

Article

Promoting Shore Power Adoption: An Evolutionary Game Analysis Considering Wind Power Heterogeneity and Policy Instruments

Mengru Yuan ¹, Xin Xu ¹, Bingjie Yang ² and Dongxu Chen ^{1,*}

¹ Faculty of Maritime and Transportation, Ningbo University, Ningbo 315211, China; 2411120137@nbu.edu.cn (M.Y.); 246001690@nbu.edu.cn (X.X.)

² Ningbo Development Planning Research Institute, Ningbo 315040, China; nbybj6813@126.com

* Correspondence: chendongxu1@nbu.edu.cn

Abstract

The promotion of shore power is a key pathway for reducing port-related emissions and achieving sustainable maritime development. This study analyzes the strategic interactions among governments, ports, and shipping companies by constructing a tripartite evolutionary game model. Specifically, it addresses three core questions: (1) how stakeholders' initial intentions and strategic choices influence the system's evolutionary path and eventual equilibrium; (2) how critical parameters—including subsidies for shore power infrastructure, wind turbine installation, and ship retrofitting, as well as electricity price support, carbon pricing, and policy implementation costs—shape the dynamics of the system and the equilibrium strategies of the three parties; and (3) how heterogeneity in national energy mixes, particularly the roles of wind turbine, affects decision-making behaviors across different countries. Simulation experiments are conducted to explore the effects of varying policy interventions and energy conditions on the stability of cooperative strategies. The results provide insights into the design of differentiated policy instruments that promote shore power adoption while accounting for the structural characteristics of national energy systems. This research enriches the theoretical application of evolutionary game theory to maritime sustainability and offers practical guidance for governments and stakeholders in advancing decarbonization in the port and shipping sectors.

Keywords: shore power; wind power; evolutionary game; subsidy policy; carbon trading policy

Academic Editor: Hua Li

Received: 29 December 2025

Revised: 4 February 2026

Accepted: 6 February 2026

Published: 9 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The decarbonization of the maritime sector has become an urgent global priority. The greenhouse gas (GHG) emissions of total shipping have increased from 977 million tons in 2012 to 1076 million tons in 2018 (9.6% increase). The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018. Emissions are projected to increase from about 90% of 2008 emissions in 2018 to 90–130% of 2008 emissions by 2050 under the business as usual (BAU) scenario [1]. Ports and coastal regions are particularly affected by ship emissions, which not only exacerbate climate change but also contribute to local air pollution, threatening human health and regional

sustainability [2]. Among the available mitigation measures, the adoption of shore power—supplying ships with electricity while at berth—has been recognized as a promising approach to reduce reliance on fossil fuel-based auxiliary engines and achieve substantial emission reductions [3]. However, the large-scale promotion of shore power is constrained not only by retrofitting costs but also by policy and market uncertainties, such as electricity price volatility and the need for coordinated multi-instrument support (e.g., subsidies, electricity price support, and carbon pricing) [4].

Existing research on shore power has largely focused on technological feasibility, cost–benefit analysis, and policy evaluation. For example, studies have examined the economic viability of port-side power facilities, the environmental benefits of replacing marine fuel with grid electricity, and the effectiveness of subsidies and carbon pricing in supporting adoption. While these studies provide valuable insights, they often rely on static analysis and fail to capture the dynamic strategic interactions among governments, ports, and shipping companies. In practice, stakeholders continuously adjust their strategies in response to policy interventions, cost changes, and market signals. This adaptive process, shaped by bounded rationality and learning over time, requires a dynamic analytical framework to better understand the conditions under which cooperative strategies emerge and persist.

Evolutionary game theory provides a suitable approach to model such interactions [5], as it incorporates the adaptive behaviors of stakeholders, the role of initial intentions, and the impact of varying policy parameters. By applying this framework, it becomes possible to investigate how subsidies for shore power infrastructure, wind power development, ship retrofitting, and electricity pricing—as well as carbon pricing and policy implementation costs—influence the strategic evolution of stakeholders. Moreover, wind power provides a cleaner electricity supply for shore power systems in many ports, thereby substantially enhancing the emission-reduction benefits of shore power. For example, ports such as Stockholm in Sweden [6], Rotterdam in the Netherlands [7], and Seattle in the United States [8] use wind-generated electricity to supply shore power, enabling berthed ships to replace onboard fuel-based generation with a lower-carbon alternative. However, given the diversity in national energy systems, particularly the varying roles of wind power and oil industries and differences in electricity generation structures, cross-country heterogeneity must also be considered to provide realistic and context-specific policy implications.

This paper aims to address three central research questions: (1) how do stakeholders' initial intentions and strategy choices affect the evolutionary trajectory and final equilibrium of the system? (2) How do critical policy parameters—such as different types of subsidies, carbon pricing, and policy costs—shape the strategic evolution of governments, ports, and shipping companies? (3) How do variations in national energy mixes and industry structures influence the decision-making processes of the three parties?

To answer these questions, we construct a tripartite evolutionary game model, conduct simulation analyses, and provide policy recommendations tailored to differentiated national contexts. The key innovation of this study lies in integrating wind-power spillover effects and carbon-pricing synergy mechanisms into a unified tripartite evolutionary game framework, thereby elucidating how heterogeneity in energy structures influences the mechanisms driving shore power promotion.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 develops the tripartite evolutionary game model. Section 4 presents simulation experiments and results. Section 5 concludes with key findings and policy implications.

2. Literature Review

This section reviews two categories of literature: (1) studies related to shore power; (2) the government's carbon trading policies.

2.1. Studies Related to Shore Power

Against the backdrop of the global shipping industry's green transition, shore power, as a key emission reduction technology [9], has attracted widespread attention. Relevant studies have been continuously advanced around its environmental benefits, economic benefits, and the impact of promotion policies. The following is a detailed review of the existing literature.

Yin et al. [10] pointed out that the use of shore power not only reduces carbon emissions but also generates considerable social and economic benefits. It is estimated that the use of shore power can reduce the emissions of SO₂, NO_x, and PM_{2.5} during the period when ships berth at ports, with annual reductions of 6.0 tons, 11.0 tons, and 0.8 tons, respectively [11]. The promotion of shore power systems relies on complex interactions and strategic choices among three core entities: governments, ports, and shipping companies. Small-scale ports hold significant potential for the development of shore power. Governments can focus on supporting small-scale ports to achieve the dual goals of environmental benefits and cost-effectiveness, while enhancing the ports' competitiveness and social responsibility [12]. To standardize the implementation of ship shore power, the government should guide shipowners and ports to sign cooperation agreements in order to enhance their willingness to use it [13]. For ports and shipping companies, large-scale reconstruction requires investments that cannot be recovered in the short term. The more subsidies the government provides to ports and shipping companies for the renovation of shore power facilities, the faster these ports and shipping companies can recover their costs [10]. The proportion of shore power deployment is affected by the government's subsidy rates for renovation costs, electricity fees, and operating costs. When formulating subsidy policies, priority should be given to subsidizing operating costs such as electricity fees, followed by subsidizing renovation costs [14]. Wu and Wang [15] constructed a shore power deployment model which indicates that the dynamic adjustment of subsidy policies (such as the withdrawal mechanism) must be coordinated with market-based policies like carbon pricing; otherwise, it will severely weaken ports' willingness to invest. Furthermore, stakeholder cooperation and the combined tool of tax and subsidy are crucial for enhancing policy effectiveness and accelerating maritime decarbonization, and they hold practical significance for the development of green ports and the low-carbon transition of the shipping industry [16]. Peng et al. [17], by comparing facility investment subsidies with shore power usage price subsidies, revealed the differential impacts of different subsidy methods on the decision-making of various stakeholders, providing an important basis for the government to optimize the subsidy structure.

From a macro perspective, the national energy structure exhibits significant heterogeneity. In particular, the penetration rate of renewable energy, such as wind power and the carbon intensity of the power grid, are important factors that determine the environmental benefits and economic feasibility of shore power, thereby profoundly influencing the strategic space of various game players. Merkel et al. [18] clearly pointed out in their research that in regions with a high proportion of renewable energy, the emission reduction advantages and cost competitiveness of shore power are more prominent. Daniel et al. [19] further confirmed through a case study on the St. Lawrence River and the Great Lakes region, where the regional electricity price level and power structure directly affect the competitive advantage of shore power compared with traditional fuel oil. Furthermore, the energy context also shapes the interaction patterns among entities. The port competition model in Lu et al. [20] indicates that a clean power structure must be paired

with a tiered electricity pricing policy to effectively address the risks posed by fuel price fluctuations.

In terms of methodology, evolutionary game theory is widely applied to the study of large-scale interactive systems and the analysis of individual behavioral strategies in complex systems [21]. As it can effectively simulate the dynamic learning process of bounded rationality agents, it has become a key tool for analyzing such problems. Chacoma et al. [22] proposed an evolutionary game whose dynamic rules are derived from field observations of human behaviors driven by social imitation and confidence. Finally, they studied the impact of this characteristic on dynamics through numerical analysis. Evolutionary game theory replaces the assumption of perfect rationality with a dynamic framework and achieves equilibrium through iterative strategy adjustment and learning. This theory has unique advantages in addressing long-term equilibrium challenges in economics, management, social sciences, and engineering [23].

In evolutionary game research, some studies have moved beyond treating the energy system as an exogenous background and have incorporated energy structure characteristics directly into game-theoretic frameworks to capture the internal mechanisms of strategic evolution during energy transition processes. Qiao and Yin [24] distinguished between conventional and clean energy options within an evolutionary game model and incorporated agents' perceptions of costs, benefits, and risks associated with alternative energy choices into the strategy evolution mechanism, showing that substitution relationships among energy use patterns can influence the evolutionary path and stability of transitions from high-carbon to low-carbon energy structures. Wang et al. [25] introduced the shares of coal and clean energy in energy consumption into replicator dynamic analysis and demonstrated that changes in energy structure proportions can alter the stability and evolutionary direction of the game system. Furthermore, in the context of port decarbonization and shore power promotion, Zhang and Song [26] incorporated power supply actors together with key electricity-side parameters, including electricity prices and investment costs, into a multi-agent evolutionary game framework, indicating that the evolutionary outcomes of low-carbon technologies such as shore power largely depend on the structure and economic characteristics of the power supply system.

To summarize, despite the progress made in existing studies, there are still obvious limitations. Firstly, the setting of key parameters in most game models remains relatively static. Secondly, there is a lack of in-depth analysis on how global policies (such as IMO carbon regulations) synergize with local subsidies and electricity pricing policies to influence the tripartite game. In view of this, it is necessary to construct a more dynamic evolutionary game model and explore the synergy mechanism of multi-level policies. Therefore, this study will systematically analyze the impact of key parameters, such as wind power subsidies, carbon pricing, and government policy costs, on the development of shore power by constructing a tripartite evolutionary game model.

2.2. Government's Carbon Trading Policies

Against the backdrop of the increasingly severe global warming, promoting green and low-carbon development has become an urgent need for countries around the world. As a means of promoting carbon emission reduction through market mechanisms, carbon trading policies are gradually becoming a key policy tool for the global response to climate change, and numerous scholars have conducted extensive and in-depth research on their effectiveness, implementation status, and other aspects. For instance, Natalia Gonzalez et al. [27] pointed out that power systems around the world are undergoing tremendous changes, and countries are making efforts to reduce carbon emissions to address climate change. Carbon trading policies can effectively achieve carbon emission reduction [28,29] and have been widely implemented in different countries and regions [30]. The European

Union Emissions Trading System (EU-ETS), officially implemented in 2005, is recognized as the world's first and largest international carbon allowance trading platform. The EU-ETS covers more than 40% of the European Union's total emissions [31,32]. In China, Cheng et al. [33] assessed the impact of carbon trading policies on the reduction of air pollutant emissions in Guangdong Province, and found that the Emissions Trading System (ETS) can not only significantly reduce greenhouse gas emissions, but also lower emission reduction costs. Zhang et al. [34] extended their research to multiple provinces in China and found that the implementation of the ETS could reduce carbon emissions in pilot provinces by 24.2%, which proves that the ETS remains important for achieving carbon emission reduction. In terms of maritime shipping, in September 2020, the European Union decided to include the maritime shipping industry in the EU-ETS [35]. It also decided that starting from 2022, all CO₂ emissions from voyages within Europe and 50% of CO₂ emissions from voyages outside Europe would be incorporated into the EU-ETS to reduce CO₂ emissions [36]. Many scholars have also explored the application of carbon trading policies in the field of maritime shipping. Chua et al. [37] explored the impact of carbon trading policies on the fleet deployment decisions of liner companies, constructed a carbon emission model, and analyzed the effects of different policy parameters on emission reduction outcomes and stakeholders. Zhu et al. [38] analyzed the carbon allowance allocation strategy among shipping companies under the carbon trading policy through a bi-level model, and revealed the impact of carbon prices and emission reduction costs on emission reduction performance and economic benefits.

Existing studies mostly treat carbon trading policies as isolated factors and fail to systematically reveal how they affect the dynamic strategic interactions among the three subjects—governments, ports, and shipping companies—when they synergize with other government intervention measures such as shore power infrastructure subsidies and wind power support. In particular, the effectiveness of carbon trading policies is inevitably profoundly influenced by the national energy structure, yet this critical dimension is often overlooked in existing game analyses. Existing game models largely ignore the dynamics of energy-structure shifts and policy interactions, and overlook the timing of three-party strategic moves.

Therefore, this study aims to construct a tripartite evolutionary game model involving governments, ports, and shipping companies, focusing on exploring how carbon trading policies can generate synergistic effects with policy tools such as subsidies and electricity price support, and conducting an in-depth analysis of the regulatory role of different national energy structures in this interaction process. This research will provide a theoretical basis and decision-making support for governments to design shore power promotion policies in specific energy contexts.

3. A Tripartite Evolutionary Game Model

3.1. Problem Description

The promotion of shore power faces significant challenges, primarily due to the installation of ship power reception equipment and the simultaneous construction of supporting shore power facilities at ports, both of which require substantial financial investment. As a result, port enterprises and shipping companies often lack sufficient incentives in practical implementation. Throughout this process, stakeholders aim to maximize their own interests, displaying bounded rationality, and dynamically adjust their decisions based on the observed strategies of others, eventually converging towards a strategic equilibrium. Consequently, a complex game-theoretic relationship is formed among the government, port enterprise, and ship company, as depicted in Figure 1.

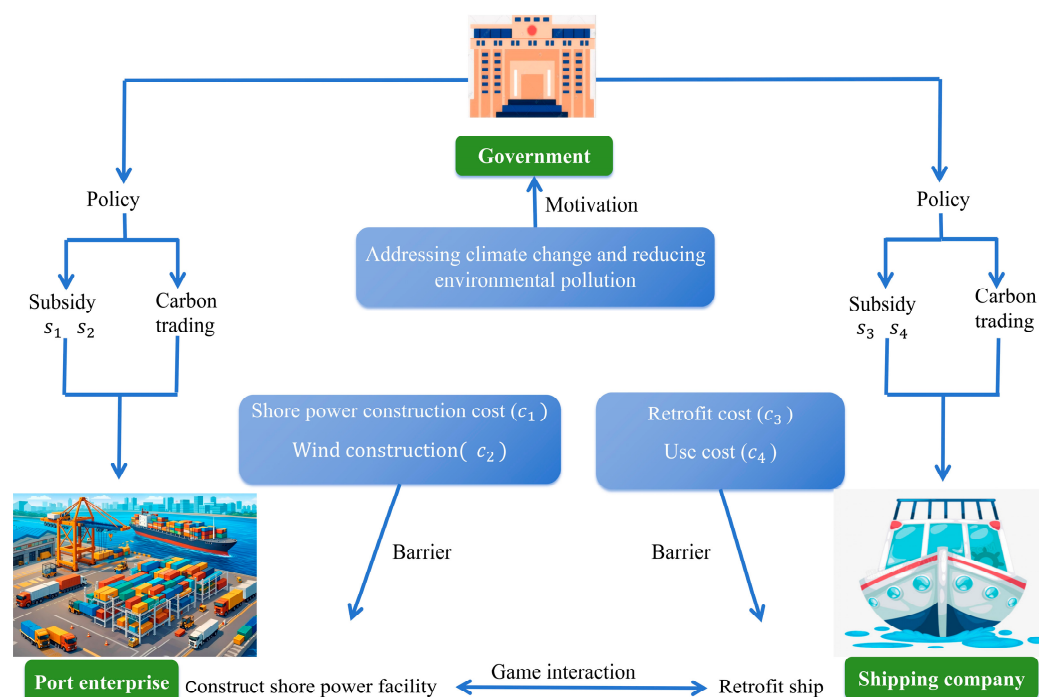


Figure 1. Strategic game relationships among the government, port enterprise, and shipping company.

As can be seen from Figure 1, driven by their own self-interest considerations, port enterprises and shipping companies are generally unwilling to voluntarily assume emission reduction responsibilities and thus exhibit low enthusiasm for the use of shore power. However, when the government implements a carbon trading scheme and provides construction subsidies for shore power facilities and wind turbine constructions to ports, with subsidy amounts denoted by s_1 and s_2 , as well as retrofit subsidies and electricity price subsidies to ships, with subsidy amounts denoted by s_3 and s_4 , these external incentive mechanisms significantly affect the strategic choices of all parties, adding significant uncertainty to their strategic decisions. In addition, in their decision-making processes, port enterprises and shipping companies must comprehensively consider multiple factors, including the cost of shore power facilities construction, the strength of government subsidies, and the national power supply situation, in order to decide whether to promote the application of shore power systems. Similarly, when formulating relevant policies, the government must weigh the costs of policy implementation, the social and environmental benefits brought by the promotion of shore power and wind turbines, and the potential impact on the traditional oil industry, so as to determine whether to strongly promote the development of shore power. On this basis, this paper employs evolutionary game theory to construct a tripartite strategic evolution model involving the government, port enterprises, and shipping companies, and conducts an in-depth analysis of the dynamic adjustment of their strategies under different policy conditions and market environments, with a view to further advancing the adoption of shore power.

3.2. Model Assumption

Assumption 1. This model comprises three types of agents: the government, port enterprises, and shipping companies. All three parties are boundedly rational decision-makers who act primarily to maximize their own interests.

Assumption 2. In terms of strategy choice, the probability that the government adopts the “implementation” strategy is x , while the probability of adopting the “non-implementation” strategy is $1-x$; the probability that port enterprises adopt the “construction” strategy is y , while the probability of adopting the “non-construction” strategy is $1-y$; and the probability that shipping companies adopt the “retrofitting” strategy is z , while the probability of adopting the “non-retrofitting” strategy is $1-z$.

Assumption 3. In real-world decision-making, each stakeholder can hardly fully grasp the true cost and benefit structures of other parties, as well as key external environmental parameters (e.g., policy enforcement intensity, carbon prices, and subsidy levels). Therefore, this study assumes that stakeholders operate under conditions of incomplete information: they can observe only limited available information and, on this basis, choose and update their strategies dynamically.

3.3. Parameter Specification

The model variables and their explanations are shown in Table 1.

Table 1. Parameter specification and interpretation.

	Parameters	Interpretation
Government	g_0	Initial revenue of the government
	R_0	The benefits generated when the government implements the policy and both the port and ships use shore power
	R_1	The benefits generated when the government does not implement the policy but both the port and ships use shore power
	c_0	The cost of government policy implementation
	s_1	The annualized subsidy for shore power facilities construction
	s_2	The annualized subsidy for the construction of wind turbine power generation systems
	s_3	The annualized subsidy for ship retrofitting
	s_4	The annualized subsidy for shore power electricity prices
	M	The direct benefits generated for the government by the development of wind turbine power generation systems
	N	The losses incurred by the national oil industry due to the development of shore power and wind turbine power generation systems
	ρ	Wind turbine spillover benefit coefficient
	θ	Oil substitution loss coefficient
Port enterprise	P_c	Carbon trading market price
	P_0	Initial revenue of the port
	P_1	The benefits accruing to the port when ships use shore power
	c_{p1}	Annualized construction cost of shore power
	c_{p2}	Annualized construction cost of wind turbine power generation systems
	σ	Power supply interruptions frequency
	W_1	Each power outage's economic loss to the port
	B_0	Initial revenue of the ship

Shipping company	c_{s1}	Annual retrofit cost of the ship
	c_{s2}	Annual electricity cost for ships utilizing shore power
	c_{s3}	Annual fuel cost of the ship
	W_2	Each power outage's economic loss to the shipping company
	Q_1	Annual carbon emission reduction of the shore power system
	Q_2	Annual carbon emission reduction of the wind power generation system
	Q_3	Annual carbon emission reduction of the ships
	$x, 1-x$	Probability of implement or no implement; $0 \leq x \leq 1$
	$y, 1-y$	Probability of construction or no construction; $0 \leq y \leq 1$
	$z, 1-z$	Probability of retrofit or no retrofit; $0 \leq z \leq 1$

3.4. Tripartite Evolutionary Game Model

Using the model parameters mentioned above, this study developed a payoff matrix involving a three-party game among the government, port enterprises, and shipping companies, as shown in Table 2. To facilitate understanding, a numerical example for the payoff-matrix cell (Government Implementation–Port Construction–Shipping Retrofit) is provided in Appendix A.

3.4.1. Government

The expected revenue under the government implementation of the policy is U_x . The expected revenue under the non-implementation of the policy is $U_{(1-x)}$. The average expected utility is $\bar{U}_x$.

$$U_x = yz(g_0 + R_0 + \rho M - \theta N - c_0 - s_1 - s_2 - s_3 - s_4) + y(1-z)(g_0 + \rho M - c_0 - s_1 - s_2) + z(1-y)(g_0 - c_0 - s_3) + (1-y)(1-z)(g_0 - c_0) \quad (1)$$

$$U_{(1-x)} = yz(g_0 + R_1 + M - N) + y(1-z)(g_0 + M) + z(1-y)(g_0) + (1-y)(1-z)(g_0) \quad (2)$$

$$\bar{U}_x = xU_x + (1-x)U_{(1-x)} \quad (3)$$

The government's replication dynamic equation is:

$$F(x) = x(x-1)(c_0 + yM + ys_1 + ys_2 + zs_3 - y\rho M - yzN - yzR_0 + yzR_1 + yzs_4 + yz\theta N) \quad (4)$$

The detailed derivation of the replicator dynamic equation is provided in Appendix B.

In the stability analysis of dynamic systems, if the equilibrium point of the system satisfies the equation $F(x) = 0$, the stability of this equilibrium point can be ensured by also satisfying the condition that its first derivative $F'(x) < 0$. From $F(x) = 0$, it can be

inferred that $x = 0$, $x = 1$, $y = y_0 = \frac{c_0 - zs_3}{M + s_1 + s_2 - \rho M - zN - zR_0 + zR_1 + zs_4}$. Tak-

ing the derivative of $F(x)$ yields:

$$F'(x) = (2x-1)(c_0 + yM + ys_1 + ys_2 + zs_3 - y\rho M - yzN - yzR_0 + yzR_1 + yzs_4 + yz\theta N) \quad (5)$$

Table 2. Three-party payoff matrix.

				Government	
				Implement (x)	Not-Implement ($1 - x$)
Port enterprise	Construction (y)	Shipping company	Retrofit (z)	$g_0 + R_0 + \rho M - \theta N - c_0 - s_1 - s_2 - s_3 - s_4$ $P_0 + P_1 - c_{p1} - c_{p2} + s_1 + s_2 - \sigma W_1 + P_c(Q_1 + Q_2)$ $B_0 - c_{s1} - c_{s2} + s_3 + s_4 - \sigma W_2 + P_c Q_3$	$g_0 + R_1 + M - N$ $P_0 + P_1 - c_{p1} - c_{p2} - \sigma W_1 + P_c(Q_1 + Q_2)$ $B_0 - c_{s1} - c_{s2} - \sigma W_2 + P_c Q_3$
			Not-retrofit ($1 - z$)	$g_0 + \rho M - c_0 - s_1 - s_2$ $P_0 - c_{p1} - c_{p2} + s_1 + s_2$ $B_0 - c_{s3}$	$g_0 + M$ $P_0 - c_{p1} - c_{p2}$ $B_0 - c_{s3}$
	Not-construction ($1 - y$)	Shipping company	Retrofit (z)	$g_0 - c_0 - s_3$ P_0 $B_0 - c_{s1} - c_{s3} + s_3$	g_0 P_0 $B_0 - c_{s1} - c_{s3}$
			Not-retrofit ($1 - z$)	$g_0 - c_0$ P_0 $B_0 - c_{s3}$	g_0 P_0 $B_0 - c_{s3}$

When $y = y_0$, $F(x) = 0$ and all xx are evolutionarily stable strategies. When $y \neq y_0$, let $H(y) = c_0 + yM + ys_1 + ys_2 + zs_3 - y\rho M - yzN - yzR_0 + yzR_1 + yzs_4 + yz\theta N$, so $\frac{\partial H(y)}{\partial y} = M + s_1 + s_2 - \rho M - zN - zR_0 + zR_1 + zs_4$;

(1) $\frac{\partial H(y)}{\partial y} = M + s_1 + s_2 - \rho M - zN - zR_0 + zR_1 + zs_4 > 0$ and $H(y)$ is an increasing function of y :

(a) When $y > y_0$, $H(y) > 0$, $F(x)|_{x=0} = 0$, $F'(x)|_{x=0} < 0$; therefore, $x = 0$ is a stable state.

(b) When $y < y_0$, $H(y) < 0$, $F(x)|_{x=1} = 0$, $F'(x)|_{x=1} < 0$; therefore, $x = 1$ is a stable state.

(2) $\frac{\partial H(y)}{\partial y} = M + s_1 + s_2 - \rho M - zN - zR_0 + zR_1 + zs_4 < 0$ and $H(y)$ is a decreasing function of y :

(a) When $y > y_0$, $H(y) < 0$, $F(x)|_{x=1} = 0$, $F'(x)|_{x=1} < 0$; therefore, $x = 1$ is a stable state.

(b) When $y < y_0$, $H(y) > 0$, $F(x)|_{x=0} = 0$, $F'(x)|_{x=0} < 0$; therefore, $x = 0$ is a stable state.

Based on the above analysis, the phase diagram of government strategy evolution can be obtained, as shown in Figure 2. In Figure 2, the arrows indicate the evolutionary trend of strategies, and the region enclosed by the dashed lines represents a stable state where any strategy combination on this curved surface remains stable.

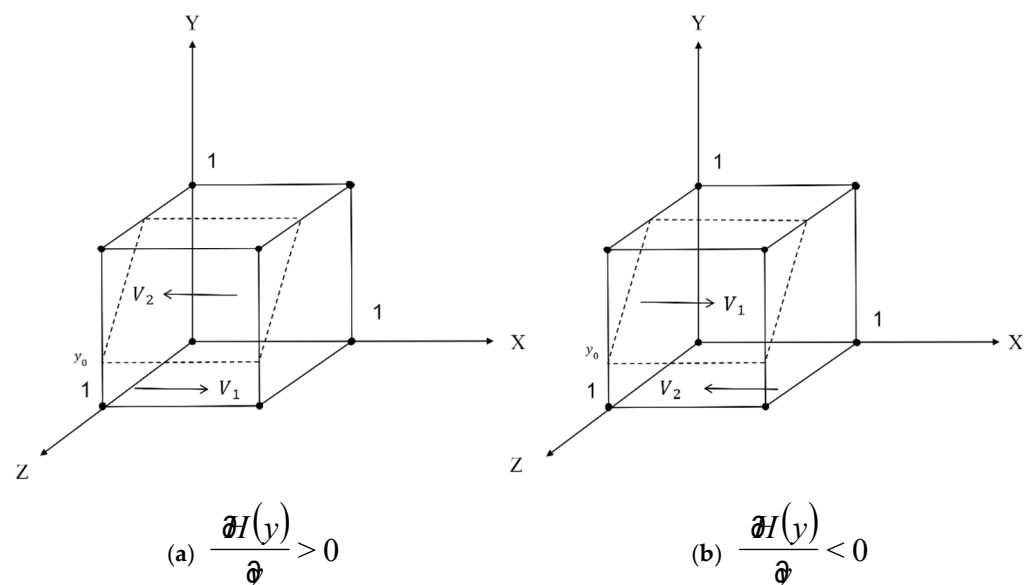


Figure 2. The strategy phase diagram of government.

3.4.2. Port Enterprise

Assuming the expected revenue for port enterprises when constructing shore power is U_y , and the expected revenue when not constructing shore power is $U_{(1-y)}$, the average expected utility is $\bar{U}_y$. Therefore,

$$U_y = xz(P_0 + P_1 + s_1 + s_2 - cp_1 - cp_2 - \sigma W_1 + Pc(Q_1 + Q_2)) + x(1-z)(P_0 + s_1 + s_2 - cp_1 - cp_2) + z(1-x)(P_0 + P_1 - cp_1 - cp_2 - \sigma W_1 + Pc(Q_1 + Q_2)) + (1-x)(1-z)(P_0 - cp_1 - cp_2) \quad (6)$$

$$U_{(1-y)} = xzP_0 + x(1-z)P_0 + z(1-x)P_0 + (1-x)(1-z)P_0 \quad (7)$$

$$\bar{U}_y = yU_y + (1-y)U_{(1-y)} \quad (8)$$

The port enterprise's replication dynamic equation is:

$$F(y) = y(1-y)(zP_1 - c_{p1} - c_{p2} + xs_1 + xs_2 + zP_cQ_1 + zP_cQ_2 - z\sigma W_1) \quad (9)$$

The detailed derivation of the replicator dynamic equation is provided in Appendix B.

In the stability analysis of dynamic systems, if the equilibrium point of the system satisfies the equation $F(y) = 0$, the stability of this equilibrium point can be ensured by also satisfying the condition that its first derivative $F'(y) < 0$. From $F(y) = 0$, it can be

inferred that $y = 0$, $y = 1$, $z = z_0 = \frac{c_{p1} + c_{p2} - xs_1 - xs_2}{P_1 + P_cQ_1 + P_cQ_2 - \sigma W_1}$. Taking the derivative of $F(y) = 0$ yields:

$$F'(y) = (1-2y)(zP_1 - c_{p1} - c_{p2} + xs_1 + xs_2 + zP_cQ_1 + zP_cQ_2 - z\sigma W_1) \quad (10)$$

When $z = z_0$, $F(y) = 0$ and all y are evolutionarily stable strategies. When $z \neq z_0$, let $H(z) = zP_1 - c_{p1} - c_{p2} + xs_1 + xs_2 + zP_cQ_1 + zP_cQ_2 - z\sigma W_1$, so $\frac{\partial H(z)}{\partial z} = P_1 + P_cQ_1 + P_cQ_2 - \sigma W_1$.

$$(1) \quad \frac{\partial H(z)}{\partial z} = P_1 + P_cQ_1 + P_cQ_2 - \sigma W_1 > 0, \quad H(z) \text{ is an increasing function of } z.$$

(a) When $z > z_0$, $H(z) > 0$, $F(y)|_{y=1} = 0$, $F'(y)|_{y=1} < 0$, so $y = 1$ is a stable state.

(b) When $z < z_0$, $H(z) < 0$, $F(y)|_{y=0} = 0$, $F'(y)|_{y=0} < 0$, so $y = 0$ is a stable state.

$$(2) \quad \frac{\partial H(z)}{\partial z} = P_1 + P_cQ_1 + P_cQ_2 - \sigma W_1 < 0, \quad H(z) \text{ is a decreasing function of } z.$$

(a) When $z > z_0$, $H(z) < 0$, $F(y)|_{y=0} = 0$, $F'(y)|_{y=0} < 0$, therefore $y = 0$ is a stable state.

(b) When $z < z_0$, $H(z) > 0$, $F(y)|_{y=1} = 0$, $F'(y)|_{y=1} < 0$, therefore $y = 1$ is a stable state.

Based on the above analysis, the phase diagram of the strategy evolution of port enterprises can be obtained, as shown in Figure 3. In Figure 3, the arrows indicate the evolutionary trend of strategies, and the region enclosed by the dashed lines represents a stable state where any strategy combination on this curved surface remains stable.

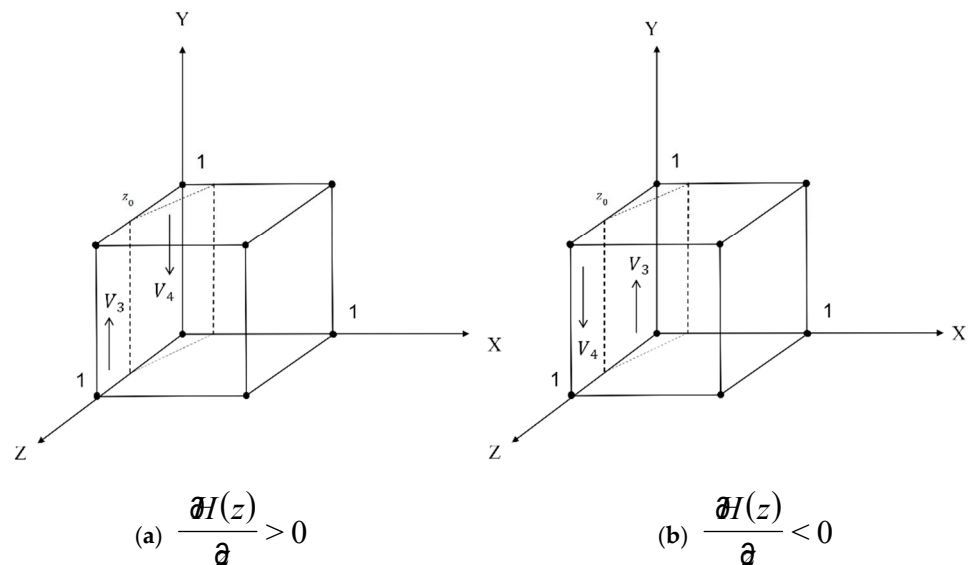


Figure 3. Phase diagram of the strategies of port enterprises.

3.4.3. Shipping Company

Assuming the expected revenue for the shipping company when using shore power is U_z , and the expected revenue when not using shore power is $U_{(1-z)}$, the average expected utility is $\bar{U}_z$. Therefore,

$$U_z = xy(B_0 + s_3 + s_4 - c_{s1} - c_{s2} - \sigma W_2 + P_c Q_3) + x(1-y)(B_0 + s_3 - c_{s1} - c_{s3}) + y(1-x)(B_0 - c_{s1} - c_{s2} - \sigma W_2 + P_c Q_3) + (1-x)(1-y)(B_0 - c_{s1} - c_{s3}) \quad (11)$$

$$U_{(1-z)} = xy(B_0 - c_{s3}) + x(1-y)(B_0 - c_{s3}) + y(1-x)(B_0 - c_{s3}) + (1-x)(1-y)(B_0 - c_{s3}) \quad (12)$$

$$\bar{U}_z = zU_z + (1-z)U_{(1-z)} \quad (13)$$

The shipping company's replication dynamic equation is:

$$F(z) = z(1-z)(c_{s3}y - c_{s2}y - c_{s1} + xs_3 + yP_c Q_3 - y\sigma W_2 + xys_4) \quad (14)$$

The detailed derivation of the replicator dynamic equation is provided in Appendix B.

In the stability analysis of dynamic systems, if the equilibrium point of the system satisfies the equation $F(z) = 0$, the stability of this equilibrium point can be ensured by also satisfying the condition that its first derivative $F'(z) < 0$. From $F(z) = 0$, it can be inferred that $z = 0$, $z = 1$, $x = x_0 = \frac{c_{s2}y - c_{s3}y + c_{s1} - yP_c Q_3 + y\sigma W_2}{s_3 + ys_4}$. Taking the derivative of $F(z)$ yields:

$$F'(z) = (1-2z)(c_{s3}y - c_{s2}y - c_{s1} + xs_3 + yP_c Q_3 - y\sigma W_2 + xys_4) \quad (15)$$

When $x = x_0$, $F(z) = 0$ and all z are evolutionarily stable strategies. When

$x \neq x_0$, let $H(x) = c_{s3}y - c_{s2}y - c_{s1} + xs_3 + yP_c Q_3 - y\sigma W_2 + xys_4$, so $\frac{\partial H(x)}{\partial a} = s_3 + ys_4$.

$$(1) \quad \frac{\partial H(x)}{\partial a} = s_3 + ys_4 > 0, \quad H(x) \text{ is an increasing function of } x.$$

- (a) When $x > x_0$, $H(x) > 0$, $F(z)|_{z=1} = 0$, $F'(z)|_{z=1} < 0$, therefore $z = 1$ is a stable state.
- (b) When $x < x_0$, $H(x) < 0$, $F(z)|_{z=0} = 0$, $F'(z)|_{z=0} < 0$, therefore $z = 0$ is a stable state.
- (2) $\frac{\partial H(x)}{\partial x} = s_3 + ys_4 < 0$, $H(x)$ is a decreasing function of x .
- (a) When $x > x_0$, $H(x) < 0$, $F(z)|_{z=0} = 0$, $F'(z)|_{z=0} < 0$, therefore $z = 0$ is a stable state.
- (b) When $x < x_0$, $H(x) > 0$, $F(z)|_{z=1} = 0$, $F'(z)|_{z=1} < 0$, therefore $z = 1$ is a stable state.

Based on the above analysis, the phase diagram of the strategy evolution of shipping companies can be obtained, as shown in Figure 4. In Figure 4, the arrows indicate the evolutionary trend of strategies, and the region enclosed by the dashed lines represents a stable state where any strategy combination on this curved surface remains stable.

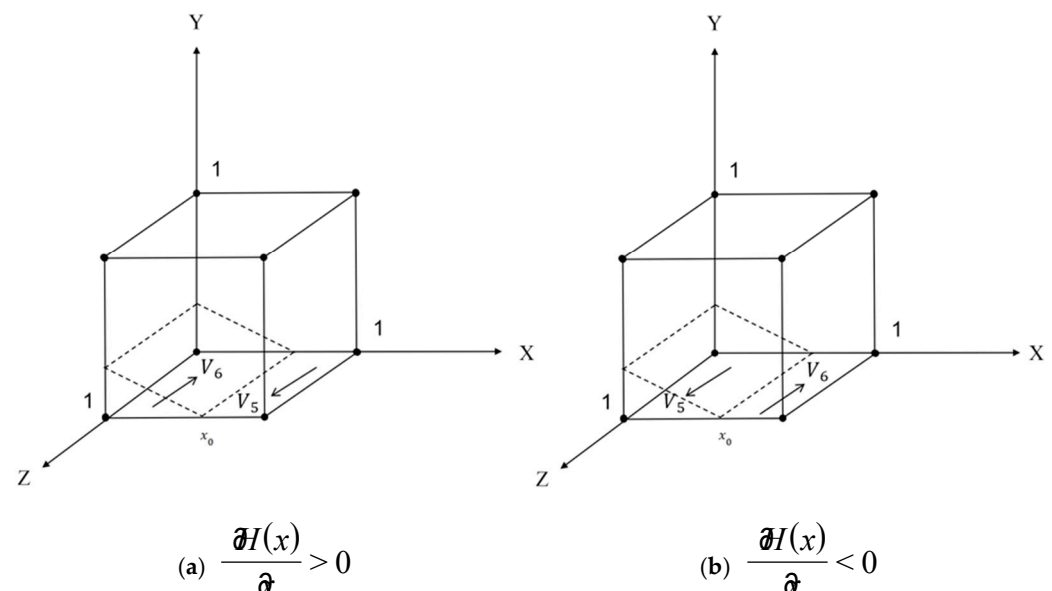


Figure 4. Phase diagram of the strategies of shipping companies.

3.5. Evolutionarily Stable Strategy

To further examine the evolutionary stable points of the tripartite game, the replicator dynamic equations of the three parties are jointly considered and set to 0, as shown below:

$$\begin{cases} F(x) = x(x-1)(c_0 + yM + ys_1 + ys_2 + zs_3 - y\rho M - yzN - yzR_0 + yzR_1 + yzs_4 + yz\theta N) \\ F(y) = y(1-y)(zP_1 - c_{p1} - c_{p2} + xs_1 + xs_2 + zP_cQ_1 + zP_cQ_2 - z\sigma W_1) \\ F(z) = z(1-z)(c_{s3}y - c_{s2}y - c_{s1} + xs_3 + yP_cQ_3 - y\sigma W_2 + xy s_4) \end{cases} \quad (16)$$

By solving this system of equations, eight equilibrium points are obtained, denoted as $E_1 = (0, 0, 0)$, $E_2 = (0, 1, 0)$, $E_3 = (0, 0, 1)$, $E_4 = (0, 1, 1)$, $E_5 = (1, 0, 0)$, $E_6 = (1, 1, 0)$, $E_7 = (1, 0, 1)$, $E_8 = (1, 1, 1)$. According to Friedman [39], certain points can only become stable equilibria of a dynamic system under specific conditions. In light of this, this study calculates the partial derivatives of the replicator dynamic equations for the government, port enterprises, and shipping companies, and constructs the Jacobian matrix for the

multi-agent system. This approach allows for an assessment of the evolutionary stability of each equilibrium point. The Jacobian matrix is presented as follows:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \quad (17)$$

Among them,

$$\frac{\partial F(x)}{\partial x} = (2x-1)(c_0 + yM + ys_1 + ys_2 + zs_3 - y\rho M - yzN - yzR_0 + yzR_1 + yzs_4 + yz\theta N) \quad (18)$$

$$\frac{\partial F(x)}{\partial y} = x(x-1)(M + s_1 + s_2 - \rho M - zN - zR_0 + zR_1 + zs_4 + z\theta N) \quad (19)$$

$$\frac{\partial F(x)}{\partial z} = x(x-1)(s_3 - yN - yR_0 + yR_1 + ys_4 + y\theta N) \quad (20)$$

$$\frac{\partial F(y)}{\partial x} = y(y-1)(s_1 + s_2) \quad (21)$$

$$\frac{\partial F(y)}{\partial y} = (1-2y)(P_1z - c_{p2} - c_{p1} + xs_1 + xs_2 + zP_cQ_1 + zP_cQ_2 - z\sigma W_1) \quad (22)$$

$$\frac{\partial F(y)}{\partial z} = y(y-1)(P_1 + P_cQ_1 + P_cQ_2 - \sigma W_1) \quad (23)$$

$$\frac{\partial F(z)}{\partial x} = z(1-z)(s_3 + ys_4) \quad (24)$$

$$\frac{\partial F(z)}{\partial y} = z(1-z)(c_{s3} - c_{s2} + P_cQ_3 - \sigma W_2 + xs_4) \quad (25)$$

$$\frac{\partial F(z)}{\partial z} = (1-2z)(c_{s3}y - c_{s2}y - c_{s1} + xs_3 + yP_cQ_3 - y\sigma W_2 + xys_4) \quad (26)$$

By inserting all equilibrium points into the Jacobian matrix, the corresponding eigenvalues $(\gamma_1, \gamma_2, \gamma_3)$ are derived, as presented in Table 3. Based on Lyapunov stability theory, the signs of the eigenvalues can be used to determine the stability of the equilibrium points. An equilibrium point is considered an Evolutionarily Stable Strategy (ESS) if all eigenvalues are negative; if all eigenvalues are positive, it is an unstable point; if the eigenvalues include both positive and negative values, the point is a saddle point. Due to $\gamma_1 = c_{p1} + c_{p2} > 0$, $\gamma_3 = c_{s1} > 0$ and $\gamma_1 = c_0 > 0$ the equilibrium points $E_2 = (0, 1, 0)$, $E_3 = (0, 0, 1)$ and $E_5 = (1, 0, 0)$ are unstable points. In addition, under the scenario where the government implements differential subsidies, $\gamma_1 = c_{p1} + c_{p2} - s_1 - s_2 > 0$, so $E_6 = (1, 1, 0)$ is also an unstable point. Similarly, because $\gamma_1 = c_0 + s_3 > 0$, the equilibrium point $E_7 = (1, 0, 1)$ is also unstable.

Table 3. The eigenvalues of the equilibrium points in the game system.

	Eigenvalue γ_1	Eigenvalue γ_2	Eigenvalue γ_3
$E_1 = (0, 0, 0)$	$-c_0$	$-c_{p1} - c_{p2}$	$-c_{s1}$
$E_2 = (0, 1, 0)$	$\rho M - c_0 - s_1 - s_2 - M$	$c_{p1} + c_{p2}$	$c_{s3} - c_{s2} - c_{s1} - \sigma_1 W_2 + P_c Q_3$
$E_3 = (0, 0, 1)$	$-c_0 - s_3$	$P_1 - c_{p1} - c_{p2} + Q_1 P_c + Q_2 P_c - \sigma W_1$	c_{s1}
$E_4 = (0, 1, 1)$	$N - M - \theta N + \rho M + R_0 - R_1 - c_0 - s_1 - s_2 - s_3 - s_4$	$c_{p1} + c_{p2} - P_1 - Q_1 P_c - Q_2 P_c + \sigma W_1$	$c_{s1} + c_{s2} - c_{s3} + \sigma W_2 - Q_3 P_c$
$E_5 = (1, 0, 0)$	c_0	$s_1 + s_2 - c_{p1} - c_{p2}$	$s_3 - c_{s3}$
$E_6 = (1, 1, 0)$	$M - \rho M + c_0 + s_1 + s_2$	$c_{p1} + c_{p2} - s_1 - s_2$	$c_{s3} - c_{s2} - c_{s1} + s_3 + s_4 - \sigma W_2 + Q_3 P_c$
$E_7 = (1, 0, 1)$	$c_0 + s_3$	$P_1 - c_{p1} - c_{p2} + s_1 + s_2 + Q_1 P_c + Q_2 P_c - \sigma W_1$	$c_{s3} - s_3$
$E_8 = (1, 1, 1)$	$R_1 - R_0 + c_0 + s_1 + s_2 + s_3 + s_4 - \rho M + M + \theta N - N$	$c_{p1} + c_{p2} - P_1 - s_1 - s_2 - Q_1 P_c - Q_2 P_c + \sigma W_1$	$c_{s1} + c_{s2} - c_{s3} - s_3 - s_4 + \sigma W_2 - Q_3 P_c$

In summary, only $E_1 = (0, 0, 0)$, $E_4 = (0, 1, 1)$ and $E_8 = (1, 1, 1)$ exhibit asymptotic evolutionary stability under certain conditions, which are analyzed in detail as follows:

Case 1: Since the eigenvalues γ_1 , γ_2 , γ_3 corresponding to $E_1 = (0, 0, 0)$ are all negative, $E_1 = (0, 0, 0)$ is an evolutionarily stable strategy (ESS). In this state, the strategies chosen by the three parties are: the government does not implement the policy, the port does not construct shore power facilities, and the shipping company does not use shore power. This equilibrium indicates that, under the current conditions, the active strategy is not economically viable. Raising the carbon price, increasing subsidies, and improving power supply reliability can enhance the cost–benefit structure, thereby steering the system toward a cooperative strategy.

Case 2: When $E_4 = (0, 1, 1)$ is an equilibrium point, the strategies chosen by the three parties are: the government does not implement the policy, the port constructs shore power facilities, and shipping companies use shore power. As shown in Table 3, only when $\gamma_1 < 0$, $\gamma_2 < 0$, $\gamma_3 < 0$, those are, $N - M - \theta N + \rho M + R_0 - R_1 - c_0 - s_1 - s_2 - s_3 - s_4 < 0$, $c_{s1} + c_{s2} - c_{s3} + \sigma W_2 - Q_3 P_c < 0$ and $c_{p1} + c_{p2} - P_1 - Q_1 P_c - Q_2 P_c + \sigma W_1 < 0$, $E_4 = (0, 1, 1)$ constitutes an ESS. This indicates that if the government benefits from promoting shore power $\rho M - M + R_0 - R_1$ are lower than the cost of policy implementation $c_0 + s_1 + s_2 + s_3 + s_4 + \theta N - N$, the government likewise lacks the willingness to implement such policies. It also shows that when the benefits generated for the port from vessels' use of shore power $P_1 + Q_1 P_c + Q_2 P_c$ exceed the corresponding construction costs and the losses caused by power interruptions $c_{p1} + c_{p2} + \sigma W_1$, port enterprises have no motivation to construct shore power facilities. When the cost for shipping companies to use shore power $c_{s1} + c_{s2}$ is lower than the pre-retrofitting fuel cost c_{s3} , and the losses due to power interruptions σW_2 are smaller than the carbon revenue obtained after retrofitting $Q_3 P_c$, shipping companies will be willing to adopt shore power. This equilibrium indicates that, in the absence of government intervention, the market can still spontaneously and stably converge to the strategy combination of "port construction–shipping company usage" as long as shore power is economically viable for both ports and shipping companies. Specifically, this requires that port revenues are sufficient to cover construction costs and outage-related losses, and that the shipping companies' total cost of using shore power is lower than the fuel cost, with carbon-related gains being sufficient to offset the associated costs.

Case 3: When $E_8 = (1, 1, 1)$ is an equilibrium point, the strategies chosen by the three parties are: the government implements the policy, the port constructs shore power facilities, and shipping companies use shore power. Therefore, we set $\gamma_1 < 0$, $\gamma_2 < 0$, $\gamma_3 < 0$, those are $R_1 - R_0 + c_0 + s_1 + s_2 + s_3 + s_4 - \rho M + M + \theta N - N < 0$, $c_{s1} + c_{s2} - c_{s3} - s_3 - s_4 + \sigma W_2 - Q_3 P_c < 0$, $c_{p1} + c_{p2} - P_1 - s_1 - s_2 - Q_1 P_c - Q_2 P_c + \sigma W_1 < 0$, so that $E_8 = (1, 1, 1)$ constitutes an ESS. This indicates that when the government benefits from promoting shore power $R_0 - R_1 - \rho M + M$ exceed its policy cost $c_0 + s_1 + s_2 + s_3 + s_4$ and the losses imposed on the petroleum industry $\theta N - N$, the government will have the incentive to adopt and implement the policy. When the benefits gained by the port after vessels adopt shore power $P_1 + s_1 + s_2 + Q_1 P_c + Q_2 P_c$ exceed both its construction costs $c_{p1} + c_{p2}$ and the losses due to power interruptions σW_1 , the port enterprise will be willing to construct shore power facilities. When the cost for shipping companies to use shore power $c_{s1} + c_{s2}$

is lower than the pre-retrofitting fuel cost c_{s3} , and the losses due to power interruptions σW_2 are smaller than the carbon revenue obtained after retrofitting $Q_3 P_c$, shipping companies will be willing to adopt shore power. This equilibrium indicates that, under policy incentives, the government, ports, and shipping companies can all benefit from adopting cooperative strategies, and the system will stably converge to “government implementation–port construction–shipping company usage.” From a policy perspective, a higher carbon price combined with synergistic subsidies for infrastructure construction, ship retrofitting, and electricity prices can further strengthen cooperative incentives, thereby enhancing the sustainability and stability of this cooperative outcome.

4. Simulation Analysis

4.1. Data Sources

The data used in this study are primarily drawn from publicly available literature, government policies, and relevant reports. To further investigate the interaction mechanisms underlying stakeholders’ strategic choices in the shore-to-ship power system, we conduct numerical simulations of the evolutionary game model using MATLAB 2016b. To simplify computation, following the annualization formula (Equation (27)), all variables such as costs and subsidies are uniformly converted into annual terms (Fang et al. [40], 2020), expressed in units of CNY million.

$$c = \frac{c_p r (1+r)^l}{(1+r)^l - 1} \quad (27)$$

Here, C denotes the annualized investment amount, c_p denotes the total investment amount before annualization, r is the discount rate, set at 5% (Li et al., 2025 [41]), and l denotes the service life. In the model, the service life of shore power facilities was set to 20 years, the operational lifetime of the wind turbine power generation system was assumed to be 25 years, and the remaining service life of ships after retrofitting was defined as 15 years. According to the studies by Sheng et al. (2023) [42] and Xu et al. (2021) [43], it is known that the construction cost of a shore power system is approximately RMB 8 million, and the cost of retrofitting a ship is about RMB 2 million. After the shore power facilities are completed, the government provides a 30% subsidy for construction costs, a 60% subsidy for retrofit costs, and a 60% subsidy for shore power electricity usage. Therefore, by annualizing the above costs and subsidies using the annualization formula (Equation (27)), we set the port shore power facility construction cost $c_{p1} = 0.65$, the ship retrofitting cost $c_{s1} = 0.19$, the shore power construction subsidy $s_1 = 0.2$, the ship retrofit subsidy $s_3 = 0.11$, the electricity price subsidy $s_4 = 0.12$, the cost of using shore power $c_{s2} = 0.2$, the fuel costs $c_{s3} = 0.3$, the policy costs $c_0 = 0.1$, the benefits of using shore power for ships at the port $p_1 = 0.85$, and carbon emission reductions from shore power $Q_1 = 2$, wind turbine carbon emission reductions $Q_2 = 3$, and ship carbon emission reductions $Q_3 = 5$. According to policy documents and related reports from Xinhua News (2025) [44], Fraunhofer ISE (2024) [45], European Commission (2024) [46], China Central Television (2023) [47], World Bank (2023) [48] and Carbon Tracker (2023) [49], and to ensure system stability, we set the wind turbine power generation systems cost $c_{p2} = 0.32$, the wind turbine construction subsidy $s_2 = 0.19$, the carbon trading market price $P_c = 0.11$, the power supply interruptions frequency $\sigma = 2$, each power outage’s economic loss to the port and ship are $W_1 = 0.2$, $W_2 = 0.1$, the wind turbine

spillover benefit coefficient $\rho = 4$, the direct benefits generated for the government by the development of wind turbine power generation systems $M = 0.63$, the oil substitution loss coefficient $\theta = 5$, the losses incurred by the national oil industry $N = 0.4$, as shown in Table 4.

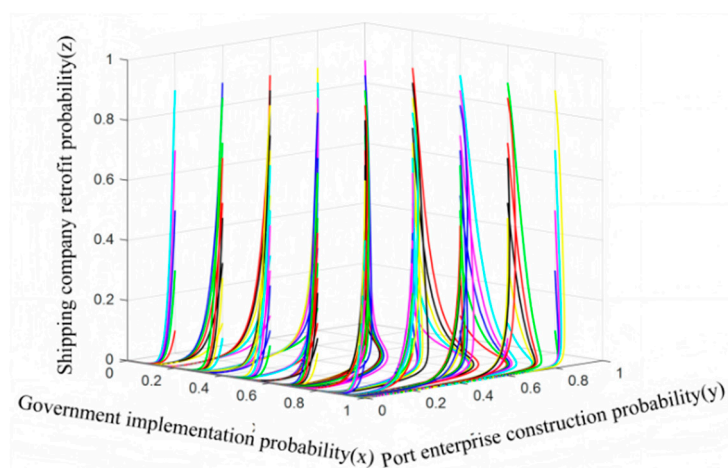
Table 4. Parameter values.

Parameters	Values	Parameters	Values	Parameters	Values
c_0	0.1	R_1	0.2	c_{p1}	0.65
s_1	0.2	M	0.63	c_{p2}	0.32
s_2	0.19	N	0.4	p_1	0.85
s_3	0.11	ρ	4	σ	2
s_4	0.12	θ	5	W_1	0.2
R_0	0.86	P_c	0.11	W_2	0.1
Q_1	2	Q_3	5	c_{s1}	0.19
Q_2	3	c_{s3}	0.3	c_{s2}	0.2

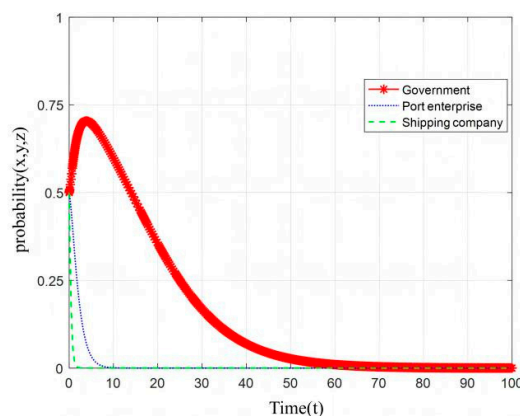
4.2. The Evolutionary Paths of ESSs

By combining the replicator dynamic equations with the stability conditions, the initial strategic willingness of the three parties was first set to $x = y = z = 0.5$. Given that the existence and stability of an ESS are jointly characterized by a set of inequality constraints and are influenced by multiple parameters acting together, to ensure that the conditions for each ESS are satisfied, this study takes Table 4 as the baseline and jointly adjusts and specifies multiple key parameters involved in each ESS (see Table 5). On this basis, three scenarios are constructed and analyzed: $E_1 = (0,0,0)$, $E_4 = (0, 1, 1)$, and $E_8 = (1, 1, 1)$, as detailed below.

- (1) While keeping all other parameters unchanged, parameter c_{s1} was adjusted to 2 and parameter c_{s2} was adjusted to 2.5 to satisfy the conditions of Scenario 1, and the evolutionary path of $E_1 = (0,0,0)$ was obtained, as shown in Figure 5a,b. In Figure 5a, each colored curve represents an evolutionary trajectory from a given set of initial strategy probabilities in a single simulation, and all trajectories eventually converge to the equilibrium point $E_1 = (0,0,0)$.



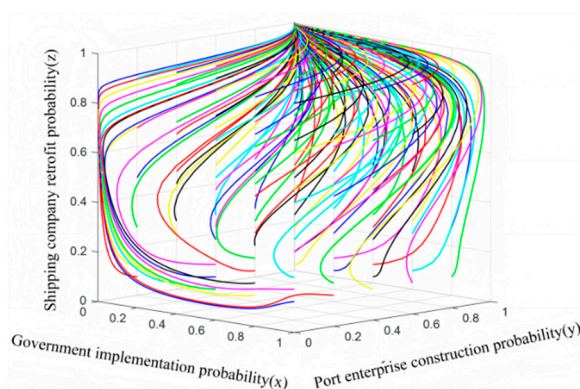
(a) 3D trajectory of three-party strategy evolution



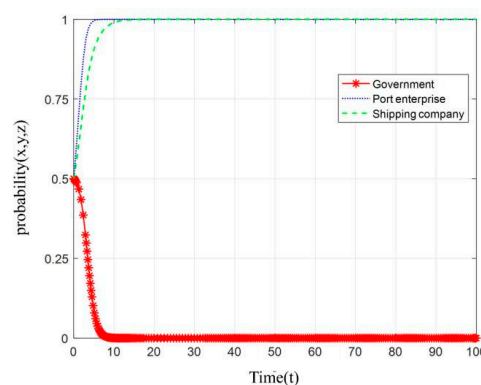
(b) Convergence path of three-party strategy evolution

Figure 5. The evolutionary paths of $E_1 = (0,0,0)$.

- (2) While keeping all other parameters unchanged, parameter R_1 was adjusted to 1.5, parameter p_1 was adjusted to 2.5, c_{s3} was adjusted to 0.5 to satisfy the conditions of Scenario 3, and the evolutionary path of $E_4 = (0, 1, 1)$ was obtained, as shown in Figure 6a, b. In Figure 6a, each colored curve represents an evolutionary trajectory from a given set of initial strategy probabilities in a single simulation, and all trajectories eventually converge to the equilibrium point $E_4 = (0, 1, 1)$.



(a) 3D trajectory of three-party strategy evolution



(b) Convergence path of three-party strategy evolution

Figure 6. The evolutionary paths of $E_4 = (0, 1, 1)$.

- (3) While keeping all other parameters unchanged, parameter R_0 was adjusted to 2, parameter p_1 was adjusted to 2.5, and c_{s3} was adjusted to 0.8 to satisfy the conditions of Scenario 4, and the evolutionary path of $E_8 = (1, 1, 1)$ was obtained, as shown in Figure 7a,b. In Figure 7a, each colored curve represents an evolutionary trajectory from a given set of initial strategy probabilities in a single simulation, and all trajectories eventually converge to the equilibrium point $E_8 = (1, 1, 1)$.

Table 5. Values of different parameters of ESS.

Parameters	(0,0,0)	(0,1,1)	(1,1,1)
c_{s1}	2	0.19	0.19
c_{s2}	2.5	0.2	0.2
c_{s3}	0.3	0.5	0.8
R_0	0.86	0.86	2
R_1	0.2	1.5	0.2
p_1	0.85	2.5	2.5

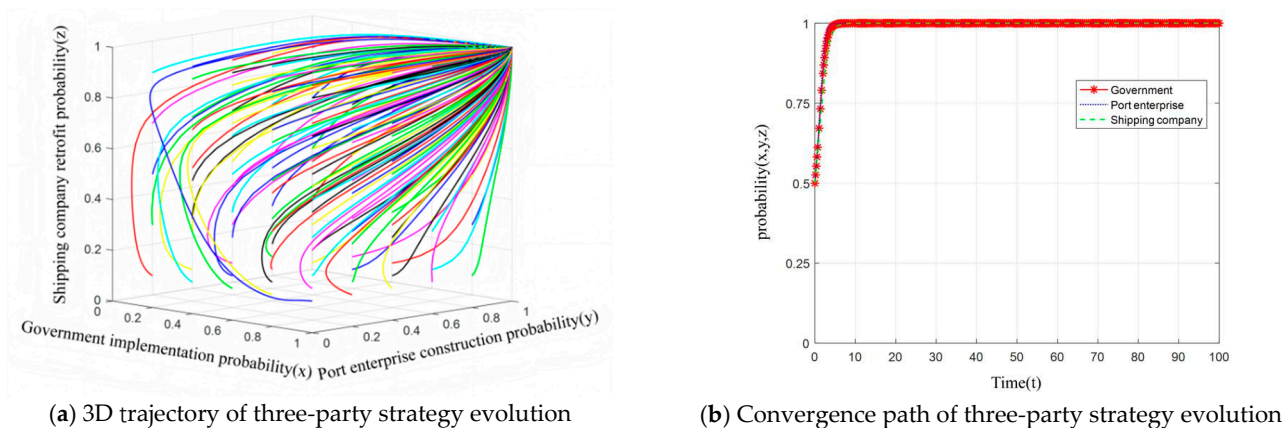


Figure 7. The evolutionary paths of $E_8 = (1, 1, 1)$.

4.3. Impact of Key Parameters on the Evolutionary Outcomes and Evolutionary Paths

4.3.1. Effect of the Initial Value of x, y, z on the Evolutionary Path

Based on the parameters listed in While keeping all other parameters unchanged, parameter R_0 was adjusted to 2, parameter p_1 was adjusted to 2.5, and c_{s3} was adjusted to 0.8 to satisfy the conditions of Scenario 4, and the evolutionary path of $E_8 = (1, 1, 1)$ was obtained, as shown in Figure 7a,b. In Figure 7a, each colored curve represents an evolutionary trajectory from a given set of initial strategy probabilities in a single simulation, and all trajectories eventually converge to the equilibrium point $E_8 = (1, 1, 1)$.

Table 5, the initial strategic willingness of the system was fixed at 0.5. By adjusting the initial probabilities of other stakeholders, this study explores the effects on the system's evolutionary path.

(1) Effects of changes in y, z on the strategic choice of the government

The initial value of $x = 0.5$ was adopted, while $y = 0.2, y = 0.8$ and $z = 0.2, z = 0.8$ were, respectively, selected as the initial values. By adjusting the values of y and z , the evolutionary process of the government's willingness x was analyzed, and the results are shown in Figure 8.

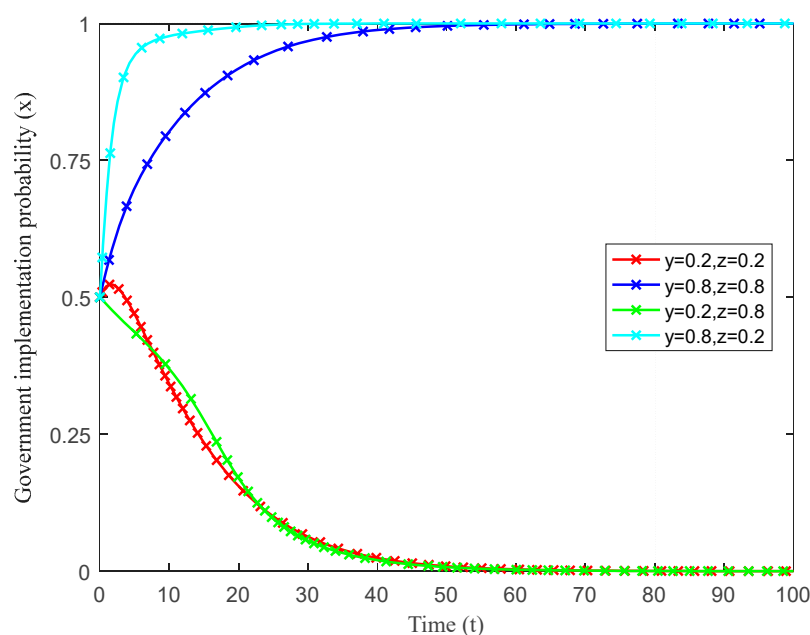


Figure 8. Effects of changes in y, z on the strategic choice of the government.

As illustrated in Figure 8, when the willingness of the port enterprise and the shipping company to use shore power is relatively high ($y = 0.8, z = 0.8$), the government's willingness increases accordingly; conversely, when the willingness of the port enterprise and the shipping company is relatively low ($y = 0.2, z = 0.2$), the government's willingness declines sharply and even approaches 0. This indicates that when the port enterprise and the shipping company exhibit a low willingness to adopt the shore power system, the government is required to bear higher policy implementation costs, which in turn weakens its willingness to promote the policy. When the willingness of the port enterprise and the shipping company is relatively high, the fiscal pressure on the government is alleviated, thereby enhancing its willingness to implement the policy. However, when the willingness of the port enterprise is extremely low ($y = 0.2$), the government's willingness remains constrained even if the shipping company shows a relatively strong willingness. This is because the port occupies a critical position in the shore power system and undertakes essential responsibilities such as power grid connection, equipment construction, and system operation. In the absence of support from the port enterprise, the shore power system cannot be effectively implemented, even when the willingness of the shipping company is relatively high.

(2) Effects of changes in x, z on the strategic choice of the port enterprise.

The initial value of $y = 0.5$ was adopted. $x = 0.2, x = 0.8$ and $z = 0.2, z = 0.8$ were selected as the initial values. By adjusting the initial willingness of the government and the shipping company, namely x and z , the evolutionary process of the port enterprise's willingness y over time was analyzed, as shown in Figure 9.

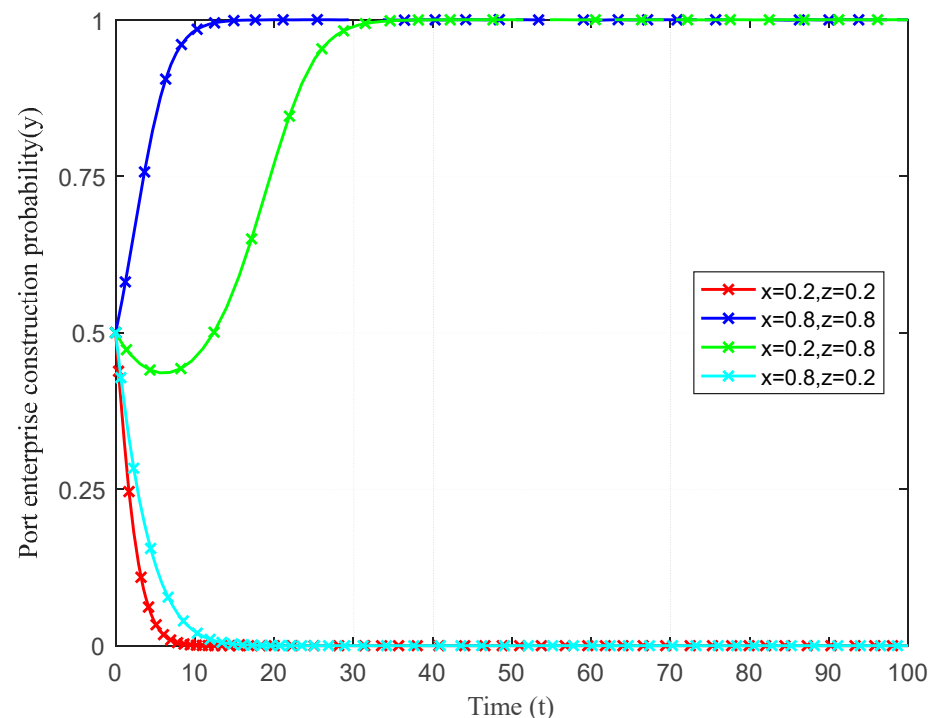


Figure 9. The effects of changes in x, z on the strategic choice of the port enterprise.

As can be observed from Figure 9, when the willingness of the government and the shipping company is relatively high ($x = 0.8, z = 0.8$), the willingness of the port enterprise gradually increases and eventually converges to 1; however, when the willingness of the government and the shipping company is relatively low ($x = 0.2, z = 0.2$), the willingness of the port enterprise decreases and approaches 0. This demonstrates that the decision of the port enterprise to participate in the construction of the shore power system is jointly influenced by government policy support and market demand. Specifically, insufficient government support results in greater financial pressure on the port enterprise, thereby reducing its willingness to participate. In contrast, strong government support and subsidies can effectively alleviate the cost burden of the port enterprise and enhance its willingness. In addition, the willingness of the shipping company also exerts a significant influence on the port enterprise's willingness. When the willingness of the shipping company is relatively high ($z = 0.8$), it indicates strong market demand for shore power, enabling the port enterprise to accelerate cost recovery, which further enhances its willingness to participate.

(3) The effects of changes in x, y on the strategic choice of the port enterprise.

The initial value of $z = 0.5$ was adopted, while $x = 0.2, x = 0.8$ and $y = 0.2, y = 0.8$ were selected as the initial values. By adjusting the initial willingness of the government and the port enterprise, namely x and y , the evolutionary process of the shipping company's willingness z over time was analyzed, as shown in Figure 10.

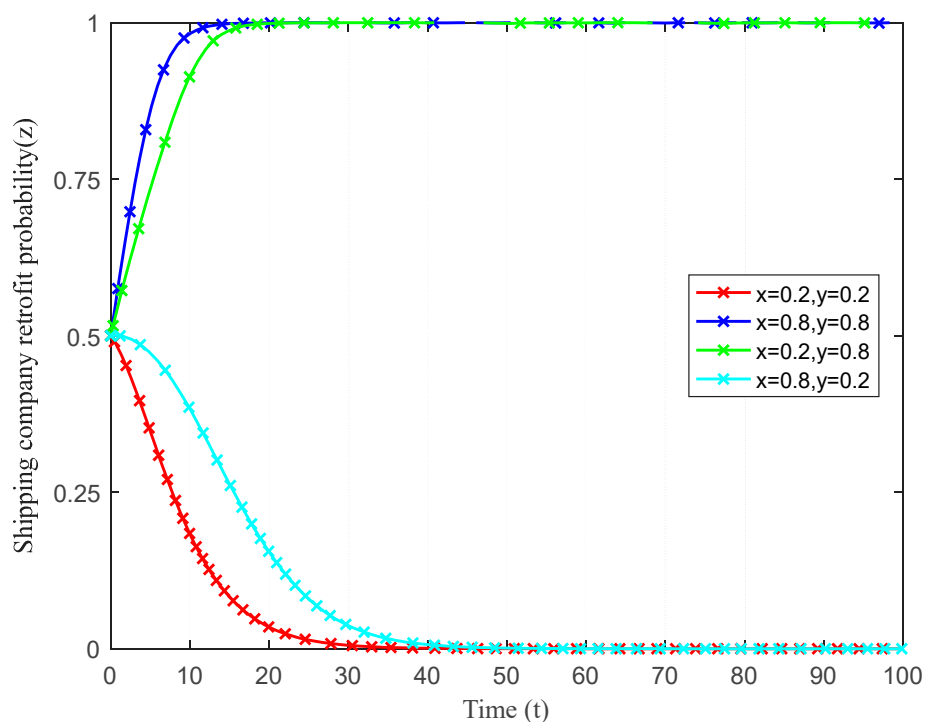


Figure 10. The effects of changes of x, y on the strategic choice of the shipping company.

As illustrated in Figure 10, when both the government and the port enterprise lack the willingness to promote shore power ($x = 0.2, y = 0.2$), the willingness of the shipping company rapidly declines to 0. Even when the government exhibits a relatively high willingness but the port enterprise responds insufficiently, the willingness of the shipping company remains difficult to sustain and shows a declining trend. This indicates that the effectiveness of government policy promotion largely depends on whether port enterprises actually implement the measures, which in turn shapes shipping companies' decisions. Conversely, when the willingness of the port enterprise is relatively high ($y = 0.8$), the willingness of the shipping company can still be significantly enhanced even if the willingness of the government is relatively weak, indicating that the direct influence of the port enterprise on the decision making of the shipping company is more critical. When both the government and the port enterprise exhibit relatively high willingness, a virtuous cycle of policy guidance and supply assurance can be formed, under which the willingness of the shipping company to use shore power increases rapidly and stabilizes at a high level. Overall, the decision making of the shipping company is influenced not only by government policies but is more strongly dependent on the response of the port enterprise, and the synergistic effect of the two is the key to enhancing the willingness of the shipping company to adopt shore power.

4.3.2. The Effects of Government Subsidies on the Evolutionary Paths of Different Stakeholders

To examine the impact of a single carbon trading policy on the promotion of shore power, all subsidies were set to 0, namely $s_1 = s_2 = s_3 = s_4 = 0$. In order to explore the effects of different subsidy levels on the development of shore power, the shore power construction subsidy $s_1 = 0.2, 0.22, 0.24$, wind turbine construction subsidy $s_1 = 0.19, 0.21, 0.23$, ship retrofitting subsidy $s_1 = 0.11, 0.13, 0.15$, and electricity price subsidy $s_1 = 0.12, 0.14, 0.16$ were separately assigned, while other parameters and

variables remained unchanged. The specific values were referenced from Table 5, and the simulation results are shown in Figure 11.

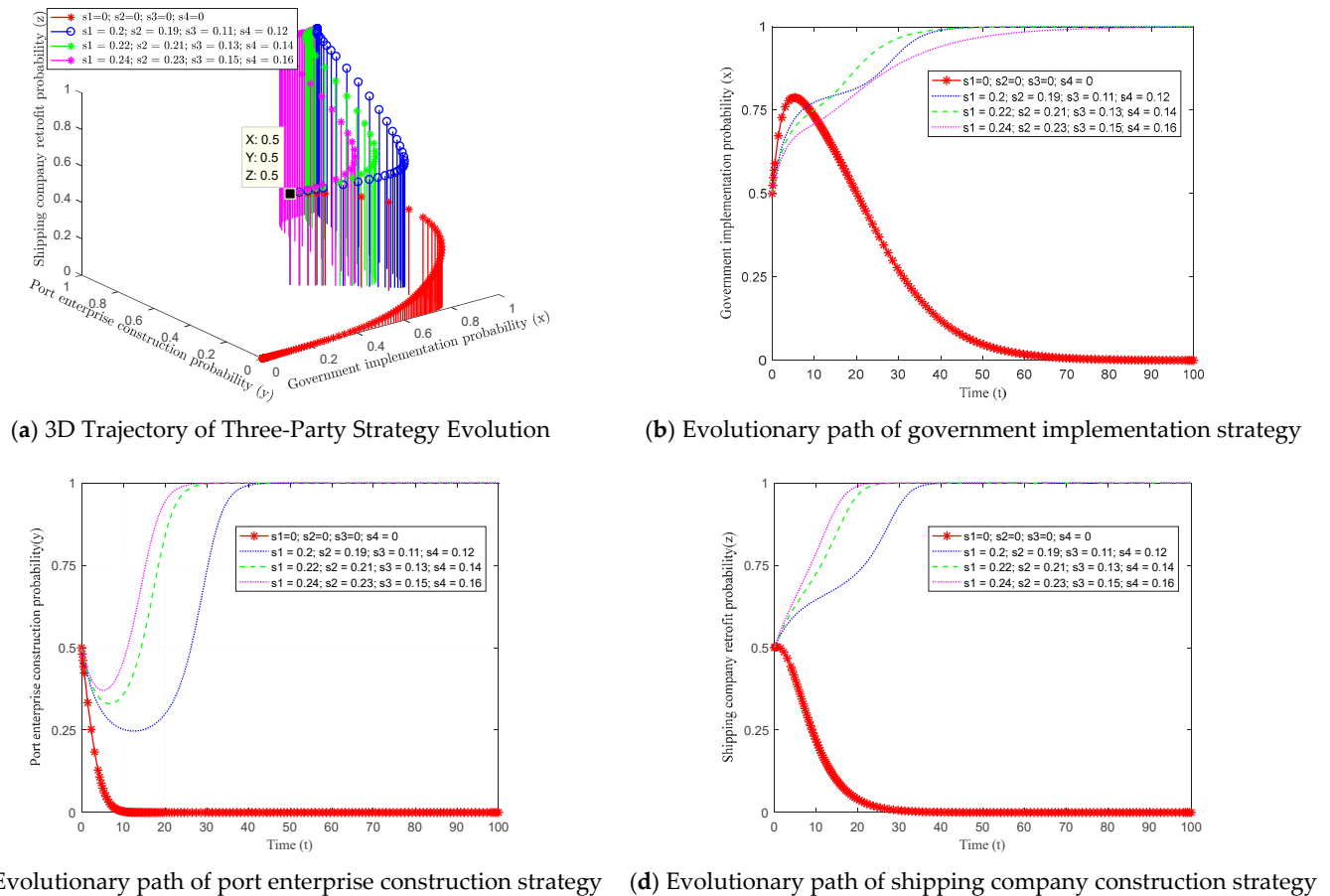


Figure 11. The effects of government subsidies on the evolutionary stabilization rate.

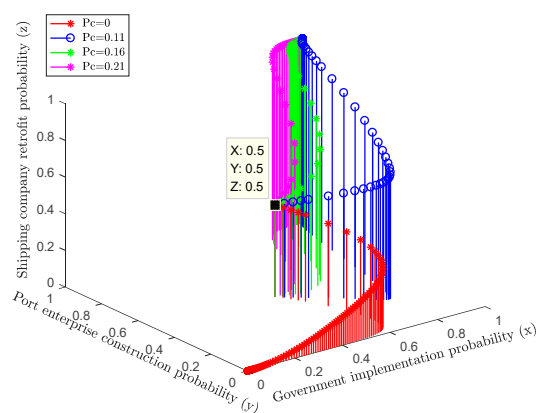
When $s_1 = s_2 = s_3 = s_4 = 0$, x initially increases and then decreases, while y, z continuously declines, and both eventually stabilize at 0. Under a single carbon trading policy, due to the absence of government subsidies, the port enterprise faces relatively high construction cost pressure, and the shipping company is also required to bear the costs associated with ship retrofitting and the use of shore power. The high cost burden reduces the incentives of both the port enterprise and the shipping company to promote and use shore power, thereby constraining the effectiveness of the policy implementation.

However, when the shore power construction subsidy s_1 increases to 0.2 and 0.22, the wind turbine construction subsidy s_2 increases to 0.19 and 0.21, the retrofitting subsidy $s_3 = 0$ increases to 0.11 and 0.13, and the electricity price subsidy s_4 increases to 0.12 and 0.14, y initially decreases and then increases, while x, z continuously increases, and both eventually converge to 1. This indicates that, in the initial stage, the construction willingness of the port enterprise is generally weak due to the high investment cost of shore power infrastructure. As the government increases fiscal subsidies, the port enterprise begins to increase investment in shore power infrastructure under economic incentives. Meanwhile, the enhancement of retrofitting subsidies and electricity price subsidies effectively promotes ship retrofitting and encourages the shipping company to use shore power more actively. This positive interaction further strengthens the government's motivation to continuously promote relevant policies.

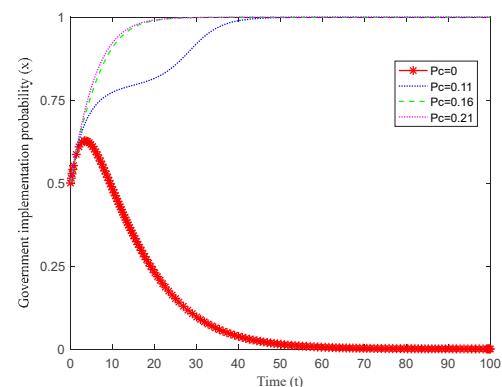
When the shore power construction subsidy increases to 0.24, the wind turbine construction subsidy increases to 0.23, the ship retrofitting subsidy increases to 0.15, and the electricity price subsidy increases to 0.16, Figure 11b shows that x converges to 1 more slowly than in the other two scenarios. This is because higher subsidy levels significantly increase the government's fiscal expenditures and intensify budgetary pressure, thereby weakening its willingness to continuously promote shore power policies.

4.3.3. The Effects of Carbon Price on the Evolutionary Paths of Different Stakeholders

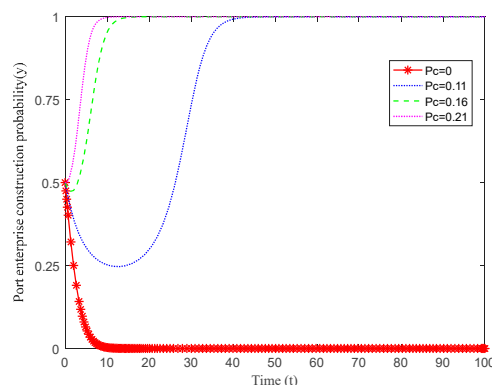
In order to analyze the impact of a single subsidy policy on the promotion of shore power, the carbon price was set to 0, namely $P_c = 0$. To explore the effects of different carbon prices on the development of shore power, we set $P_c = 0.11, 0.16, 0.21$, while other coefficients and variables remained unchanged. The specific values were referenced from Table 5, and the simulation results are shown in Figure 12.



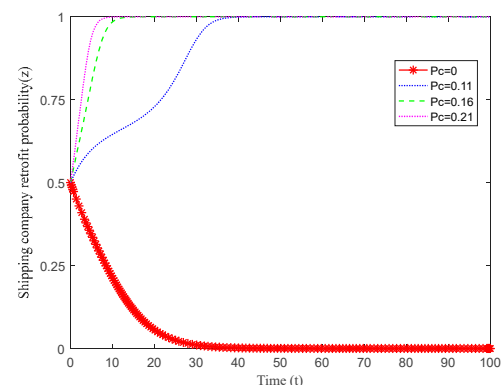
(a) 3D Trajectory of Three-Party Strategy Evolution



(b) Evolutionary path of government implementation strategy



(c) Evolutionary path of port enterprise construction strategy



(d) Evolutionary path of shipping company construction strategy

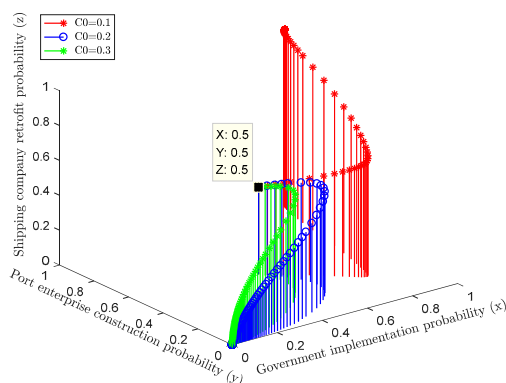
Figure 12. The effects of carbon price on the evolutionary stabilization rate.

As depicted in Figure 12, when $P_c = 0$, x initially increases and then decreases and y, z exhibit an overall downward trend, indicating that under a single subsidy policy, although initial investment costs are reduced, the limited profit margin during the later operational stage results in insufficient participation incentives for both the port enterprise and the shipping company, which in turn weakens the government's willingness to further promote related policies. When $P_c = 0.11$, $P_c = 0.16$ and $P_c = 0.21$, x, y, z generally present an upward trend, and a higher carbon price leads to a faster convergence toward 1. This indicates that, with increasing carbon prices, the benefits obtained by ports and vessels through carbon emission reduction are significantly enhanced,

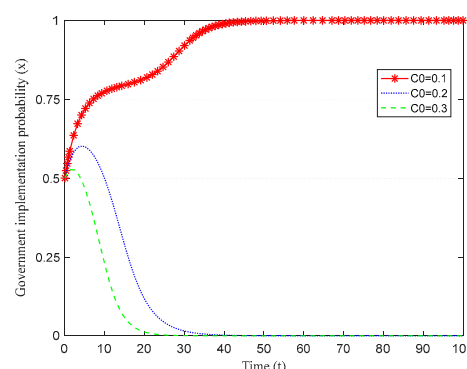
thereby substantially increasing their willingness to participate, which further strengthens the government's motivation to continue promoting related policies.

4.3.4. The Effects of Government Policy Cost on the Evolutionary Paths of Different Stakeholders

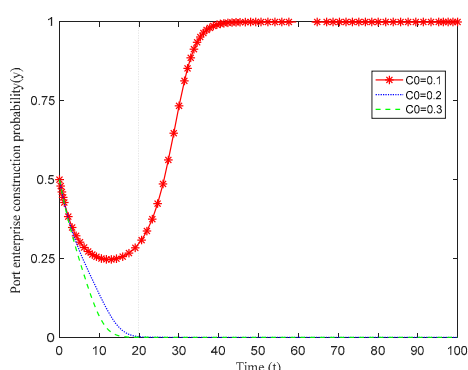
When the parameter c_0 takes values of 0.1, 0.2, and 0.3, respectively, while other coefficients and variables remain unchanged, with specific values shown in Table 5, the simulation results are illustrated in Figure 13.



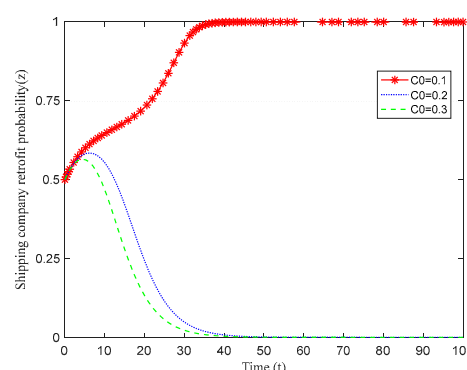
(a) 3D Trajectory of Three-Party Strategy Evolution



(b) Evolutionary path of government implementation strategy



(c) Evolutionary path of port enterprise construction strategy



(d) Evolutionary path of shipping company construction strategy

Figure 13. The effects of government policy cost on the evolutionary stabilization rate.

As depicted in Figure 13, when the policy cost $c_0 = 0.1$, x, z continues to increase, y initially decreases and then increases, and all three variables eventually converge toward 1. This indicates that under relatively low policy costs, the government exhibits a strong willingness to continuously promote shore power projects, thereby driving a gradual increase in the participation willingness of both the port enterprise and the shipping company. It should be noted that the port willingness y experiences a brief decline at the initial stage, which is mainly attributed to the relatively large scale of early investment required by ports and the fact that the utilization rate of shore power by vessels has not yet increased, resulting in a longer investment payback period. However, with the continuous implementation of policy incentives and the enhancement of vessel retrofitting willingness, the port's willingness to participate is correspondingly strengthened.

When $c_0 = 0.2$ and $c_0 = 0.3$, x and z initially increases and then decreases, while y continue to decline, and all three variables eventually converge toward 0. This indicates that although the government demonstrates a certain level of promotion willingness during the initial stage of policy implementation, its driving motivation gradually

weakens as policy costs increase, which subsequently leads to a decline in the participation willingness of both the port enterprise and the shipping company.

4.3.5. The Effects of the Presence or Absence of a Wind Turbine Power Generation System on the Evolutionary Paths of the Three Parties

Before the introduction of the wind turbine power generation system, the parameters related to the wind turbine system were set to 0 in this study, namely $c_2 = 0, s_2 = 0, \rho = 0, \theta = 0, M = 0, N = 0, Q_2 = 0$, while all other parameter values remained unchanged. The specific values are provided in Table 5. The simulation results are shown in Figure 14, where the willingness of all parties remains at a relatively low level and converges toward 0.

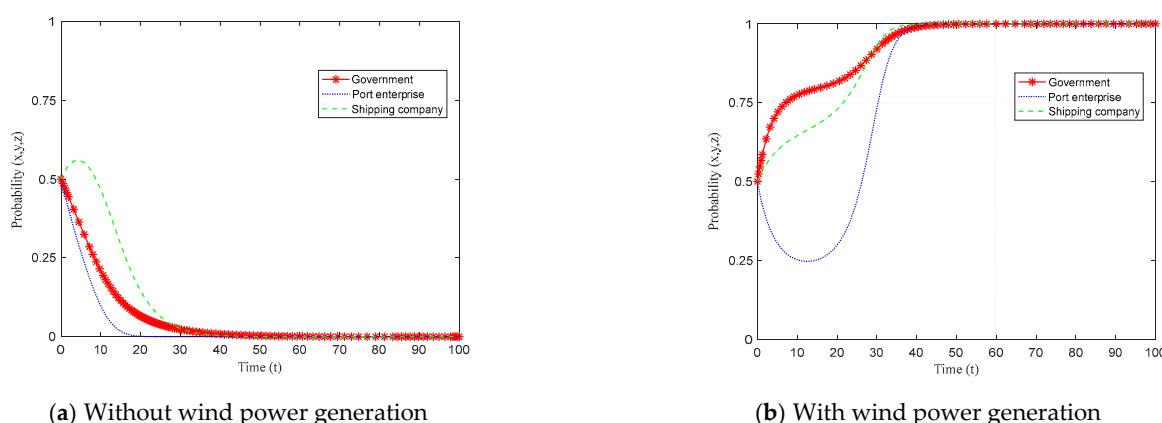
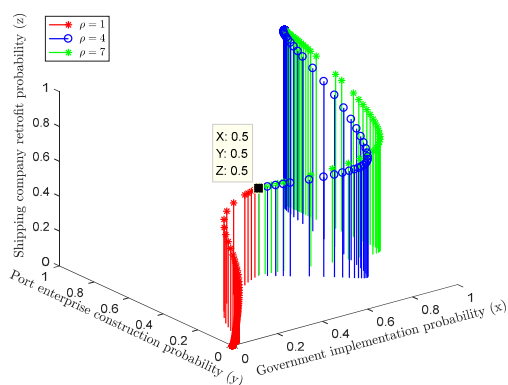


Figure 14. The evolutionary paths with and without the wind turbine power generation system.

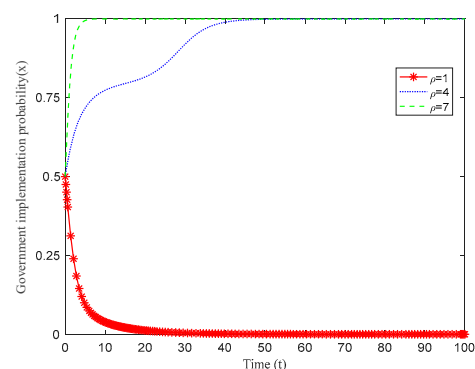
By comparing Figure 14a, b, it can be observed that after the introduction of the wind turbine power generation system, the willingness of the government, the port enterprise, and the shipping company increases significantly and converges toward 1. This difference can be attributed to the following reasons. When the application of the wind turbine power generation system is promoted by the government within the shore power system, the overall benefits of the system are enhanced, thereby strengthening the government's willingness to promote the development of shore power. For the port enterprise, although the initial investment increases, operating costs can be reduced in the long term through self-generation and self-consumption, which enhances its participation enthusiasm. The shipping company can benefit from improved power supply stability ensured by the wind turbine power generation system and can also enjoy advantages in electricity prices, which increases its willingness to adopt shore power. However, without the configuration of a wind turbine power generation system, the port enterprise would rely on the external power grid, the shipping company might face higher electricity prices or unstable power supply, and the government would find it difficult to achieve sustainable policy benefits, which would weaken its willingness to promote the development of shore power. Overall, the introduction of the wind turbine power generation system significantly enhances the driving force for the promotion of the shore power system.

4.3.6. The Effects of Wind Turbine Spillover Benefit Coefficient on the Evolutionary Paths of Different Stakeholders

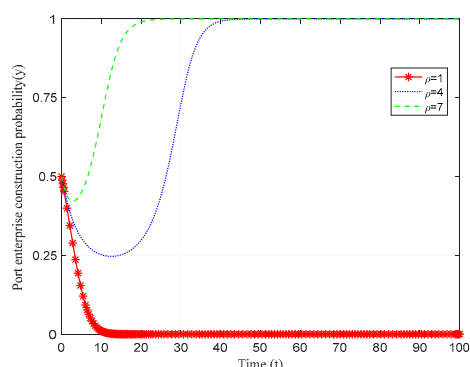
When the parameter ρ takes values of 1, 4, and 7, respectively, while other parameters and variables remain unchanged, with specific values shown in Table 5, the simulation results are presented in Figure 15.



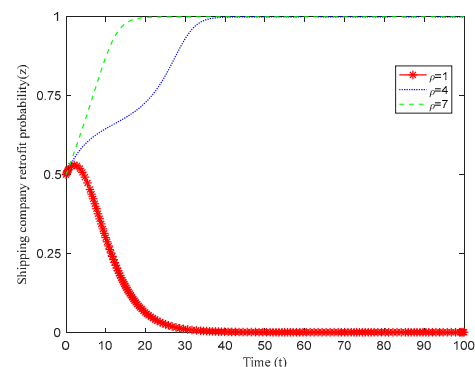
(a) 3D Trajectory of Three-Party Strategy Evolution



(b) Evolutionary path of government implementation strategy



(c) Evolutionary path of port enterprise construction strategy



(d) Evolutionary path of shipping company construction strategy

Figure 15. The effects of wind turbine spillover benefit coefficient on the evolutionary stabilization rate.

As depicted in Figure 15, when $\rho = 1$ (characterize the low wind penetration scenario, <10%), x, y exhibit a downward trend and z first increase slightly, then decrease rapidly. The main reason is that under low wind penetration, the spillover benefits generated by the wind power system are relatively low, which weakens the government's motivation to promote shore power policies, which leads to a reduced willingness among both port enterprises and shipping companies to adopt shore power. Taking Singapore as an example, constrained by limited land and wind resources, it has a low level of wind power penetration and limited spillover benefits, which weakens the government's incentive to promote coordinated shore power–wind power policies and further reduces the willingness of both port enterprises and shipping companies to adopt shore power.

However, when $\rho = 4, 7$ (characterize the medium wind power share scenario, 10–30% and the high wind power share scenario, >30%), both x, z show an upward trend, while y initially decreases and then increases, eventually converging toward 1. This indicates that under medium and high wind power penetration conditions, as the spillover benefits of the wind turbine power generation system increase, the government can obtain more significant economic returns and is therefore more willing to promote the construction of shore power and related wind power facilities. Although the port enterprise experiences fluctuations in willingness at the initial stage due to investment pressure, its participation willingness gradually recovers under the guidance of government policies, which jointly enhance the motivation of the shipping company to adopt shore power. Taking Denmark as an example, its high wind power penetration and pronounced spillover benefits give the government stronger incentives to promote coordinated shore power–wind power development through carbon trading and subsidies. As a result,

Denmark's shore power rollout is faster and exhibits a more systematic, well-structured approach.

5. Conclusions

5.1. Research Conclusions

Based on evolutionary game theory, this study constructs a tripartite game model involving the government, the port enterprise, and the shipping company, with a focus on analyzing the dynamic evolution process of strategies adopted by each party under conditions of bounded rationality. Combined with MATLAB simulations, the impacts of different factors on the evolutionary stable strategies are systematically examined. The results indicate that the effective promotion of shore power facilities relies on a multi-stakeholder collaborative mechanism. Based on the above analysis, the following conclusions are drawn.

- (1) The initial willingness of the three-party stakeholders has a significant impact on the evolutionary paths. When the initial willingness of two parties increases from 0.2 to 0.8, the strategy of the remaining party shifts from a passive strategy to an active strategy. This demonstrates that when two parties exhibit relatively high willingness, the third party is more likely to choose an active strategy and converge toward 1, thereby promoting the evolution of a stable strategy characterized by active cooperation among the three parties, namely, the implementation of policy support by the government, the construction of shore power facilities by the port enterprise, and the adoption of shore power technology by the shipping company.
- (2) When the government implements only a single subsidy policy or a carbon trading policy, the strategies adopted by the port enterprise and the shipping company in the promotion of shore power tend to be passive. However, when both subsidy policies and carbon trading policies are implemented simultaneously, the port enterprise and the shipping company tend to adopt active strategies. Furthermore, when the subsidy for shore power infrastructure construction is increased to 0.20, 0.22 and 0.24, the subsidy for wind power system construction to 0.19, 0.21 and 0.23, the subsidy for ship retrofitting to 0.11, 0.13 and 0.15, and the electricity price subsidy to 0.12, 0.14 and 0.16, and the carbon price is raised to 0.11, 0.16, and 0.21, the probabilities that port enterprises choose to build shore power facilities and that shipping companies choose to use shore power rise markedly from about 0.5 to nearly 1, driving the system to shift from "partial participation" to "near-universal adoption." In particular, when subsidies and carbon prices are further increased, the evolutionary speed of such active behaviors is markedly accelerated, which fully demonstrates the guiding role of government shore power policies.
- (3) The development of the wind turbine power generation system generates significant spillover benefits for the government. As the spillover benefit coefficient increases by 300% and 600%, the strategy adoption probabilities of the government, ports, and shipping companies rise markedly from about 50% to nearly 100%, thereby making the system more likely to evolve toward an actively cooperative equilibrium. However, the construction and use of shore power and the wind turbine power generation system exert impacts on the oil industry, which in turn weakens the government's motivation to support shore power. Under conditions of stable power supply, the port enterprise and the shipping company are more inclined to adopt shore power.

5.2. Policy Recommendations

To promote the adoption of shore power, this study proposes the following policy recommendations:

- (1) Government should promote the deployment of shore power through a synergistic policy mix that coordinates emissions trading with fiscal subsidies. A carbon pricing mechanism can make the benefits of emissions reductions explicit and provide sustained, stable market-based incentives, while fiscal subsidies can alleviate the burden of upfront investment and electricity-use costs. Together, these instruments strengthen the continuity and stability of incentives across both the construction and operational stages, thereby improving policy implementation efficiency and overall effectiveness.
- (2) During the promotion of shore power adoption, greater emphasis should be placed on the pivotal role of ports. Policy design should focus on strengthening oversight and constraints on ports, urging them to accelerate the construction of shore power facilities and enhance service and supply assurance so as to provide ships with a stable and predictable environment for using shore power. This, in turn, can encourage shipping companies to adopt shore power more proactively and consistently, facilitating the transition toward routine and large-scale deployment.

This study examines how heterogeneity in national energy structures affects shore power promotion. In the model specification, wind power is used as a representative clean energy source to characterize the combined effects of the energy mix on electricity prices, carbon reduction, and stakeholders' strategic choices, but other energy sources such as solar, hydropower, and nuclear power are not incorporated. Future research could extend this framework by integrating multiple clean energy types, thereby enabling a more systematic assessment of the applicability and effectiveness of shore power promotion policies under different energy structures.

Author Contributions: Conceptualization, D.C.; methodology, M.Y.; software, M.Y.; formal analysis, M.Y. and X.X.; investigation, M.Y. and X.X.; resources, B.Y.; writing—original draft preparation, D.C., M.Y. and X.X.; writing—review and editing, D.C. and B.Y.; visualization, M.Y. and X.X.; supervision, D.C. and B.Y.; project administration, D.C.; funding acquisition, D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Natural Science Foundation of Ningbo [grant number 2024J127] and the National Natural Science Foundation of China [grant numbers U24A20197 and 72271132].

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. A Numerical Example for a Payoff-Matrix–Cell (Government Implementation–Port Construction–Shipping Retrofit)

To enhance the reproducibility of the payoff matrix (Table 2), this paper provides, in the Appendix, a numerical example illustrating the calculation of a “single payoff cell.” We consider a representative scenario in which all parties adopt active strategies: the government chooses to implement the policy (Implement), the port chooses to construct shore power facilities (Construction), and the shipping company chooses to retrofit vessels and use shore power (Retrofit). This scenario corresponds to the cell $(x, y, z) = (1, 1, 1)$ in the payoff matrix.

As shown in Table 2, the payoff expressions for the three parties are $g_0 + R_0 + \rho M - \theta N - c_0 - s_1 - s_2 - s_3 - s_4$, $P_0 + P_1 - c_{p1} - c_{p2} + s_1 + s_2 - \sigma W_1 + P_c(Q_1 + Q_2)$, and

$B_0 - c_{s1} - c_{s2} + s_3 + s_4 - \sigma W_2 + P_c Q_3$, Substituting the baseline parameters in Table 4 and computing each term yields a government payoff of $g_0 + 0.66$, a port payoff of $P_0 + 0.42$, and a shipping company payoff of $B_0 + 0.19$. In the above results, g_0 , P_0 , and B_0 are strategy-independent baseline terms (provided that they take the same constant value across all strategy profiles). They merely shift the absolute payoff levels without affecting payoff differences among strategies. Therefore, they are normalized to zero uniformly. Under this normalization, the purely numerical payoff for this cell is 0.66, 0.42, 0.19.

Appendix B. Detailed Derivation of the Replicator Dynamic Equations (Taking the Government as an Example)

Under the mixed-strategy assumption, port enterprises and shipping companies independently randomize their strategy choices in each round of the game. Therefore, the joint probability of any strategy profile can be expressed as the product of the corresponding marginal probabilities. In each round, there are four possible strategy combinations, with joint occurrence probabilities given by: port enterprise invests in shore power and shipping company retrofits, yz ; port enterprise invests and shipping company does not retrofit, $y(1-z)$; port enterprise does not invest and shipping company retrofits, $(1-y)z$; and port enterprise does not invest and shipping company does not retrofit, $(1-y)(1-z)$. Accordingly, when the government's strategy is fixed to a given action (e.g., "implement the policy" or "not implement the policy"), the government's expected payoff can be written as the probability-weighted sum of its payoffs across these four cases by summing the payoff in each strategy combination multiplied by its corresponding joint probability, as follows.

The government's expected payoff under the "policy implementation" strategy:

$$U_x = yz(g_0 + R_0 + \rho M - \theta N - c_0 - s_1 - s_2 - s_3 - s_4) + y(1-z)(g_0 + \rho M - c_0 - s_1 - s_2) + z(1-y)(g_0 - c_0 - s_3) + (1-y)(1-z)(g_0 - c_0) \quad (A1)$$

The government's expected payoff under the "non-implementation" strategy:

$$U_{(1-x)} = yz(g_0 + R_1 + M - N) + y(1-z)(g_0 + M) + z(1-y)(g_0) + (1-y)(1-z)(g_0) \quad (A2)$$

The government's average expected payoff:

$$\bar{U}_x = xU_x + (1-x)U_{(1-x)} \quad (A3)$$

According to the definition of replicator dynamics, the evolutionary equation for the government's "policy implementation" strategy is: $F(x) = x(U_x - \bar{U}_x)$.

Since $\bar{U}_x = xU_x + (1-x)U_{(1-x)}$, it follows that $U_x - \bar{U}_x = (1-x)(U_x - U_{(1-x)})$.

Substituting the probability-weighted expressions of U_x and $U_{(1-x)}$ into the above equation and simplifying by expanding the terms and collecting like terms yields the government's replicator dynamic equation (Equation (A4)):

$$F(x) = x(x-1)(c_0 + yM + ys_1 + ys_2 + zs_3 - y\rho M - yzN - yzR_0 + yzR_1 + yzs_4 + yz\theta N) \quad (A4)$$

Similarly, the expected payoffs of port enterprises and shipping companies under their respective strategy choices can be probability-weighted, based on which their average expected payoffs and replicator dynamic equations are constructed. This leads to the replicator dynamic equations presented in Sections 3.4.2 and 3.4.3 of the main text (Equations (9) and (14)).

References

1. IMO. Fourth IMO Greenhouse Gas Study 2020—Full Report. 2021. Available online: https://ghgsmart.imo.org/wp-content/uploads/2023/05/Fourth-IMO-GHG-Study-2020-Full-report-and-annexes_compressed.pdf (accessed on 27 January 2026).
2. Tan, Z.; Sheng, D.; Yin, Y. Shore-power capacity allocation in a container shipping network under ships' strategic behaviors. *Transp. Res. Part B Methodol.* **2025**, *192*, 103151.
3. Chen, J.; Zheng, T.; Garg, A.; Xu, L.; Li, S.; Fei, Y. Alternative maritime power application as a green port strategy: Barriers in China. *J. Clean. Prod.* **2019**, *213*, 825–837.
4. Cheng, L.; Huang, P.; Zhang, M.; Yang, R.; Wang, Y. Optimizing electricity markets through game-theoretical methods: Strategic and policy implications for power purchasing and generation enterprises. *Mathematics* **2025**, *13*, 373.
5. Yu, N.; Lu, M. Analysis of the dynamic evolution game of government, enterprise and the public to control industrial pollution. *Sustainability* **2024**, *16*, 2760.
6. Offshore Energy. Sweden Inaugurates Its Second Onshore Power Facility for Cruise Vessels. 2025. Available online: https://www.offshore-energy.biz/sweden-inaugurates-its-second-onshore-power-facility-for-cruise-vessels/?utm_source (accessed on 27 January 2026).
7. Port of Rotterdam. Port of Rotterdam Authority and Eneco to Build Green Shore Electric Facility for Boskalis Ships in Waalhaven. 2022. Available online: https://www.portofrotterdam.com/en/news-and-press-releases/port-of-rotterdam-authority-and-eneco-to-build-green-shore-electric?utm_source (accessed on 27 January 2026).
8. Port of Seattle. The Past, Present, and Future of Shore Power. 2025. Available online: https://www.portseattle.org/blog/past-present-and-future-shore-power?utm_source (accessed on 27 January 2026).
9. Kumar, J.; Kumpulainen, L.; Kauhaniemi, K. Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions. *Int. J. Electr. Power Energy Syst.* **2019**, *104*, 840–852.
10. Yin, M.; Wang, Y.; Zhang, Q. Policy implementation barriers and economic analysis of shore power promotion in China. *Transp. Res. Part D Transp. Environ.* **2020**, *87*, 102506.
11. Zhang, X.; Zhang, L.; Xi, H.; Shao, Z.; Bell, M.G.H. Implications of government subsidies on shipping companies' shore power usage strategies in port. *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *165*, 102840.
12. Zhang, S.; Song, X. Carbon emissions reduction in shipping based on four-party evolutionary game. *Front. Mar. Sci.* **2025**, *12*, 1527598.
13. Radwan, M.E.; Chen, J.; Wan, Z.; Zheng, T.; Hua, C.; Huang, X. Critical barriers to the introduction of shore power supply for green port development: Case of Djibouti container terminals. *Clean Technol. Environ. Policy* **2019**, *21*, 1293–1306.
14. Gong, Y.; Zhou, Y.; Liu, X.; Huang, Y.; Lu, Q. Identifying effective incentive policies for promoting widespread adoption of shore power technology. *Transp. Res. Part D Transp. Environ.* **2024**, *126*, 103998.
15. Wu, L.; Wang, S. The shore power deployment problem for maritime transportation. *Transp. Res. Part E Logist. Transp. Rev.* **2020**, *135*, 101883.
16. Zhang, X.; Zhang, L.; Xi, H.; Shao, Z.; Bell, M.G.H. Shore power adoption strategies of shipping companies and pricing decisions of the port under subsidies and carbon taxes: A game theoretical analysis. *Transp. Res. Part E Logist. Transp. Rev.* **2026**, *205*, 104490.
17. Peng, Y.-T.; Wang, Y.; Li, Z.-C.; Sheng, D. Subsidy policy selection for shore power promotion: Subsidizing facility investment or price of shore power? *Transp. Policy* **2023**, *140*, 128–147.
18. Merkel, A.; Nyberg, E.; Ek, K.; Sjöstrand, H. Economics of shore power under different access pricing. *Res. Transp. Econ.* **2023**, *101*, 101330.
19. Daniel, H.; Trovão, J.P.F.; Williams, D.; Boulon, L. Unlocking shore power in St. Lawrence and Great Lakes for cargo ships. *Transp. Res. Part D Transp. Environ.* **2024**, *131*, 104230.
20. Lu, B.; Xu, X.; Qin, X.; Cheng, T.C.E. Optimal shore power adoption decisions with government regulation considering port competition. *Transp. Res. Part E Logist. Transp. Rev.* **2024**, *188*, 103629.
21. Brunetti, I.; Hayel, Y.; Altman, E. State-policy dynamics in evolutionary games. *Dyn. Games Appl.* **2016**, *8*, 93–116.
22. Chacoma, A.; Kuperman, M.N.; Zannette, D.H. Payoff nonmonotonic dynamics IN an evolutionary game. *Adv. Complex Syst.* **2016**, *19*, 1650007.
23. Zhang, T.; Hong, C.; Kramberger, T.; Wang, Y. Integrating carbon tax and subsidies: An evolutionary game theory-based shore power promotional strategy analysis. *Systems* **2025**, *13*, 239.
24. Qiao, W.; Yin, X. Understanding the impact on energy transition of consumer behavior and enterprise decisions through evolutionary game analysis. *Sustain. Prod. Consum.* **2021**, *28*, 231–240.

25. Wang, X.P.; Zhang, Z.M.; Guo, Z.H.; Su, C.; Sun, L.H. Energy structure transformation in the context of carbon neutralization: Evolutionary game analysis based on inclusive development of coal and clean energy. *J. Clean. Prod.* **2023**, *398*, 136626.
26. Zhang, S.; Song, X. Synergies between government, ports, shipping companies, and power companies. *Front. Mar. Sci.* **2025**, *12*, 1671057.
27. Gonzalez, N.; Serna-Torre, P.; Sánchez-Pérez, P.A.; Davidson, R.; Murray, B.; Staadecker, M.; Szinai, J.; Wei, R.; Kammen, D.M.; Sunter, D.A.; et al. Offshore wind and wave energy can reduce total installed capacity required in zero-emissions grids. *Nat. Commun.* **2024**, *15*, 6826.
28. Fang, C.; Ma, T. Technology adoption with carbon emission trading mechanism: Modeling with heterogeneous agents and uncertain carbon price. *Ann. Oper. Res.* **2021**, *300*, 577–600.
29. Jin, J.; Zhang, X.; Xu, L.; Wen, Q.; Guo, X. Impacts of carbon trading and wind power integration on carbon emission in the power dispatching process. *Energy Rep.* **2021**, *7*, 3887–3897.
30. Chameides, W.; Oppenheimer, M. Carbon trading over taxes. *Science* **2007**, *315*, 1670.
31. Demailly, D.; Quirion, P. European Emission Trading Scheme and competitiveness: A case study on the iron and steel industry. *Energy Econ.* **2008**, *30*, 2009–2027.
32. Wang, S.; Zhen, L.; Psaraftis, H.N.; Yan, R. Implications of the EU's inclusion of maritime transport in the emissions trading system for shipping companies. *Engineering* **2021**, *7*, 554–557.
33. Cheng, B.; Dai, H.; Wang, P.; Zhao, D.; Masui, T. Impacts of carbon trading scheme on air pollutant emissions in Guangdong Province of China. *Energy Sustain. Dev.* **2015**, *27*, 174–185.
34. Zhang, W.; Li, J.; Li, G.; Guo, S. Emission reduction effect and carbon market efficiency of carbon emissions trading policy in China. *Energy* **2020**, *196*, 117117.
35. Sun, Y.; Zheng, J.; Yang, L.; Li, X. Allocation and trading schemes of the maritime emissions trading system: Liner shipping route choice and carbon emissions. *Transp. Policy* **2023**, *148*, 60–78.
36. Wang, T.; Wu, Z.; Cheng, P.; Wang, Y. The effect of carbon quota allocation methods on maritime supply chain emission reduction. *Transp. Policy* **2024**, *157*, 155–166.
37. Chua, Y.J.; Soudagar, I.; Ng, S.H.; Meng, Q. Impact analysis of environmental policies on shipping fleet planning under demand uncertainty. *Transp. Res. Part D Transp. Environ.* **2023**, *120*, 103744.
38. Zhu, M.; Shen, S.; Shi, W. Carbon emission allowance allocation based on a bi-level multi-objective model in maritime shipping. *Ocean Coast. Manag.* **2023**, *241*, 106665.
39. Friedman, D. Evolutionary games in economics. *Econom. J. Econom. Soc.* **1991**, *59*, 637–666.
40. Fang, Y.; Wei, W.; Mei, S.; Chen, L.; Zhang, X.; Huang, S. Promoting electric vehicle charging infrastructure considering policy incentives and user preferences: An evolutionary game model in a small-world network. *J. Clean. Prod.* **2020**, *258*, 120753.
41. Li, N.; Lv, T.; Guo, Y.; Xu, J.; Zang, X.; Guo, J.; Li, M. Can government supervision ensure compliance by photovoltaic enterprises? An evolutionary game analysis. *Energy Policy* **2025**, *206*, 114740.
42. Sheng, J.; Tang, L.; Yang, Z.; Yu, M.; Liu, X. Strategies of stakeholders' selection of shore-to-ship power in China. *Transp. Res. Part D* **2023**, *119*, 103729.
43. Xu, L.; Di, Z.; Chen, J.; Shi, J.; Yang, C. Evolutionary game analysis on behavior strategies of multiple stakeholders in maritime shore power system. *Ocean Coast. Manag.* **2021**, *202*, 105508.
44. Xinhua News. Shandong Rizhao: Enhancing Development 'Gold Content' with Ecological 'Green Content'. 2025. Available online: <http://www.sd.xinhua.org/20251231/2a98ccabb0e048688d9652433ab866af/c.html> (accessed on 28 January 2026).
45. Fraunhofer, I.S.E. Levelized Cost of Electricity (LCOE) Renewable Energy Technologies. 2024. Available online: <https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html> (accessed on 28 January 2026).
46. European Commission. What Is the Innovation Fund? 2024. Available online: https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/what-innovation-fund_en?utm_source (accessed on 28 January 2026).
47. China Central Television. The First Blue Carbon Auction in China Concluded in Xiangshan, Zhejiang. 2023. Available online: <https://eco.cctv.com/2023/03/01/ARTIwKVp2eoAoGJCddViWOpY230301.shtml> (accessed on 28 January 2026).

48. World Bank. Value Loss Due to Power Outage in the Electricity Sector (as a Proportion of Sales Revenue). 2023. Available online: https://data.worldbank.org.cn/indicator/IC.FRM.OUTG.ZS?end=2024&name_desc=true&start=2023&type=shaded&view (accessed on 28 January 2026).
49. Carbon Tracker. Petro States of Decline: Oil and Gas Producers Face Growing Fiscal Risks as the Energy Transition Unfolds. 2023. Available online: <https://carbontracker.org/reports/petrostates-of-decline/> (accessed on 28 January 2026).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.