z}(\mathrm{z}-1)[C_{S_1} + (F_{S_3} - F_{S_2})(x_1 + x_2 - x_1x_2) - C_{S_1}\gamma y + (F_{S_1} \\ - F_{S_3})(x_1y + x_2y - x_1x_2y) + F_{S_1}(a\beta - a\alpha - \beta)x_1x_2] \end{aligned} \tag{4}$$

In the system of replicating dynamic equations, the evolutionary process reaches a steady state when $F(y) = F(\mathrm{x}_1) = F(\mathrm{x}_2) = F(z) = 0$.

3.4 Stability analysis of the evolutionary game

The Jacobian matrix analysis is used in this research to determine the stability of the equilibrium. Therefore, in order to

TABLE 1 Model variables and the explanations.

Variant	Account for
R_{g_0}	Government's Initial Social Benefits
$R_{P_{A1}}$	Port company A1's initial incomes
$R_{P_{A2}}$	Port company A2's initial incomes
$R_{g_{A1}}$	Government's environmental benefits after port company A1 using shore electricity
$R_{g_{A2}}$	Government's environmental benefits after port company A2 using shore electricity
$R_{g_{A12}}$	Government's environmental benefits after both port company A1 and port company A2 using shore electricity
$R'_{P_{A1}}$	Additional revenues from port company A1's use of shore electricity
$R'_{P_{A2}}$	Additional revenues from port company A2's use of shore electricity
$R'_{g_{A1}}$	Government's environmental benefits after port company A1 uses shore electricity when there is no policy
$R'_{g_{A2}}$	Government's environmental benefits after port company A2 uses shore electricity when there is no policy
$R'_{g_{A12}}$	Government's environmental benefits after both port company A1 and port company A2 use shore electricity when there is no policy
R_{S_0}	Initial revenue from shipping corporation
ω_1	Government subsidy for port company A1 implementation of shore electricity
ω_2	Government subsidy for port company A2 implementation of shore electricity
γ	Government subsidy for shipping corporation to modify shore electricity facilities
C_g	Costs of government for driving shore electricity policy
C_{P_1}	Costs of using shore electricity in port company A1
C_{P_2}	Costs of using shore electricity in port company A2
C_{S_1}	Costs of shipping corporation for modifying shore electricity receiving equipment
C_{S_2}	Berthing fees for ships
E_{A1}	Port size of port company A1
E_{A2}	Port size of port company A2
$P_{E_{A1}}$	Fees to be paid when A1 doesn't implement shore electricity
$P_{E_{A2}}$	Fees to be paid when A2 doesn't implement shore electricity
F_{S_1}	The fees paid by ships for shore electricity with favorable policy
F_{S_2}	Costs of bunker oil for ships
F_{S_3}	The fees paid by ships for shore electricity without favorable policy
L	Government's loss due to bad actions of port shipping corporation in using shore electricity
m	Subsidy from port company A1 to port company A2 when port company A1 doesn't use shore electricity and port company A2 does use shore electricity
n	Subsidy from port company A2 to port company A1 when port company A2 doesn't use shore electricity and port company A1 does use shore electricity
R	Revenues of both the port company A1 and port company A2 use shore electricity
α	Subsidy from port company A1 to ship company when ship company chooses A1 in the case of both port corporations use shore electricity
β	Subsidy from port company A2 to ship company when ship company chooses A2 in the case of both port corporations use shore electricity
a	Probability of shipping corporation chooses port company A1
1-a	Probability of shipping corporation chooses port company A2

understand the preconditions and related proceshore electricitys for the formation of stable strategies of the four-party evolutionary game, which is the government, the port company A1, the port company A2 and the shipping corporation, in the process of choosing the shore electricity strategy, according to the replicated dynamic equations of the above four-party game subjects, the Jacobian matrix of this dynamic can be obtained as J:

$$J = \begin{bmatrix} \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial x_1} & \frac{\partial F(y)}{\partial x_2} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(x_1)}{\partial y} & \frac{\partial F(x_1)}{\partial x_1} & \frac{\partial F(x_1)}{\partial x_2} & \frac{\partial F(x_1)}{\partial z} \\ \frac{\partial F(x_2)}{\partial y} & \frac{\partial F(x_2)}{\partial x_1} & \frac{\partial F(x_2)}{\partial x_2} & \frac{\partial F(x_2)}{\partial z} \\ \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial x_1} & \frac{\partial F(z)}{\partial x_2} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

The following Table 2 shows the stability of each equilibrium point and the stability conditions.

In addition, in order to better analyze the positive and negative matrix eigenvalues under different equilibrium points, the following assumptions are made in light of the actual situation: a. The additional income from the use of shore electricity in the port is usually higher than its cost. The subsidy given by Port Company A1 to Port Company A2 for the implementation of shore electricity is usually smaller than the cost of Port Company A1 itself for the implementation of shore electricity. b. The cost of using auxiliary engines by ships is usually higher than the cost of using shore electricity by ships. The cost of modifying shore electricity receiving equipment is usually higher than the cost of using auxiliary engines on ships.

Scenario 1 Stability point E1(0,0,0,0) represents which the government doesn't promote the policy on the use of shore electricity, the port company A1 and A2 don't implement shore electricity, and the shipping corporation doesn't modify shore electricity receiving equipments.The condition under this stability point is: $P_{E_{A1}} + P_{E_{A2}} < C_g$. in the early stages, the government is ready to promote the policy, due to the initial stage of policy implementation, various factors need to be considered. To give port corporations a period of adaptation, the government gradually

TABLE 2 Stabilization of equilibrium points.

	Eigenvalue	Positive or negative	Stability and conditions
E1(0,0,0,0)	$m - C_{P_2}$ $n - C_{P_1}$ $-C_{S_1}$ $P_{E_{A1}} + P_{E_{A2}} - C_g$	− − − ×	ESS (condition 1)
E2(0,0,0,1)	C_{S_1} $R'_{P_{A2}} - C_{P_2} + m$ $R'_{P_{A1}} - C_{P_1} + n$ $P_{E_{A1}} - C_g + P_{E_{A2}} - C_{S_1}\gamma$	+ + + ×	No ESS
E3(0,0,1,0)	$C_{P_2} - m$ $m - E_{A1}$ $P_{E_{A1}} - C_g - C_{P_2}\omega_2$ $F_{S_2} - C_{S_1} - F_{S_3}$	+ − − −	No ESS
E4(0,1,0,0)	$C_{P_1} - n$ $n - E_{A2}$ $P_{E_{A2}} - C_g - C_{P_1}\omega_1$ $F_{S_2} - C_{S_1} - F_{S_3}$	+ − − −	No ESS
E5(1,0,0,0)	$C_{S_1}(\gamma - 1)$ $C_g - P_{E_{A1}} - P_{E_{A2}}$ $P_{E_{A2}} - C_{P_2} + m + C_{P_2}\omega_2$ $P_{E_{A1}} - C_{P_1} + n + C_{P_1}\omega_1$	− × × ×	ESS (condition 2)
E6 (0,0,1,1)	$C_{P_2} - R'_{P_{A2}} - m$ $C_{S_1} - F_{S_2} + F_{S_3}$ $m - E_{A1} + Ra - F_{S_1}a\alpha$ $P_{E_{A1}} - C_g + R_{g_{A2}} - R'_{g_{A2}} - C_{S_1}\gamma - C_{P_2}\omega_2$	− + × ×	No ESS
E7 (0,1,0,1)	$C_{P_1} - R'_{P_{A1}} - n$ $C_{S_1} - F_{S_2} + F_{S_3}$ $R - E_{A2} + n - F_{S_1}\beta - Ra + F_{S_1}a\beta$ $P_{E_{A2}} - C_g + R_{g_{A1}} - R'_{g_{A2}} - C_{S_1}\gamma$ $- C_{P_1}\omega_1$	− + × ×	No ESS
E8 (1,0,0,1)	$C_{S_1} - C_{S_1}\gamma$ $C_g - P_{E_{A1}} - P_{E_{A2}} + C_{S_1}\gamma$ $P_{E_{A2}} - C_{P_2} + R'_{P_{A2}} + m + C_{P_2}\omega_2$ $P_{E_{A1}} - C_{P_1} + R'_{P_{A1}} + n + C_{P_1}\omega_1$	+ × + +	No ESS
E9 (0,1,1,0)	$m - E_{A1}$ $n - E_{A2}$ $- C_g$ $F_{S_2} - C_{S_1} - F_{S_3} + F_{S_1}\beta + F_{S_1}a\alpha$ $- F_{S_1}a\beta$	− − − ×	ESS (condition 3)
E10 (1,1,0,0)	$C_g - P_{E_{A2}} + C_{P_1}\omega_1$ $P_{E_{A2}} - E_{A2} + n$ $C_{P_1} - P_{E_{A1}} - n - C_{P_1}\omega_1$ $F_{S_2} - F_{S_1} - C_{S_1} + C_{S_1}\gamma$	+ × − −	No ESS
E11 (1,0,1,0)	$C_g - P_{E_{A1}} + C_{P_2}\omega_2$ $P_{E_{A1}} - E_{A1} + m$ $C_{P_2} - P_{E_{A2}} - m - C_{P_2}\omega_2$ $F_{S_2} - F_{S_1} - C_{S_1} + C_{S_1}\gamma$	+ + − −	No ESS
E12 (0,1,1,1)	$R_{g_{A12}} - C_g - R'_{g_{A12}} - C_{S_1}\gamma$ $E_{A1} - m - Ra + F_{S_1}a\alpha$ $C_{S_1} - F_{S_2} + F_{S_3} - F_{S_1}\beta - F_{S_1}a\alpha$ $+ F_{S_1}a\beta$ $E_{A2} - R - n + F_{S_1}\beta + Ra - F_{S_1}a\beta$	− × × ×	ESS (condition 4)

(Continued)

TABLE 2 Continued

	Eigenvalue	Positive or negative	Stability and conditions
E13 (1,1,0,1)	$C_{S_1}(1-\gamma)+F_{S_1}-F_{S_2}$ $C_{P_1}-P_{E_{A1}}-R'_{g_{A1}}-n-C_{P_1}\omega_1$ $C_g-P_{E_{A2}}-R_{g_{A1}}+R'_{g_{A2}}+C_{S_1}\gamma$ $+C_{P_1}\omega_1$ $P_{E_{A2}}-E_{A2}+R+n-F_{S_1}\beta-Ra$ $+F_{S_1}a\beta$	+ − × ×	No ESS
E14 (1,0,1,1)	$C_{S_1}(1-\gamma)+F_{S_1}-F_{S_2}$ $P_{E_{A1}}-E_{A1}+m+Ra-F_{S_1}a\alpha$ $C_{P_2}-P_{E_{A2}}-R'_{g_{A2}}-m-C_{P_2}\omega_2$ $C_g-P_{E_{A1}}-R_{g_{A2}}+R'_{g_{A2}}+C_{S_1}\gamma$ $+C_{P_2}\omega_2$	+ × × ×	No ESS
E15 (1,1,1,0)	$C_gE_{A1}-P_{E_{A1}}-m$ $E_{A2}-P_{E_{A2}}-n$ $F_{S_2}-F_{S_1}-C_{S_1}+F_{S_1}\beta+C_{S_1}\gamma$ $+F_{S_1}a\alpha-F_{S_1}a\beta$	+ − − +	No ESS
E16(1,1,1,1)	$C_g-R_{g_{A12}}-R'_{g_{A12}}+C_{S_1}\gamma$ $E_{A1}+F_{S_1}a\alpha-P_{E_{A1}}-m-Ra$ $E_{A2}-P_{E_{A2}}-R(1-a)-n$ $+F_{S_1}\beta(1-a)$ $C_{S_1}(1-\gamma)+F_{S_1}-F_{S_2}-F_{S_1}\beta(1-a)$ $-F_{S_1}a\alpha$	× − − −	ESS (condition 5)

increases the penalty. And the government needs to invest a lot of resources in publicizing and supervising the implementation of the shore electricity policy, so the cost of the government's implementation will be much larger than the fine imposed on the port. At this time, the government, port corporations, shipping corporation need to face the high cost of shore electricity system construction, the high cost of shore electricity use, technical difficulties and other practical factors, so the four parties choose to adopt a negative strategy to ensure that their benefits do not decrease,at this stage.

Scenario 2 Stability point E5(1,0,0,0) represents that the government promote the policy on the use of shore electricity, port corporations A1 and A2 don't implement shore electricity, and shipping corporation don't modify shore electricity receiving equipments. The conditions under this stablility point are $C_g < P_{E_{A1}} + P_{E_{A2}}$, $P_{E_{A2}} + m + C_{P_2}\omega_2 < C_{P_2}$,$P_{E_{A1}} + n + C_{P_1}\omega_1 < C_{P_1}$. The condition is opposite to the condition under the stable point of Scenario 1, because the government has started to promote the shore electricity implementation policy, the implementation of the policy has been gradually stabilized, the promotion cost is reduced. To increase the intensity of the port company's use of shore electricity and to improve the government's deterrent, the government increases the fines which the port company doesn't use shore electricity. Thus port corporations start implementing shore electricity to maximize the benefits. The initial cost of using shore electricity in ports is much greater than the penalties and subsidies for not using shore electricity. This is due to the large construction costs of shore electricity, as well as the lager expenses associated with building existing power facilities and the large operating costs incurred by port corporations in the early stages of using shore electricity. In this case, the port company in order to maintain better income, the port company and the shipping corporation's choice of gaming strategy has not changed.

Scenario 3 Stability point E9 (0,1,1,0) represents that the government doesn't promote the policy, the port corporations A1 and A2 use shore electricity, and the shipping corporation don't modify shore electricity receiving equipments. The condition under this stability point is $F_{S_2} + F_{S_1}\beta(1-a) + F_{S_1}a\alpha < C_{S_1} + F_{S_3}$. This scenario is still in the early stage. In order to modify shore electricity receiving equipment, during the preliminary stage shipping corporation requires a certain amount of investment. Due to the ship's tonnage and type of different, its needs in terms of frequency, voltage and capacity of the power supply will also vary. It is necessary to use the ship's shore electricity receiving equipment must meet the characteristics of the standard, so the transformation of shore electricity receiving equipment requires expensive technology and equipment.Thus, this will result the hight initial investment cost. Even if the port company gives subsidies to the shipping corporation, it cannot offset the cost of expensive modification and the use of shore electricity. And from the short-term economic point of view, the cost of auxiliary engines generation will be lower.

Scenario 4 Stability point E12 (0,1,1,1) represents the government doesn't promote the policy, port corporations A1 and A2 use shore electricity and shipping corporation modify shore electricity receiving equipments. The conditions under this stability point are $E_{A1} + F_{S_1} a\alpha < m + Ra, C_{S_1} + F_{S_3} < F_{S_2} + F_{S_1} \beta(1 - a) + F_{S_1} a\alpha, E_{A2} + F_{S_1} \beta(1 - a) < R(1 - a) + n$. Although the initial investment is large, the use of shore electricity can bring great economic benefits to the port company in the long run. With the development of technology, the cost of construction and operation of the shore electricity system is expected to be further reduced, which makes the economy of shore electricity more prominent.At the same time it will result in the cost of using shore electricity on ships being lower than the cost of using fuel oil auxiliary engines to generate electricity, bringing more economic benefits to ports and shipping corporations.

Scenario 5 Stability point E16(1,1,1,1) represents the government promote the policy, with port company A1 using shore electricity, port company A2 using shore electricity, and the shipping corporation modifying shore electricity receiving equipments. The condition under this stability point is $C_g + C_{S_1}\gamma < R_{g_{A12}} + R'_{g_{A12}}$. The four parties adopt active strategies to maximize the benefits. Even though the government needs to give subsidies to the shipping corporation to modify shore electricity receiving equipments, since both port company A1 and port company A2 use shore electricity and the shipping corporation also modify shore electricity receiving equipments, the use of shore electricity in port operations generates enough revenue to the government to cover the subsidies given by the government to the shipping corporation and the cost of the implementation based on the assumption of successful use of shore electricity (Assumption 4).

4 Simulation of the four-party evolutionary game

By reviewing relevant literature (Xu et al., 2021; Meng et al., 2022a; Sheng et al., 2023) and information, and investigating some major ports as well as some participating shipping corporations. We checked the relevant data of Shanghai Port and COSCO. Finally, as shown in Table 3, we get the following data.

The following numerical simulation is carried out by using MATLAB to simulate the evolution trajectory of each game party.

4.1 Impact of the cost of implementing government policy

Setting $C_g = \{2, 6, 12\}$. Figure 2 illustrates the strategy evolution process and the four parties' outcomes when the government's execution expenses rise.

As illustrated in Figure 2, the cost level of implementing government policy affects not only the government's strategic evolution but also that of the other three parties, with the most notable changes observed in the strategic evolution of port corporations A1 and A2. According to the above experimental data, when $C_g = 2$ the evolution of the government, port companies A1, A2 and shipping company from the initial probability gradually increased, and finally converge to 1. When $C_g = 6$, it can be seen that in the evolution process, the shipping company is a decreasing trend, gradually become 0, and the government and port companies A1, A2 in the time range of t<21, the wave-like up and down fluctuations and amplitude gradually reduced, and the final evolution of the equilibrium probability of between 0.2 and 0.3. When $C_g = 12$ the evolution of the government, port companies A1, A2 and shipping companies gradually decreases from the initial probability and finally tends to 0. Further, we can specifically judge that, as the cost of government implementation increases, the willingness of the government, port corporations and shipping corporation to promote the application of shore electricity decreases.

Based on the simulation data as well as the evolutionary path diagrams, we begin to further discuss the reasons for the evolution of each subject. From an economic perspective, if the government's cost for promoting shore electricity increases, it may result in insufficient incentives for both the port and the shipping corporation to adopt the shore electricity system. When the government's cost of implementation increases to $C_g = 6$, the willingness of the shipping corporation to modify shore electricity receiving equipment gradually drops to 0. At this time, the probability of both the two port corporations and the government choosing to use shore electricity and implementing the policy fluctuates, eventual leveling off, but the probability is still decreasing. This indicates that, under the current economic and policy environment, port and shipping corporation have no incentive to use or modify the facilities to adapt to the shore electricity.The reason for this phenomenon may be that, as the government's implementation costs rise, it has less funding available to subsidize the adoption of shore electricity systems by port and shipping corporations. Consequently, these companies are left to bear the associated costs, which may be far beyond their willingness or ability to pay. Due to the lack of government support for the use of shore electricity systems, the future economic advantages of using shore electricity are not obvious, and port and shipping corporation cannot get enough returns. The use of other types of energy (e.g., LNG, fuel oil, etc.) is more economical or convenient for shipping corporation. shipping corporation not only needs to take into account the costs associated with modifying their facilities for shore electricity use, but also need to consider the technical complexity and compatibility issues,

TABLE 3 Parameter assignment.

C_g	C_{P_1}	C_{P_2}	C_{S_1}	$P_{E_{A1}}$	$P_{E_{A2}}$	E_{A1}	E_{A2}	γ	β	α	ω_1	ω_2	R
2	5	5	2	5	5	8	8	0.4	0.2	0.2	0.3	0.3	9
$R'_{P_{A1}}$	$R'_{P_{A2}}$	$R_{g_{A1}}$	$R_{g_{A2}}$	$R_{g_{A12}}$	$R'_{g_{A2}}$	$R'_{g_{A12}}$	n	m	a	F_{S_1}	F_{S_2}	F_{S_3}	
10	10	12	12	13	5	3	4	4	0.5	1	3	2	

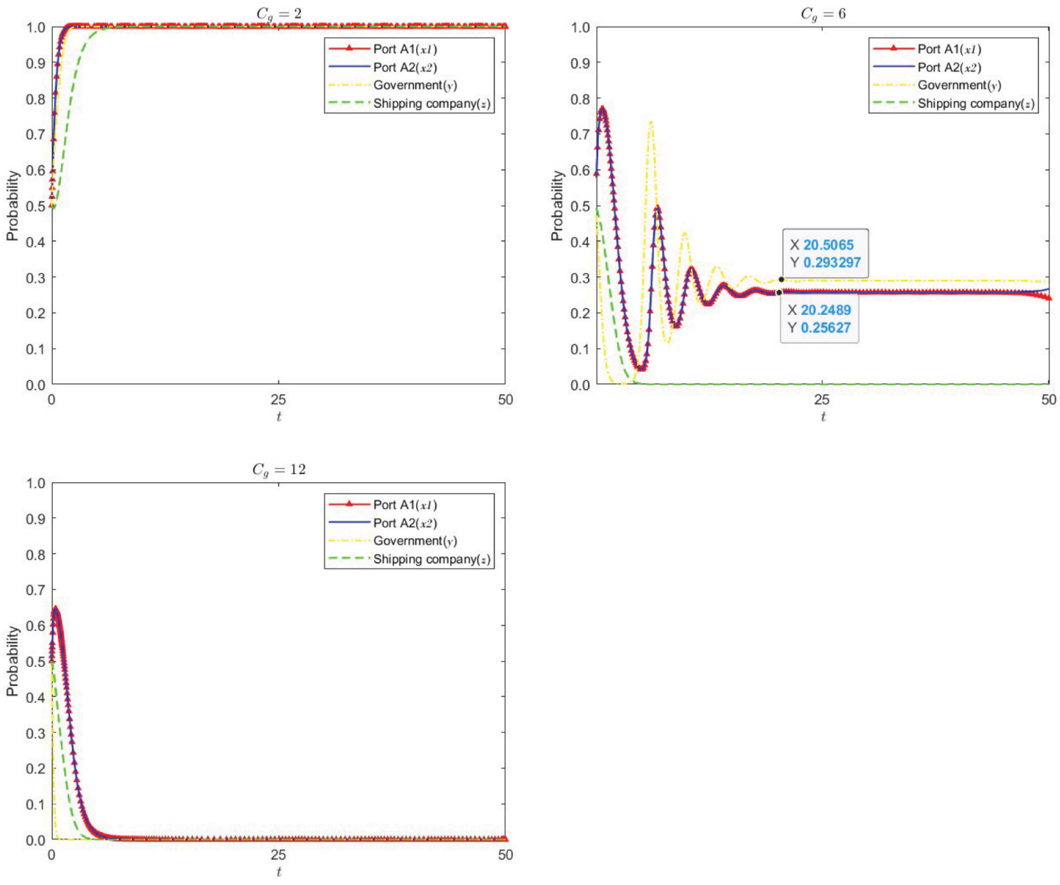

FIGURE 2
The effect of execution expenses of government policies on the evolution of parties' tactics.

as well as the limitations of navigational flexibility after modifying. shipping corporation are more concerned with short-term economic returns. If the government's policy to promote shore electricity is not firm enough or there is uncertainty in the future, shipping corporation may wait for clearer policy signals to emerge and be reluctant to take the lead in making investments. On the contrary, ports as operating entities are more sensitive to cost changes compared to the government. Increased government implementation costs directly increase the operating costs of ports. And during the period of use, ports will conduct an ashore electricityssment of the economic benefits of shore electricity use. It may slow down the rate of adoption if the increase in costs leads to a lower return on investment. In terms of risk management, ports may be more inclined to adopt a conservative strategy to manage risk, which may choose to wait and see or look for alternatives in the event of unclear government policies or rising costs. shipping corporation may place more emphasis on immediate economic benefits and operational flexibility in their decision-making, while ports may need to consider a wider range of policy, environmental and market factors. As a result, when governments increase the cost of promoting of the shore electricity, shipping corporation may respond more quickly and extremely, as indicated by a steeper decline.

In reality, the cost of implementing government policies has a direct impact on the strength and determination of the government to promote shore electricty. Lower implementation costs mean that the government can invest more resources in subsidizing ports and shipping companies, lowering their threshold for adopting shore electricty systems and thus promoting the widespread use of shore electricty technology. For example, the government can use the savings to provide subsidies for equipment purchase, subsidies for construction funding or tax incentives to encourage ports and shipping companies to actively participate in shore electricty projects. On the contrary, a higher implementation cost will limit the government's allocation of funds and may not be able to provide sufficient incentives, resulting in a lack of motivation for ports and shipping companies. For example, in some developing countries or regions, due to limited financial resources, high implementation costs of shore electricty may hinder the effective implementation of the policy and slow down the process of shore electricty promotion.

4.2 Impact of government penalties on port corporations

Setting $P_{E_{A1}}$ 、 $P_{E_{A2}} = \{1, 3, 6\}$. Figure 3 illustrates the strategy evolution process and outcomes for the four parties when port firms pay fee is growing because they fail to use shore electricity.

As can be seen in Figure 3, the extent to which governments penalize port corporations for not using shore electricity affects not only the choice of port company strategy, but also the choice of shipping corporation strategy. Based on the experimental data above, it is concluded that the ship company evolves in a decreasing trend, gradually becoming 0 when $P_E = 1$. The government and port companies A1 and A2 fluctuate up and down over the time horizon t< 30, and the government fluctuates more widely, with an amplitude of 0.862 and an eventual stabilization probability of 0.584. During the evolution process, port companies A1 and A2 reach the steady state faster than the government, reaching stability at t = 26.67, with a final stability probability of 0.113. When $P_E = 3$, the evolution of the government, port companies A1, A2 and shipping companies gradually increases from the initial probability and finally tends to 1. When $P_E = 6$, the evolution of the government, port companies A1, A2 and shipping companies gradually decreases from the initial probability and finally tends to 0. From the simulation results, we can further conclude that the willingness of port companies and shipping lines to use shore electricity is not as strong when penalties are low as it is when penalties are high.

Based on the simulation data as well as the evolution path diagram, we start further discussion to analyze the reasons for the evolution of each subject. When the penalty is low, port corporations may regard the fine as part of the operating costs and don't have a strong incentive to spend a lot of costs to invest in shore electricity systems. The lack of governmental regulation and enforcement makes the port corporations choose to ignore this potential cost and continue to preserve their current mode of operation. Successful use of shore electricity in port operations requires that both the ship and the port have the conditions to use shore electricity, so the port company's failure to use shore electricity will result in the shipping corporation's preference for preserving its current mode of operation. As the government's penalties for port corporations to not implement shore electricity increase, the probability of the government's policy on shore electricity usage increases, the probability of port company A1 and port company A2 choosing to use shore electricity increases, and the probability of the shipping corporation carrying out the modification of the equipments for shore electricity usage increases significantly. Ultimately the four parties stabilize their choice of promoting or applying the shore electricity system. To avoid costly fines, port corporations will choose to either modify their existing facilities for shore electricity or adopt the technology for building new facilities. Higher fines may cause ports to increase regulation of shipping corporation to ensure they comply with regulations to use shore electricity. Therefore the probability of shipping corporation modifying shore electricity receiving equipments increases again. An increase in government fines could serve as a strong incentive for port corporations to take positive action to modify and use shore electricity facilities. This will not only help reduce environmental pollution, but may also bring long-term economic and social benefits.

In actual policy formulation, the level of penalties is an important means of regulating the behavior of port companies. A moderate level of punishment can prompt port companies to incorporate shore electricty use into their operational planning and actively invest in the construction of shore electricty facilities, so as to avoid greater losses due to fines. At the same time, in order to comply with the regulations, port companies will strengthen the supervision of shipping companies and require them to modify shore electricty use facilities, thus promoting the synergistic development of the whole industrial chain. For example, in the ports of some developed countries, strict penalties have prompted port companies to respond positively, not only by accelerating the construction of shore electricty facilities themselves, but also by signing cooperation agreements with shipping companies and other ways to jointly promote the use of shore electricty. However, if the penalty is too high and beyond the affordability of port companies and shipping companies, it may lead to the enterprises facing operational difficulties, or even choosing to withdraw from the market or adopting other evasive measures, which is not conducive to the long-term promotion and sustainable development of shore electricty technology.

4.3 Impact of the size of port corporations

Figure 4 displays the outcomes of the four-party game parties and the strategy evolution process when port companies A1 and A2 have varied sizes.

As can be seen in Figure 4, differences in port company size not only affect the choice of port company strategies, but also it have a more significant impact on the choice of government and shipping corporation strategies. Based on the experimental data above, it is concluded that, when $E_{A1} = E_{A2}$, the government, port companies A1, A2 and shipping companies have the same evolutionary path but different evolutionary stabilization times. The port company and the shipping company converge to a steady state at roughly t=3.516, and the probability of stability converges to 1. The government evolves and stabilizes at roughly t=8.424, and eventually converges to 1, which shows that the government evolves more slowly. When $E_{A1} = 1.8E_{A2}$, the evolution of the port company A1 and the shipping company tends to gradually decrease and eventually converge to 0, and the port company A1 stabilizes at t=1.116 and the shipping company stabilizes at t = 7.238. Government and port company A2 fluctuate up and down, with the frequency of government fluctuations more stable than that of port company fluctuations. It can be seen that the government fluctuates to its first maximum value at t=2.143, which tends to 1, and then begins to decrease gradually, and when t=16.718, the government evolves to its minimum value, which tends to 0. Port Company A2 fluctuates to its maximum value for the first time only at t=18.909, tends to 1, and then immediately begins to decrease. With the simulation results, we can further conclude that larger port corporations have less willingness to use shore electricity, while the probability of smaller port corporations using shore electricity fluctuates up and down over time.

Based on the simulation data as well as the evolution path diagrams, we started to further discuss and analyze the reasons for the evolution of each subject. The fluctuations generated by the two evolutionary path diagrams of this simulation are due to the fact that large-scale port corporations have invested a large amount of money in existing infrastructure. If they proceed with the use of shore electricity at this time, they will face higher sunk costs, which will lead to their decision-making more inclined to maintain the status rather than making large-scale investments. For risk management, large-scale port corporations are more inclined to

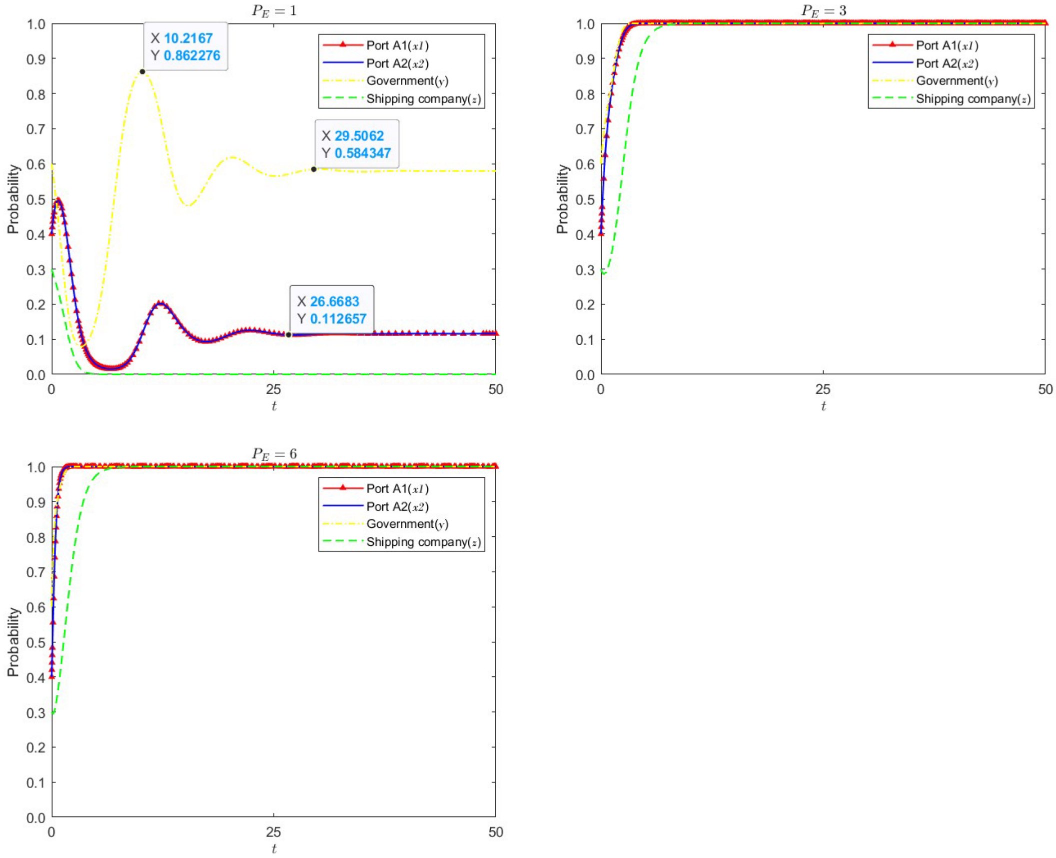

FIGURE 3
Impact of the intensity of government penalties on port corporations on the evolution of each party's strategy.

adopt a conservative risk management strategy, avoiding large-scale investment in the case of high uncertainty. On the other hand, small-scale port corporations are more flexible and can adapt faster to policy changes and market demands. In response to greater competitive pressures, small-scale port corporations may adopt new technologies to gain a competitive advantage, and they are more likely to rely on government subsidies and support due to their small size and small revenues. Government policies on the use of shore electricity are being pursued to promote environmental protection and sustainable development, and these goals fluctuate over time and in the political environment. Thus, the decisions of smaller port corporations also fluctuate over time. Policy changes in larger ports may have a greater impact on shipping corporation, while policies in smaller ports may be more volatile. shipping corporation generally choose to cooperate with larger port corporations in order to load and unload more cargoes and

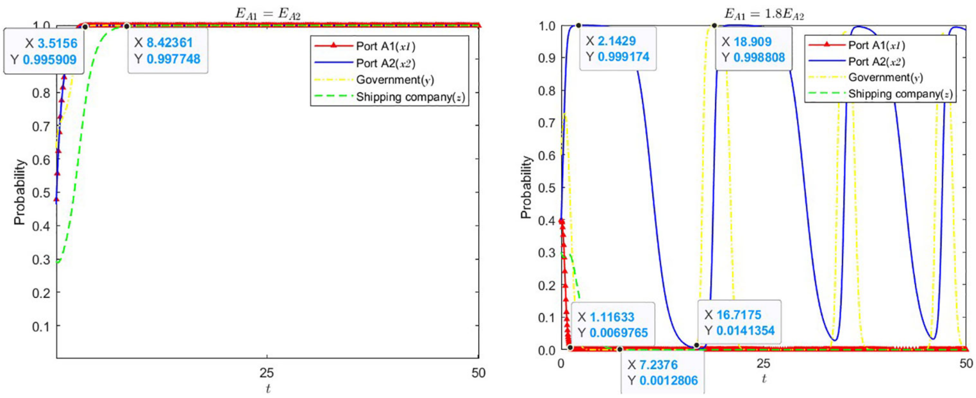

FIGURE 4
Impact of port company size on the evolution of each party's strategy.

obtain higher profits. It usually chooses not to modify their shore electricity receiving equipments and maintain their original mode of operation in order to adapt to the operational requirements of large-scale port corporations.

In reality, differences in port size can lead to different performance in their choice of shore electricty strategies. Large-scale ports usually invest heavily in existing infrastructure and face higher sunk costs, and therefore are more cautious in their decision-making. For new shore electricty technologies, they may be concerned about long payback periods and technology compatibility, and choose to wait and see or move forward slowly. For example, when considering the construction of shore electricty, large hub ports need to comprehensively assess its impact on the entire port operation, including the interface with existing handling equipment and logistics processes. In contrast, small-scale ports are more flexible and can adapt to policy changes and market demand more quickly. When formulating policies to promote shore electricty, the government can adopt differentiated strategies for the characteristics of ports of different scales. For small-scale ports, more technical guidance and financial subsidies can be provided to help them overcome initial investment difficulties and use shore electricty technology to enhance competitiveness; for large-scale ports, policy guidance and communication need to be strengthened to address their concerns in the transition process, such as coordination with long-term strategic planning and impact on the stability of port operations.

4.4 Impact of shore electricity usage costs for shipping corporation.

Setting $F_{S_1} = \{2, 3, 4\}$ When the cost of shore electricity usage of shipping corporation increases, the strategy evolution process and outcomes of the four parties' game subjects are shown in Figure 5.

As illustrated in Figure 5, an increase in the cost of shore electricity usage for shipping corporation will significantly affect the rate at which their undertake to modify their shore electricity receiving equipment. According to the experimental data above, it is concluded that, when $F_{S_1} = 2$, the trend of the evolution path of the quadrilateral subject is the same, both gradually increase, and finally converge to 1, but the evolution speed is different. Port companies A1, A2 and the government stabilize at t=3.111, while shipping companies stabilize at t=7.447, which shows that the government's evolution rate is smaller than that of the ports and shipping companies under the condition of $F_{S_1} = 2$. When $F_{S_1} = 3$, the trend of the evolutionary paths of the four subjects remains the same, and eventually all converge to 1. Port companies A1, A2 and the government stabilize at t = 3.985, while shipping companies stabilize at t = 12.270, and it can be seen that the rate of evolution of the government is still smaller than that of the ports and the shipping companies under the condition of $F_{S_1} = 3$. At the same time, the evolution of the quadrilateral subjects slows down with the increase of the F_{S_1}. When $F_{S_1} = 4$, the port company A1, A2 has the same trend, from the initial probability began to gradually increase,

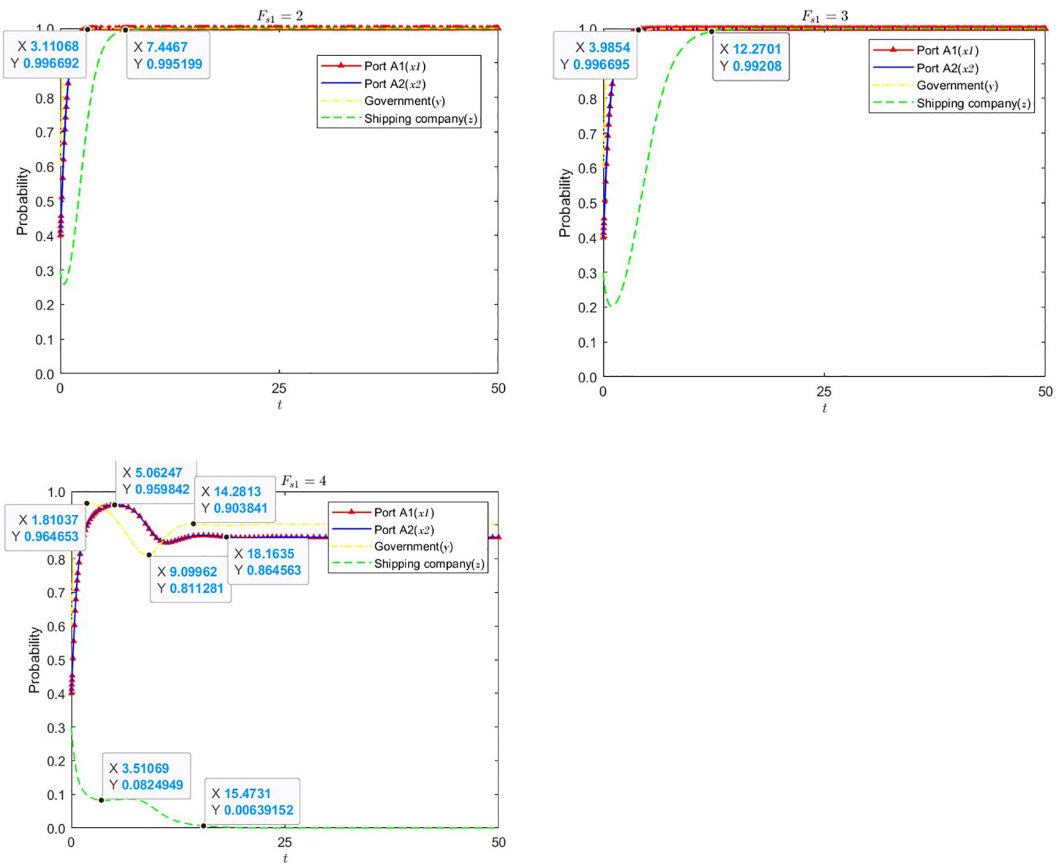

FIGURE 5
Impact of shore electricity usage costs for shipping corporation on the evolution of each party's strategy.

when t=5.063 increased to a maximum value of 0.959, and then gradually began to decrease, and finally when t=18.164 tended to stabilize, the probability of stabilization of 0.865. The government increases to a maximum value of 0.965 at t=1.810, then there is a decreasing trend, decreases to 0.811 and then begins to slowly increase, and finally stabilizes at t=14.281, with a stable value of 0.904. However, the trend of the evolution of shipping companies is opposite to that of ports and governments, with a value of 0.082 for the evolution of port companies at t = 3.511, when it tends to stabilize for a while, then begins to decrease again, and finally stabilizes at t=15.473, with a stabilization value of 0. From the simulation results, we can further conclude that an increase in the shore electricity usage fees of shipping companies affects the evolution paths and evolution speeds of the government, port companies A1, A2, and shipping companies at the same time. And the shipping companies and the government are more sensitive to the changes in the shore electricity usage fees.

Based on the simulation data as well as the evolution path diagrams, we started to further discuss and analyze the reasons for the evolution of each subject. It will also affect the trend in the evolution of government and port company strategies when the cost of shore electricity usage for shipping corporation increases to the point where it exceeds the cost of generating power for the ship's auxiliary engines. The shipping industry is a highly competitive industry. shipping corporation are usually very sensitive to costs, and a high increase in the cost of shore electricity usage may reduce the willingness of shipping corporation to modify. And when shipping corporation choose to invest in the transformation of shore electricity use facilities, they will evaluate the payback period of the investment. An increase in shore electricity use fees means that the time to recover the investment will be extended, which may slow down the transformation speed of the shipping corporation. However, over the long term, the cost of shore electricity usage varies within a certain range. Although it slows down the speed of the shipping corporation's modify, the shipping corporation will still choose to carry out the modify in the end, and the four-party game's main body achieves stability in its tactical evolution. In order to encourage ports and shipping corporation to build and use shore electricity facilities, the government usually takes some incentives. These incentives are very effective in the short term, but its marginal effect may diminish over time. Under the combined impetus of policy guidance, economic incentives, market competition, technological progress, social awareness and regulatory efforts, the government's implementation of shore electricity use policies and the probability of shore electricity use in ports may show a pattern of rising and then falling and eventually stabilizing. The increase of shore electricity use cost of shipping corporation directly affects their financial situation and cost-benefit analysis, so the shore electricity use cost is an important consideration when deciding whether and when to carry out the transformation of shore electricity receiving equipments. Governments and port corporations need to take these factors into account when setting shore electricity usage fees in order to develop a reasonable fee policy that encourages shipping corporation to adopt environmentally friendly technologies rather than being an obstacle to modifyting.

In the shipping industry, shipping companies are highly sensitive to costs, and changes in shore electricty usage fees directly affect their operating costs and investment decisions. A lower shore electricty usage charge is conducive to attracting shipping companies to retrofit their equipment and use shore electricty, thus promoting the popularization of shore electricty technology. Governments and port companies need to weigh the interests of all parties when formulating policies on shore electricty usage fees. If the fee is too high, shipping companies may reduce the use of shore electricty due to the increase in cost, affecting the utilization rate of shore electricty facilities and environmental benefits of ports. For example, in some highly competitive shipping markets, shipping companies may choose lower-cost energy supply options and forego shore electricty. Therefore, the government can reduce the cost of shore electricty usage by shipping companies through subsidies and tax incentives, or cooperate with port companies to optimize the shore electricty supply system to improve efficiency and reduce costs, so as to improve the competitiveness of shore electricty in the shipping market. At the same time, with technological progress and the emergence of scale effects, gradually reducing the cost of shore electricty use will help to form a sustainable shore electricty development model.

4.5 Summary

The results of the simulation analysis for the above four cases have been compared as shown in the following Table 4.

4.6 Particular options or tactics

(1) Government

A. Implement a policy for the use of shore electricity: Governments can promote the use of shore electricity by developing incentive policies. This includes providing incentives such as subsidies and tax breaks to port companies that adopt shore electricity systems. In addition, governments can legislate to mandate the use of shore electricity for certain types of ships or ships in specific areas.

B. Increase penalties: The government can increase the amount of fines for port companies that do not adopt shore electricity systems as a deterrent for these companies to change their strategies.

(2) Port Companies

A. Active implementation of shore electricity: Port companies may choose to invest in shore electricity facilities and actively participate in the shore electricity network. This will not only improve the environmental image of the port, but also bring new sources of income to the port, e.g. by providing shore electricity services to ships calling at the port.

B. Cooperation with shipping companies: Port companies can cooperate with shipping companies to share the cost of the shore electricity system and share the resulting economic benefits.

TABLE 4 Comparison table of four simulation cases.

Factor	Evolution	Evolutionary trend	The Reality Revealed
Costs of implementing government policies	C_g rise	Shipping companies fall first, governments and port companies fluctuate and then decline	Rationalize implementation costs to ensure adequate resources to incentivize ports and shipping lines; develop a phased policy based on the financial situation
Government penalties for port companies	Increase in fines	Parties fluctuate and shipping companies decline with low fines; parties tend to be positive with moderate fines; parties tend to be negative with high fines	Setting appropriate penalties to balance deterrence with affordability; strengthening regulation to ensure penalties are enforced
Size of port	Difference in size (E_{A1} and E_{A2})	Same evolutionary path but different speeds for the same size; large-scale ports (A1) are negative and small-scale ports (A2) are volatile	Developing policies for scale differences to help small-scale ports start shore power projects; guiding large-scale ports to overcome transition difficulties
Ship companies's shore power usage costs	F_{s1} rise	Four-way evolution slows down, shipping companies are sensitive, strategy changes when costs are high	Optimize fee policy and subsidize cost reduction for shipping companies; cooperate to improve shore power supply efficiency and promote long-term cost reduction

(3) Shipping companies

A. Modification of equipment for use of shore electricity: Shipping companies can choose to modify the equipment on their ships to adapt to the shore electricity system, thus reducing the reliance on auxiliary power generation during port operations and lowering fuel consumption and emissions.

B. Selection of partners: In selecting ports of call, shipping companies may consider ports that have adopted or are willing to adopt shore electricity systems in order to take advantage of the shore electricity services provided by these ports.

5 Conclusions and insights

5.1 Conclusions

This artical builds a four-party evolutionary game model based on the government, two homogeneous port corporations, and shipping corporation. It is concluded as follows:

(1) This paper constructs a four-party evolutionary game model, clarifies the strategic choices and probabilities of each party, and derives a benefit matrix and 16 equilibrium points. By analyzing the impacts of the stabilization points, it is found that the environmental benefits are greatest at E12(0,1,1,1).

(2) Shore electricity development through three stages of five stable period, the initial high cost of promotion is difficult, the government incentives under the port shipping companies to get the economic benefits of active use, the market matures after the formation of a stable use of the system.

(3) Cost payments influence the speed of choice of shore electricity strategies, with parties setting appropriate standards for high returns, ports cooperating to take on high investments in the absence of policy, and shipping companies retrofitting facilities to maximize environmental benefits.

(4) There is a great potential for the development of shore electricity in small ports. The government can focus its support on realizing the objectives of environmental efficiency and cost-effectiveness, as well as enhancing competitiveness and social responsibility. Reasonable government policies and effective communication and coordination with all parties are needed.

5.2 Limitations and research directions

5.2.1 Research limitations

This paper's fundamental research can be applied to various fields. Unlike earlier research on energy conservation and reducing emissions from shore electricity, this paper chooses an evolutionary game model with four players, which has spanning extensibility, and the selection of multi-party game subjects is more relevant to reality. But there are limitations.

The research object of this paper is the government, two homogeneous port companies and shipping companies, which may ignore the influence of other stakeholders. In practice, shore electricity strategy choices may also be influenced by other stakeholders, such as environmental organizations and energy suppliers. This may result in the model not fully capturing all key factors. The model may focus too much on the static analysis of decisions at a given moment in time and neglect the dynamic decision-making process over time. This may affect the understanding of long-term strategy changes. However, real-world decisions are often accompanied by uncertainty and risk, and the model may fail to adequately consider the impact of these factors on strategy choice.

5.2.2 Directions for future research

When studying the shore electricty system, key stakeholders other than the government, port companies and shipping companies, such as environmental organizations, energy suppliers, residents of the surrounding communities, ship manufacturers, etc., can be precisely identified by applying stakeholder analysis and other methods. Detailed analysis of each stakeholder's core interests, concerns, motivations, and potential impacts will clarify their roles in the ecology of shore electricty strategy selection, e.g., environmental organizations may consider carbon emission reduction as their primary goal, while residents in the surrounding communities are more concerned about the impacts of the construction of shore electricty facilities on their living environments. In analyzing the evolutionary game among the government, port companies and shipping companies in the selection of shore electricity strategies, in addition to the use of evolutionary game theory models, other models or methods can be considered to enhance the depth and breadth of the study. Consider specific steps for merging other stakeholders or alternative modeling techniques (e.g., merging stochastic elements or agent-based modeling). Conduct a comprehensive sorting and in-depth analysis of the various types of uncertainties that exist in the process of selecting shore electricty strategies, and accurately identify the main sources of stochastic elements, such as the uncertainty of governmental policy adjustments (including the frequency of changes in subsidy policies, the magnitude of adjustments in tax incentives, etc.), and the stochastic fluctuations in the costs of port companies and shipping companies. Models or methods such as system dynamics models or optimization algorithms can be used. Although the system dynamics model has been used in the paper to construct a four-party evolutionary game model, the model can be further refined by adding more feedback loops and delay links to simulate more complex dynamic behaviors. For example, the long-term effects of policy changes on the behavior of the parties can be studied, or how technological advances affect the economic efficiency of the shore electrivity system can be analyzed. For the problem of finding an optimal policy, mathematical optimization algorithms (e.g., linear programming, nonlinear programming) can be used to solve for the optimal solution under specific constraints. This can help determine how to allocate investments in shore electricity facilities to maximize environmental benefits under given resource constraints.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

XS: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. SZ: Conceptualization, Formal analysis, Funding acquisition, Investigation, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

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