Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 2359911, 12 pages
https://doi.org/10.1155/2022/2359911

Research Article

Decisions on Technologies for Emissions Control in Port Areas under Subsidy and Low-Carbon Preferences of Customers

Haiying Zhou

Department of Port and Shipping Management, Guangzhou Maritime University, Guangzhou 510725, China

Correspondence should be addressed to Haiying Zhou; cindychou@163.com

Received 24 August 2022; Accepted 17 October 2022; Published 15 November 2022

Academic Editor: Reza Lotfi

The emission control technologies decisions of port and shipping enterprises under subsidy and customers' low-carbon preferences are discussed from a supply chain perspective. The game models are established under three game models (port-leader Stackelberg game, ship-leader Stackelberg game, and Nash game). The obtained results show that the impact of subsidy and low-carbon preference on demand in its pricing always is considered by the leader in the port supply chain. The profits and emissions in the Nash game are higher than that in the Stackelberg game. When subsidies and customers' low-carbon preferences are low, the supply chain's overall profits of using low sulfur oil are higher than that of using shore power. But the supply chain's carbon emissions of adopting low sulfur oil are also higher than that of adopting shore power. When subsidies and low-carbon preferences of customers are high, the supply chain's overall profits of using shore power are higher than that of using low sulfur oil. But the supply chain's carbon emissions of adopting shore power are also higher than that of adopting low sulfur oil. When subsidy and low-carbon preference of customers are in the appropriate(medial) range, the supply chain would choose shore power to reduce emissions from the perspective of profits, and the whole carbon emissions of using shore power are lower than that of using low sulfur oil, so the regulator(government) and enterprises can achieve a win-win situation. Hence for a regulator who has to balance emission control and enterprises' profits, implementing moderate subsidy within the appropriate range is the better strategy.

1. Introduction

The Global port and shipping network is an important driving force for world economic growth. However, frequent shipping activities bring a large mount of pollutants such as CO, SO_2, NO_x, particulate matter, and CO_2 [1]. As an essential part of international shipping, the port industry also produces many above pollutants, seriously threatening the health of coastal residents. As a country with so many ports worldwide, the Chinese government has been aware of the port pollution problem and implemented strict measures. In December 2015, MOT of the People's Republic of China set up Domestic Emission Control Areas in the Waters of the Pearl River Delta, the Yangtze River Delta, and Bohai Rim (Beijing, Tianjin, and Hebei). At the end of 2018, the scope of China's ECAs extended to the country's coastal areas and major inland waters. In July 2019, The government of China required ships equipped with shore power (SP) facilities to use SP when docking in ports capable of providing shore power for more than three hours in ECAs, with no effective alternative emissions reduction measures used [2].

Now, low sulfur oil (LSFO) and shore power(SP) are the popular emission reduction technologies used by ships in port areas. Using SP requires joint efforts and investment from ports and vessels. Ports build shore-side facilities to transmit power, while ships install receiving facilities to receive power. The construction of SP facilities requires a large initial investment from ports and vessels, but SP can effectively reduce emissions. Hall [3] proposed ships in British berths could reduce NOx by 91.6% and carbon emissions by about 24.5% when using SP. LSFO is a kind of clean energy with less than 0.1% sulfur. Using LSFO is without upgrading and adding equipment, so there is no initial investment for port and ship. But LSFO is expensive and produces more carbon emissions than SP.

Chinese government subsidized ports and shipping enterprises to promote the use of SP. Statistics released by MOT of China show that from 2016 to 2018, the central government provided subsidies for ports and ships in coastal and inland port areas to construct SP. In the three years, a total of 740 million yuan has been arranged to support the use of SP. In addition, local governments also subsided the use of SP. For example, from March 2015 to December 2019, Shenzhen of China issued a total subsidy of 75.5568 million yuan for SP [4]. With support from the government, more than 40 percent of the major Chinese ports have installed SP infrastructure. However, the current penetration rate of SP refitted ships is less than 1% [5], and the willingness of ships to use SP is low.

At the same time, consumers are increasingly aware of environmental protection and tend to pay higher prices for low-carbon products [6]. Wang and Zhao [7] studied the carbon emission reduction behavior and decision of manufacturers and retailers under the circumstance that consumers with low carbon preference for products and found that consumers' low carbon preference played an important role in enterprise decision making.

What is the influence of subsidy and customers' low-carbon preference on the decision of emission control technologies for the port and ship? What is the effect of power structures on the choice of emission control technologies for the port and ship? In order to compare the two technologies (SP and LSFO), a port supply chain consisting of one port and one shipping company is proposed. In the port supply chain, the port is an upstream member and provides services to the shipping company, while the shipping company provides services to customers. So the game models are built under three scenarios(port-leader Stackelberg (PS), ship-leader Stackelberg (SS) [8], and Nash (NS) game), and the equilibrium results are obtained for comparative analysis.

There are three main contributions in this paper. Firstly, the choice of emission control technologies is studied from a supply chain perspective, which is seldom investigated in the available literature. Secondly, two kinds of technologies (SP and LSFO) are compared under subsidy, and the low-carbon preference of customers respects economic and social benefits. At last, the influence of the customers' low-carbon preference on the technologies decision of the port supply chain is considered, which is seldom studied in the existing literature. The obtained results help the port and shipping company choose the appropriate emission reduction technologies and provide insights on government policies.

2. Literature Review

The carbon emissions emitted by the supply chain have aroused widespread concern, and some governments implemented subsidy policies to promote carbon emissions reduction. In this context, the influence of subsidies on the supply chain and the related operational decisions are widely studied by academics. Yang and Nie [9] studied the impacts of subsidies on improving clean innovation considering technological spillover. They concluded subsidy promoted firms' innovation and more subsidies yielded less emission, but the subsidy environmental efficiency decreased with subsidy intensity. Meng et al. [10] considered three innovation subsidy scenarios in a supply chain and concluded that the government would subsidize the core manufacturer rather than the manufacturer and upstream supplier. Huang et al. [11] investigated a supply chain with a capital-limited green manufacturer and compared the three modes (manufacturing subsidy, green credit, and sales subsidy) to find the win-win subsidy mode. Gu et al. [12] proposed a closed-loop supply chain model of two-stage battery secondary use consisting of secondary user, battery (re) manufacturer, and government. Wang et al. [13] explored the influence of government subsidies and remanufacturer's altruistic preferences on decision-making in a low-carbon e-commerce closed-loop supply chain. Chen et al. [14] analyzed a hybrid subsidy mechanism that considered both input and output subsidies by stochastic optimization methods. Mondal and Giri [15] set a two-level green closed-loop supply chain under government subsidy to explore the effects of government intervention on the optimal results. Miao et al. [16] explored the government's subsidy policies for manufacturers, retailers, and consumers in a secondary supply chain. Mu et al. [17] modeled a platform supply chain considering consumers' green preferences. In the platform supply chain, the manufacturer implemented green research and development activities, and the third-party platform adopted data-driven marketing (DDM) activities to promote green products. Liu et al. [18] modeled a fresh supply chain consisting of one producer, one blockchain-based traceability service provider, and one retailer as the research object considering government subsidies, which were divided into a fixed strategy and a varying strategy. Li et al. [19] examined a two-echelon maritime supply chain consisting of a port and a shipping line under a government green subsidy. They concluded that the SP reliability was affected by shipper SP preference and decision period. The actual shipper's subsidies and government subsidies were inefficient when the shipper's preference was high. Wange and Jiao [20] developed a game model under three different power structures to investigate the equilibrium solutions of two carriers. Sun et al. [21] explored the influence of subsidy participants on cruise home ports in the cruise supply chain. They proposed that subsidy policies accelerated the integration of the cruise supply chain and improved the competitiveness between cruise home ports. Li and Jiao [22] constructed the LNG-fuelled ship supply chain of a manufacturer and an owner considering government subsidy and studied the pricing, market demand, and supply chain benefits. However, most of the existing literature studied subsidy policy with respect to the product supply chain, and the present investigates the emission reduction decision under subsidy from the perspective of the port and navigation supply chain, which fills the gap to some extent.

In the background of the global low-carbon economy, consumers' low-carbon preference has also attracted the attention of scholars worldwide. In the port and shipping supply chain, customers' low-carbon preference also plays a positive role in port emission reduction, but there are few pieces of research on this aspect. In the studies related to product supply chains, Yu and Hou [23] investigated how the consumer's low-carbon preference influences market demand. A green supply chain pricing decision model under consumer's green preference considering different forms of subsidy and various power structures is built in [24]. Cheng et al. [25] investigated the optimal strategies in an economically constrained closed-loop supply chain low-carbon preferences of customers. Sana [26] proposed a dual channel inventory model in which the capacity of the market of a particular product was uncertain. The optimal subsidy rate and production of a supply chain considering consumer environmental consciousness are studied by Chen et al. [27]. Long [28] proposed a three-echelon manufacturing closed-loop supply chain under consumers' low-carbon preference to construct Stackelberg game models under government subsidies. Most of the above-given literature considered the green preference from the perspective of product consumers without considering the low-carbon preference of customer groups in the port and shipping field. This paper investigates the influence of customers' low-carbon preference on the port and shipping supply chain, which fills the gap to a certain extent.

SP and LFSO are the two popular technologies to reduce emissions. Thalis et al. [29] analyzed the prospect of SP by testing the quantitative framework and concluded that the regulators' support is vital for promoting SP. A calculation method estimating concrete environmental charges in ports was proposed in [30], which can encourage short route ships to adopt shore power. Reusser and Perez [31] evaluated the emission impact by using the bidirectional power flow control strategy when ships used SP in berths and optimized the auxiliary engine operating profile. Martínez–López et al. [32] evaluated the effect of emission reduction of shore power and LNG in Switzerland by calculation method. Piccoli et al. [33] analyzed the regulatory, economic, and environmental elements that could facilitate SP as a standard installation in the Mediterranean Sea.

Bakar et al. [34] provided a data-driven berthing prediction method for ship suing SP with various models such as artificial neural networks, decision tree, random forest, multiple linear regression, and extreme gradient boosting. Concerning low sulfur fuel oil, Panasiuk and Lebedevas [35] compared the advantages and disadvantages of using LSFO and scrubber in ECAs. Xing et al. [36] carry out A technological review to identify the most promising alternative marine fuels taking into account the reduction of nitrogen oxides, carbon dioxide emissions, and sulfur oxides as well as sustainability. At present, the most relevant literature analyzes the feasibility of the two technologies from the aspect of emission reduction and cost. The comparative analysis of the two technologies is lacking. This study compares the two technologies regarding technological technical differences and economic and social benefits, which enriched the relevant research.

The rest of this article is as follows: the problem is stated in Section 3. The results, including solutions, comparative analysis, and discussion, are given in Section 4. Managerial insights and practical implications are proposed in Section 5. At last, Section 6 provides the conclusions.

3. Problem Statement

3.1. Problem Description. In a port supply chain (Figure 1), the ship provides services for customers and obtains revenues but pays the port for berthing services. So the total service price of customers includes the port's charges and the fee of the ships. Under subsidy and low-carbon preference, the supply chain can choose SP and LSFO to reduce emissions. SP increases the cost of the port and the shipping company for equipping SP facilities, whereas LSFO only increases the ship's costs. The demand correlation and competition among berthed ships are weak. Therefore, this paper proposes a supply chain composed of a port and a ship for simple illustration. This setting somewhat describes reality and is widely used in available literature [10]. Of course, it can also be extended to multiple ports and ships in future studies.

3.2. Notation. Table 1 shows the relevant parameters and variables. SP and LSFO are represented by subscript i ($i = E, L$). Three types of games (PS, SS, and NS) are denoted by subscript j ($j = P, S, N$). The superscript k ($k = s, p, sc$) indicates the object of the ship, port, and the supply chain. p denotes the supply chain's service price and satisfies $p = m + w$.

3.3. Basic Assumptions. Two key assumptions are presented to facilitate the subsequent modelling and analysis.

Assumption 1: $e_E \langle e_L, c_E + c_s \rangle c_L$.

Compared with LSFO, SP produces less carbon emissions [37], i.e., $e_E < e_L$. The costs of SPareassumed higher, i.e., $c_E + c_s > c_L$.

Assumption 2: Following Qian et al. [38], Yang et al. [39], the function of demand is $q = a - bp + \gamma(e - e_i) = a - b(m + w) + \gamma(e - e_i)$, $a, b > 0$.

3.4. Models. When SP is adopted, the profits of port, ship, and supply chain are

$$U_E^p = (m - c_E)q. \tag{1}$$

$$U_E^s = (w - c_t - c_s)[a - b(m + w)] + q(e - e_E)\theta. \tag{2}$$

$$U_E^{sc} = U_E^s + U_E^p. \tag{3}$$

The total carbon emissions are

$$T_E = qe_E. \tag{4}$$

In formula (2), the first term denotes the ship's revenue from serving customers when SP is used, and the second part represents the subsidy from the government.

When LSFO is adopted, the models are derived as follows:

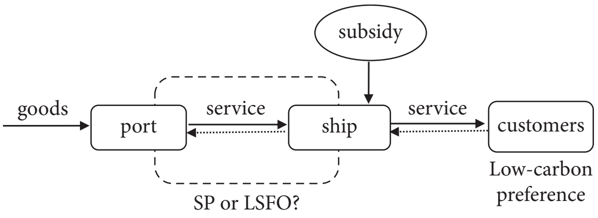

Figure 1: The emission control technology choices of the port supply chain.

Table 1: Notation and definition.

Notation	Description
Parameters	
a	Market size, $a > 0$
b	The sensitivity factor of the market demand to the price$b > 0$
q	Demand for services
c_t	Ship's unit ocean transportation cost
c_s	Ship' sunit service cost with adoption SP
c_L	Ship's unit service cost when LSFO is adopted
c_E	Port's unit service cost when SP is adopted
γ	Low-carbon preference of customers
θ	Subsidy on unit carbon emissions reduction
e_i	Unit carbon emissions of technology i
e	Unit carbon emissions with no emissions reduction technology
U^k_{i-j}	The profits of$k$with application of i in j game
T_{i-j}	The total carbon emissions of the supply chain with adoption i in j game
sw_{i-j}	The social welfare of the supply chain with adoption i in j game decision variables
Decision variables	
w_{i-j}	Ship's service price with adoption i in j game
m_{i-j}	Port's service price with adoption i in j game

$$U^p_L = mq, \tag{5}$$

$$U^s_L = (w - c_t - c_L)[a - b(m + w)] + q(e - e_L)\theta, \tag{6}$$

$$U^{sc}_L = U^s_L + U^p_L, \tag{7}$$

$$T_L = qe_L. \tag{8}$$

In formula (6), the first term represents the revenue of ship from serving for customers when LSFO is used, and the second part represents the subsidies from the government.

4. Results

In this section, the computational results of the above models are obtained by standard backward induction. The comparative analysis, sensitivity analysis, and discussion are given based on the computational results.

4.1. The Equilibrium Solutions of the Models. In the port supply chain, When SP is adopted, the equilibrium solutions of equations (1)–(4) under three different power structures are obtained by standard backward induction.

(1) In ship-leader Stackelberg, the profits of port are: $U^p_E = (m - c_E)q$.
Because $(\partial^2 U^p_E/\partial m^2) < 0$, solving $(\partial U^p_E/\partial m) = 0$, then $m^* = (a + bc_E - bw + \gamma(e - e_E)/2b)$.
Substituting m^* into equation (2), and solving $(\partial U^s_E/\partial w) = 0$, thus

$$\begin{aligned}
w_{E-S} &= \frac{a - bc_E + bc_s + bc_t + (\gamma - b\theta)(e - e_E)}{2b},\\
m_{E-S} &= \frac{a + (\gamma + b\theta)(e - e_E) + b(3c_E - c_s - c_t)}{4b},\\
U^p_{E-S} &= \frac{(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{16b},\\
U^s_{E-S} &= \frac{(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{8b},\\
U^{sc}_{E-S} &= \frac{(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{16b},\\
T_{E-S} &= \frac{1}{4}e_E(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta)).
\end{aligned} \tag{9}$$

(2) In Nash game, the profits of the shipping company are: $U^s_E = (w - c_t - c_s)[a - b(m + w)] + q(e - e_E)\theta$.
Because $(\partial^2 U^s_E/\partial w^2) < 0$, Solving $(\partial U^s_E/\partial w) = 0$, thus

$$w^* = \frac{a + bc_s + bc_t - bm + (\gamma - b\theta)(e - e_E)}{2b}. \tag{10}$$

The port's profits are: $U_E^p = (m - c_E)q$. Because $(\partial^2 U_E^p/\partial m^2) < 0$, solving $(\partial U_E^p/\partial m) = 0$, thus

$$m^* = \frac{a + bc_E - bw + \gamma(e - e_E)}{2b}, \tag{11}$$

Now solving equations (9)-(10) simultaneously, thus

$$\begin{aligned}
m_{E-N} &= \frac{a + \gamma(e - e_E) + b(2c_E - c_s - c_t + e\theta - e_E\theta)}{3b},\\
w_{E-N} &= \frac{a + \gamma(e - e_E) - b(c_E - 2c_s - 2c_t + 2e\theta - 2e_E\theta)}{3b},\\
U_{E-N}^p &= \frac{(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{9b},\\
U_{E-N}^s &= \frac{(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{9b},\\
U_{E-N}^{sc} &= \frac{2(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{9b},\\
T_{E-N} &= \frac{1}{3}e_E(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta)).
\end{aligned} \tag{12}$$

(3) In port-leader game, the profits of shipping company are: $U_E^s = (w - c_t - c_s)[a - b(m + w)] + q(e - e_E)\theta$. Because $(\partial^2 U_E^s/\partial w^2) < 0$, solving $(\partial U_E^s/\partial w) = 0$, $w^* = a + bc_s + bc_t - bm + (\gamma - b\theta)(e - e_E)/2b$ .Substituting w^* into equation (2), and solving $(\partial U_E^p/\partial m) = 0$, thus,

$$\begin{aligned}
m_{E-P} &= \frac{a + \gamma(e - e_E) + b(c_E - c_s - c_t + e\theta - e_E\theta)}{2b},\\
w_{E-P} &= \frac{a + \gamma(e - e_E) - b(c_E - 3c_s - 3c_t + 3e\theta - 3e_E\theta)}{4b},\\
U_{E-P}^p &= \frac{(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{8b},\\
U_{E-P}^s &= \frac{(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{16b},\\
U_{E-P}^{sc} &= \frac{3(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta))^2}{16b},\\
T_{E-P} &= \frac{1}{4}e_E(a + \gamma(e - e_E) - b(c_E + c_s + c_t - e\theta + e_E\theta)).
\end{aligned} \tag{13}$$

When LSFO is adopted by the supply chain, similar to SP, equations (5)–(8) are solved by standard backward induction again. Since the process is the same, here is not repeated. Table 2 gives the results when LSFO is adopted.

where $B = a + \gamma(e - e_L) - b(c_L + c_t - e\theta + e_L\theta)$.

4.2. Analysis.

In this section, the impacts of different parameters on optimal price, profits, and total emissions are obtained through the comparative analysis and sensitivity analysis, which can help the shipping company to choose suitable technologies and provide insights for government policies.

4.2.1. Optimal Service Price Analysis.

Taking the partial derivative of m_{i-j} and w_{i-j} with respect to different parameters:

$$\begin{aligned}
&\frac{\partial m_{E-j}}{\partial c_E} > 0, \frac{\partial m_{E-j}}{\partial \gamma} > 0, \frac{\partial m_{E-j}}{\partial \theta} < 0, \frac{\partial m_{E-j}}{\partial c_s} < 0, \frac{\partial m_{E-j}}{\partial c_t}\\
&\quad < 0, \frac{\partial w_{E-j}}{\partial c_E} < 0, \frac{\partial w_{E-j}}{\partial \theta} < 0, \frac{\partial w_{E-j}}{\partial \gamma} > 0, \frac{\partial w_{E-j}}{\partial c_s} > 0, \frac{\partial w_{E-j}}{\partial c_t} > 0.\\
&\frac{\partial m_{L-j}}{\partial c_L} < 0, \frac{\partial m_{L-j}}{\partial \gamma} > 0, \frac{\partial m_{L-j}}{\partial \theta} < 0, \frac{\partial m_{L-j}}{\partial c_t} < 0, \frac{\partial w_{L-j}}{\partial \theta}\\
&\quad < 0, \frac{\partial w_{L-j}}{\partial \gamma} > 0, \frac{\partial w_{E-j}}{\partial c_t} > 0.
\end{aligned} \tag{14}$$

Therefore, Lemma 1 can be obtained as follows:

Lemma 1. *In the port supply chain, when SP is used, m_{E-j} is increasing in $c_E\gamma$, but decreasing in c_s, c_t, $\theta.w_{E-j}$ is increasing in c_sc_t and γ, but decreasing in $c_E\theta$. When LSFO is used, m_{L-j} is increasing in c_L and γ, but decreasing in c_t, θ. w_{L-j} is increasing in c_t, c_L and γ, but decreasing in θ.*

Obviously, the price of port and ship increases in their own operational costs, and the total service price of the supply chain increases in γ, and decreases in θ. However, both members of the supply chain may decrease the prices when the costs of the other increase to earn more profits.

It can be proved that:

$$m_{E-P} - m_{E-N} = \frac{a + (\gamma + b\theta)(e - e_E) - b(c_E + c_s + c_t)}{6b}, m_{E-S} - m_{E-N} = -\frac{a + (\gamma + b\theta)(e - e_E) - b(c_E + c_s + c_t)}{12b}$$

Table 2: Results when LSFO is adopted.

Cases	m_{L-j}	w_{L-j}	T_{L-j}
$j=S$	$a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)/4b$	$a+(\gamma-b\theta)(e-e_L)+b(c_L+c_t)/2b$	$e_LB/4$
$j=N$	$a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)/3b$	$a+(\gamma-2b\theta)(e-e_L)+2b(c_L+c_t)/3b$	$e_LB/3$
$j=P$	$a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)/2b$	$a+(\gamma-3b\theta)(e-e_L)+3b(c_L+c_t)/4b$	$e_LB/4$
Cases	U^p_{L-j}	U^s_{L-j}	U^{sc}_{L-j}
$j=S$	$B^2/16b$	$B^2/8b$	$3B^2/16b$
$j=N$	$B^2/9b$	$B^2/9b$	$2B^2/9b$
$j=P$	$B^2/8b$	$B^2/16b$	$3B^2/16b$

Note: Where $B=a+\gamma(e-e_L)-b(c_L+c_t-e\theta+e_L\theta)$.

$$\begin{aligned}
m_{E-P}-m_{E-S}&=\frac{a+(\gamma+b\theta)(e-e_E)-b(c_E+c_s+c_t)}{4b},\ w_{E-P}-w_{E-N}=-\frac{a+(\gamma+b\theta)(e-e_E)-b(c_E+c_s+c_t)}{12b}\\
w_{E-P}-w_{E-S}&=-\frac{a+(\gamma+b\theta)(e-e_E)-b(c_E+c_s+c_t)}{4b},\ w_{E-S}-w_{E-N}=\frac{a+(\gamma+b\theta)(e-e_E)-b(c_E+c_s+c_t)}{6b}\\
m_{L-P}-m_{L-N}&=\frac{a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)}{6b},\ m_{L-S}-m_{L-N}=-\frac{a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)}{12b}\\
m_{L-P}-m_{L-S}&=\frac{a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)}{4b},\ w_{L-P}-w_{L-N}=-\frac{a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)}{12b}\\
w_{L-P}-w_{L-S}&=-\frac{a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)}{4b},\ w_{L-S}-w_{L-N}=\frac{a+(\gamma+b\theta)(e-e_L)-b(c_L+c_t)}{6b}.
\end{aligned}\tag{15}$$

Since $q>0$, θ must satisfies $\theta>b(c_E+c_s+c_t)-a/b(e-e_E)-\gamma/b$, $\theta>b(c_L+c_t)-a/b(e-e_L)-\gamma/b$, therefore, $m_{i-P}>m_{i-N}>m_{i-S}$, $w_{i-P}<w_{i-N}<w_{i-S}$.

Thus, Proposition 1 is as follows:

Proposition 1. *The optimal prices satisfy*

$$m_{i-P}>m_{i-N}>m_{i-S},\ w_{i-P}<w_{i-N}<w_{i-S}. \tag{16}$$

Lemma 1 and Proposition 1 indicate that under all three power structures, the impact of subsidy and customer's low-carbon preference on demand in its pricing always is considered by the leader. Therefore, the optimal price in the Nash game is lower than that in one dominant game.

4.2.2. Profits Analysis. Taking the partial derivative of U^{sc}_{i-P}, U^{sc}_{i-P} and U^{sc}_{i-N} with respect to different parameters:

(1) when $j=P$: $\partial^2U^{sc}_{i-P}/\partial^2c_i=(3b/8)>0$, $\partial^2U^{sc}_{i-P}/\partial^2c_t=\partial^2U^{sc}_{i-P}/\partial^2c_s=(3b/8)>0$, $\partial^2U^{sc}_{i-P}/\partial^2c_i=3be_i^2/8>0$, $\partial^2U^{sc}_{i-P}/\partial^2\theta=3b(e_i-e)^2/8>0$, $\partial^2U^{sc}_{i-P}/\partial^2\gamma=3(e_i-e)^2/8>0$ and $\partial^2U^{sc}_{i-P}/\partial^2e_i=3b\theta^2/8>0$

(2) when $j=S$: $\partial^2U^{sc}_{i-S}/\partial^2c_i=(3b/8)>0$, $\partial^2U^{sc}_{i-S}/\partial^2c_t=\partial^2U^{sc}_{i-S}/\partial^2c_s=(3b/8)>0$, $\partial^2U^{sc}_{i-S}/\partial^2c_i=(3be_i^2/8)>0$, $\partial^2U^{sc}_{i-P}/\partial^2\theta=3b(e_i-e)^2/8>0$, $\partial^2U^{sc}_{i-P}/\partial^2\gamma=3(e_i-e)^2/8>0$ and $\partial^2U^{sc}_{i-S}/\partial^2e_i=(3b\theta^2/8)>0$

(3) when $j=N$: $\partial^2U^{sc}_{i-N}/\partial^2c_i=4b/9>0$, $\partial^2U^{sc}_{i-N}/\partial^2c_t=\partial^2U^{sc}_{i-N}/\partial^2c_s=4b/9>0$, $\partial^2U^{sc}_{i-N}/\partial^2c_i=4be_i^2/9>0$, $\partial^2U^{sc}_{i-P}/\partial^2\theta=4b(e_i-e)^2/9>0$, $\partial^2U^{sc}_{i-P}/\partial^2\gamma=4(e_i-e)^2/9>0$ and $\partial^2U^{sc}_{i-N}/\partial^2e_i=4b\theta^2/9>0$.

Thus, Lemma 2 is expressed as follows.

Lemma 2. *The* $\mathbf{U^{sc}_{i-j}}$ *is concave with respect to* $\mathbf{c_i}$, $\mathbf{c_t}$, θ, γ**an de**$_\mathbf{i}$. *In addition,* $\mathbf{U^{sc}_{E-j}}$ *is also a concave function of* $\mathbf{c_s}$.

When the subsidy is very low, the supply chain first suffers from the high cost. With the increase of subsidy, the overall costs and service price decrease, and the market demand increases. So the overall profits of the supply chain increase rapidly. When customers' low-carbon preference is low, the market demand is also low because of the high service price of the supply chain. However, with the increase of customers' low-carbon preferences, the market demand increases, and the overall profits of the supply chain increase.

Comparing the optimal profits between two technologies as follows.

The optimal profits of port:

$$U^p_{E-P}-U^p_{E-S}=\frac{(a+\gamma e-\gamma e_E-b(c_E+c_s+c_t-e\theta+e_E\theta))^2}{16b}\geq 0,$$

$$U^p_{E-P}-U^p_{E-N}=\frac{(a+\gamma e-\gamma e_E-b(c_E+c_s+c_t-e\theta+e_E\theta))^2}{72b}\geq 0,$$

$$\begin{aligned}
U^{p}_{E-S}-U^{p}_{E-N}&=-\frac{\left(a+\gamma e-\gamma e_E-b\left(c_E+c_s+c_t-e\theta+e_E\theta\right)\right)^2}{144b}\le 0,\\
U^{p}_{L-P}-U^{p}_{L-S}&=\frac{\left(a+\gamma e-\gamma e_L-b\left(c_L+c_t-e\theta+e_L\theta\right)\right)^2}{16b}\ge 0,\\
U^{p}_{L-P}-U^{p}_{L-N}&=\frac{\left(a+\gamma e-\gamma e_L-b\left(c_L+c_t-e\theta+e_L\theta\right)\right)^2}{72b}\ge 0,\\
U^{p}_{L-S}-U^{p}_{L-N}&=-\frac{\left(a+\gamma e-\gamma e_L-b\left(c_L+c_t-e\theta+e_L\theta\right)\right)^2}{144b}\le 0.
\end{aligned}\tag{17}$$

The optimal profits of ship:

$$\begin{aligned}
U^{s}_{E-P}-U^{s}_{E-S}&=-\frac{\left(a+\gamma e-\gamma e_E-b\left(c_E+c_s+c_t-e\theta+e_E\theta\right)\right)^2}{16b}\le 0,\\
U^{s}_{E-P}-U^{s}_{E-N}&=-\frac{\left(a+\gamma e-\gamma e_E-b\left(c_E+c_s+c_t-e\theta+e_E\theta\right)\right)^2}{72b}\le 0,\\
U^{s}_{E-S}-U^{s}_{E-N}&=\frac{\left(a+\gamma e-\gamma e_E-b\left(c_E+c_s+c_t-e\theta+e_E\theta\right)\right)^2}{144b}\ge 0\\
U^{s}_{L-P}-U^{s}_{L-S}&=-\frac{\left(a+\gamma e-\gamma e_L-b\left(c_L+c_t-e\theta+e_L\theta\right)\right)^2}{16b}\le 0,\\
U^{s}_{L-P}-U^{s}_{L-N}&=-\frac{\left(a+\gamma e-\gamma e_L-b\left(c_L+c_t-e\theta+e_L\theta\right)\right)^2}{72b}\le 0,\\
U^{s}_{L-S}-U^{s}_{L-N}&=\frac{\left(a+\gamma e-\gamma e_L-b\left(c_L+c_t-e\theta+e_L\theta\right)\right)^2}{144b}\ge 0.
\end{aligned}\tag{18}$$

The optimal overall profits of supply chain:

$$\begin{aligned}
U^{sc}_{E-P}-U^{sc}_{E-S}=0, U^{sc}_{E-P}-U^{sc}_{E-N}&=\frac{\left(a+\gamma e-\gamma e_E-b\left(c_E+c_s+c_t-e\theta+e_E\theta\right)\right)^2}{72b}\ge 0,\\
U^{sc}_{L-P}-U^{sc}_{L-S}=0, U^{sc}_{L-P}-U^{sc}_{L-N}&=\frac{\left(a+\gamma e-\gamma e_L-b\left(c_L+c_t-e\theta+e_L\theta\right)\right)^2}{72b}\ge 0.
\end{aligned}\tag{19}$$

Therefore, $U^{p}_{i-P}\ge U^{p}_{i-N}\ge U^{p}_{i-S}, U^{s}_{i-P}\le U^{s}_{i-N}\le U^{s}_{i-S}$, $U^{sc}_{i-N}\ge U^{sc}_{i-P}=U^{sc}_{i-S}$. Thus, we can get Proposition 2.

Proposition 2. *Profits in the port supply chain satisfy.*

$$U^{p}_{i-P}\ge U^{p}_{i-N}\ge U^{p}_{i-S},\ U^{s}_{i-P}\le U^{s}_{i-N}\le U^{s}_{i-S}, U^{sc}_{i-N}\ge U^{sc}_{i-P}=U^{sc}_{i-S}.\tag{20}$$

Proposition 2 shows, in the port supply chain, acting as leaders in the game always obtain more profits than the cases when they are followers, whether for port or ship. The supply chain's profits in the Nash game are the highest, while profits of the other two Stackelberg games are the same. So the equal relationships between port and ship should be encouraged if the regulators are more concerned about the supply chain's overall profits.

Comparing the profits under two different technologies:

$$\begin{aligned}
U^{s}_{E-j}-U^{s}_{L-j}&=\beta\left(2a+\gamma\left(e-e_E\right)+\gamma\left(e-e_L\right)-b\left(c_E+c_L+c_s+2c_t+e_L\theta+e_E\theta\right)\right)\left(c_L-c_E-c_s+\theta e_L-\theta e_E\right),\\
U^{p}_{E-j}-U^{p}_{L-j}&=\delta\left(2a+\gamma\left(e-e_E\right)+\gamma\left(e-e_L\right)-b\left(c_E+c_L+c_s+2c_t+e_L\theta+e_E\theta\right)\right)\left(c_L-c_E-c_s+\theta e_L-\theta e_E\right),\\
U^{sc}_{E-j}-U^{sc}_{L-j}&=\varphi\left(2a+\gamma\left(e-e_E\right)+\gamma\left(e-e_L\right)-b\left(c_E+c_L+c_s+2c_t+e_L\theta+e_E\theta\right)\right)\left(c_L-c_E-c_s+\theta e_L-\theta e_E\right).
\end{aligned}\tag{21}$$

where β, δ, φ are constants.

Therefore, when $\theta + (\gamma/b) > (c_L - c_E - c_s/e_E - e_L)$, then $U^p_{E-j} > U^p_{L-j}, U^s_{E-j} > U^s_{L-j}, U^{sc}_{E-j} > U^{sc}_{L-j}$, otherwise

$$U^p_{E-j} \le U^p_{L-j},\ U^s_{E-j} \le U^s_{L-j},\ U^{sc}_{E-j} \le U^{sc}_{L-j}. \tag{22}$$

Thus, Proposition 3 is elaborated as follows.

Proposition 3. *The profits of the port supply chain satisfy: If* $\theta + \gamma/b > c_L - c_E - c_s/e_E - e_L$, *then* $U^p_{E-j} > U^p_{L-j}$, $U^s_{E-j} > U^s_{L-j}, U^{sc}_{E-j} > U^{sc}_{L-j}$. *Otherwise* $U^p_{E-j} \le U^p_{L-j}, U^s_{E-j} \le U^s_{L-j}, U^{sc}_{E-j} \le U^{sc}_{L-j}$.

Proposition 3 indicates when the subsidy is low, from the perspective of profits, LSFO is preferred in the advantage of low overall costs. When the subsidy is high, the advantage of low emissions of SP gradually emerges, and SP becomes preferred instead of LSFO. Customers' low-carbon preference helps promote port and ship to reduce emissions. When customers' low-carbon preference is high, the government can encourage ships to reduce emissions with lower subsidies. Therefore, the government should actively promote environmental protection and cultivate consumers' awareness of low carbon.

4.2.3. Total Carbon Emissions Analysis. Taking the partial derivative of T_{i-j} with respect to different parameters:

(1) when $j = P, S$: $\partial T_{i-j}/\partial c_i = -(b/4)e_i < 0$, $\partial T_{i-j}/\partial c_t = \partial T_{i-j}/\partial c_s = -(b/4)e_i < 0$, $\partial T_{i-j}/\partial \theta = -(b/4)e_i^2 < 0$, and $\partial^2 T_{i-j}/\partial^2 e_i = -2b\theta < 0$.

(2) when $j = N$: $\partial T_{i-N}/\partial c_i = -(b/3)e_i < 0$, $\partial T_{i-N}/\partial c_t = \partial T_{i-N}/\partial c_s = -(b/3)e_i < 0, \partial T_{i-N}/\partial \theta = -(b/3)e_i^2 < 0$, and $\partial^2 T_{i-N}/\partial^2 e_i = -2b\theta < 0$.

Therefore Lemma 3 is given as follows.

Lemma 3. T_{E-j} *increases in* θ, γ, *but decreases in* c_s, c_t, e_L, c_L. T_{L-j} *increases in* θ, γ, *but decreases in* c_t, e_L, c_L.

When operational costs increase, the service prices of the supply chain also increase, which leads to market demands declining, so the whole carbon emissions decrease. When the subsidy increases, the costs of the supply chain decrease, and the whole service price declines, which expands the market demands, so the overall carbon emissions of the port supply chain increase. When the low-carbon preference of customers increases, the market demands increase, so the whole carbon emissions increase.

Comparing the carbon emissions under three power structures are as follows:

$$\begin{aligned} T_{i-P} - T_{i-S} = 0, T_{L-P} - T_{L-N} &= -\frac{e_L}{12}\left(a + \gamma\left(e - e_E\right) - b\left(c_E + c_t + c_s + e_E\theta - e\theta\right)\right),\\ T_{E-P} - T_{E-N} &= -\frac{e_E}{12}\left(a + \gamma\left(e - e_L\right) - b\left(c_L + c_t + e_L\theta - e\theta\right)\right). \end{aligned} \tag{23}$$

Since $q > 0$, θ must satisfies $\theta > b(c_E + c_s + c_t) - a/b(e - e_E) - (\gamma/b)$, $\theta > b(c_L + c_t) - a/b(e - e_L) - (\gamma/b)$, Therefore, $T_{i-P} = T_{i-S} < T_{i-N}$. Thus Proposition 4 can be given as follows.

Proposition 4. *The supply chain's carbon emissions satisfy* $T_{i-P} = T_{i-S} \le T_{i-N}$.

Proposition 4 shows that when port and ship are in a relatively equal relationship, they are tended to price lowly to attract more customers and expand the market, thus generating more carbon emissions. While in a Stackelberg game, the leader always limits the motivation of the other to offer services, leading to emissions reduction. It is noted that Proposition 3 indicates the total supply chain profits in the Nash game are highest, but when the carbon emissions are the concern of regulators, the Stackelberg games are preferred.

Comparing the carbon emissions under different technologies:

$$T_{E-j} - T_{L-j} = \frac{e_E\left(a + \gamma\left(e - e_E\right) - b\left(c_E + c_t + c_s + e_E\theta - e\theta\right)\right) - e_L\left(a + \gamma\left(e - e_L\right) - b\left(c_L + c_t + e_L\theta - e\theta\right)\right)}{4}. \tag{24}$$

Therefore, if $\theta + (\gamma/b) < \tau$, then $T_{E-j} < T_{L-j}$; otherwise $T_{E-j} \ge T_{L-j}$.

$$\text{where}\,\tau = \frac{ae_L - ae_E + bc_Le - bc_Ee - bc_se + bc_Ee_E + bc_se_E + bc_te_E - bc_Le_L - bc_te_L}{b\left(e_E - e_L\right)\left(e - e_E - e_L\right)}. \tag{25}$$

Thus, Proposition 5 can be expressed as follows.

Proposition 5. *Under different technologies, the total carbon emissions satisfy:*

If $\theta + (r/b) < \tau$*, then*$T_{E-j} < T_{L-j}$*; otherwise* $T_{E-j} \geq T_{L-j}$*.*

Here,
$\tau = bc_L e - bc_E e - bc_s e - ae_E + bc_E e_E + bc_s e_E + bc_t e_E + ae_L - bc_L e_L - bc_t e_L / b(e_E - e_L)(e - e_E - e_L)$

In the port supply chain, if e satisfies $e_E < e < e_E + e_L$, then $(c_L - c_E - c_s/e_E - e_L) < \tau$. At this time, when the $\theta + (\gamma/b) < (c_L - c_E - c_s/e_E - e_L)$, from Proposition 3, LSFO is preferred in the advantage of low overall costs, but according to Proposition 5, using LSFO produces more emissions than that of using SP. When $(c_L - c_E - c_s/e_E - e_L) < \theta + (\gamma/b) < \tau$, combined with Proposition 3 and 5, using SPis preferred with respect to profits, and the total emissions of adopting SP is lower than that of using LSFO. However, with the increase of subsidy and customers' low-carbon preferences to a threshold $(\theta + (\gamma/b) > \tau)$, even if the unit emissions of SP is low, the total emission of adopting SP surpasses that of adopting LSFO, because the supply chain may tend to offer more services. So when the subsidy is very high, the supply chain's profits of using SP are higher than that of using LSFO, but the total emissions of adopting SP also are more than that of adopting LSFO. Therefore, when subsidy and customers' low-carbon preference is within the appropriate range of $((c_L - c_E - c_s/e_E - e_L) < \theta + (\gamma/b) < \tau)$, using SP is preferred to using LSFO not only from the perspective of profits but also from the perspective of emission control. The government and enterprises can achieve a win-win situation.

If e satisfies $e > e_E + e_L$, then $(c_L - c_E - c_s/e_E - e_L) > \tau$. At this time, when $\theta + (\gamma/b) < \tau$, according to Proposition 3 and 5, using LSFOis preferred with respect to low costs but leads to more emissions than that of using SP. When $\tau < \theta + (\gamma/b) < (c_L - c_E - c_s/e_E - e_L)$, using LSFOis still preferred, and produces fewer emissions than that of using SP. When $(c_L - c_E - c_s/e_E - e_L) < \theta + (\gamma/b)$, using SP is preferred from the perspective of profits, but produces more emissions than that of using LSFO because the supply chain may tend to offer more services. Therefore, when subsidy and customers' low-carbon preferences are within the appropriate range of $(\tau < \theta + (\gamma/b) < (c_L - c_E - c_s/e_E - e_L))$, adopting LSFO is preferred to adopting SP not only from the perspective of profits but also from the perspective of emission control. The government and enterprises can achieve a win-win situation. These findings can help regulars to formulate reasonable subsidy policies according to the differences between technologies.

4.3. Numerical Examples Analysis. In this section, some numerical examples are given to illustrate the above-obtained lemmas and propositions. The relevant parameters in the model are given as follows [39], $a = 200, b = 3.5, c_E = 2.8$, $c_t = 3.6$, $c_s = 0.6, c_L = 1.6$, $e = 5.4, e_E = 4.2, e_L = 4.9$.

4.3.1. Influence of Subsidy and Customers' Low-Carbon Preference on Profits. The port's profits under three power structures are shown in Figure 2, while Figure 3 shows the changes of the shipping company's profits. Consistent with Proposition 3, acting as followers always achieve lower profits than the cases when they are leaders, whether for port or ship. It is apparently shown that the profits of the supply chain in the Nash game are the highest in Figure 4.

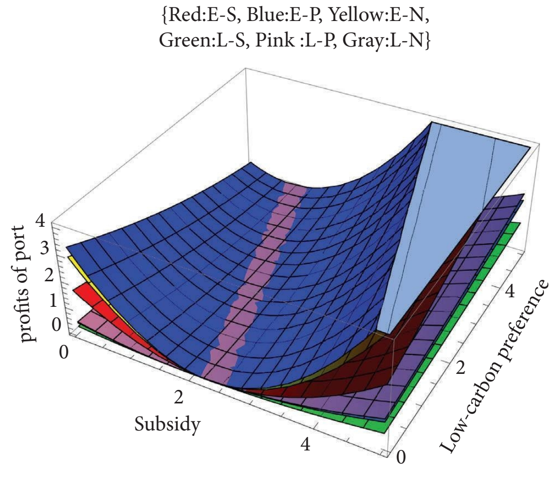

Figure 2: Profits of the port.

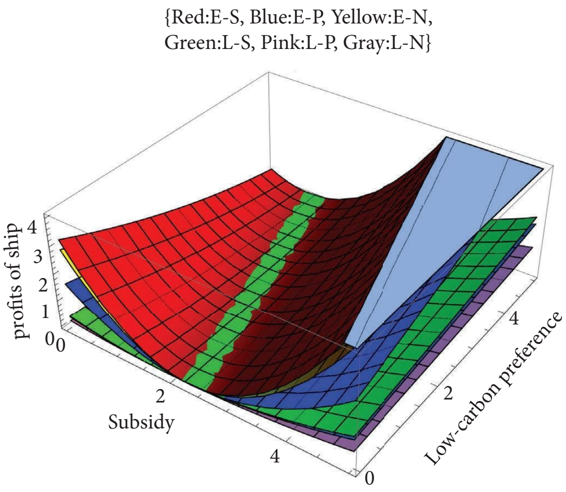

Figure 3: Profits of the ship.

In the port supply chain, the technology comparison with respect to profits is complicated. When subsidies and low-carbon preferences are very low, the emission costs are high. At this time, the shipping company may not offer services but obtains a subsidy. As the subsidy and low-carbon preference increase, SP is preferred to LSFO because of the emission reduction advantage. So, high subsidies and customers' low-carbon preferences are helpful in promoting SP.

4.3.2. Influence of Subsidy and Low-Carbon Preference on Carbon Emissions. Figure 5 shows the case that e satisfies $e_L < e < e_E + e_L$, the carbon emissions under Nash game is the highest, as described in Proposition 4. When subsidy and customers' low-carbon preferences are very low, the service offered by the port supply chain in all power structures drops to a shallow level, and the emissions of the three power

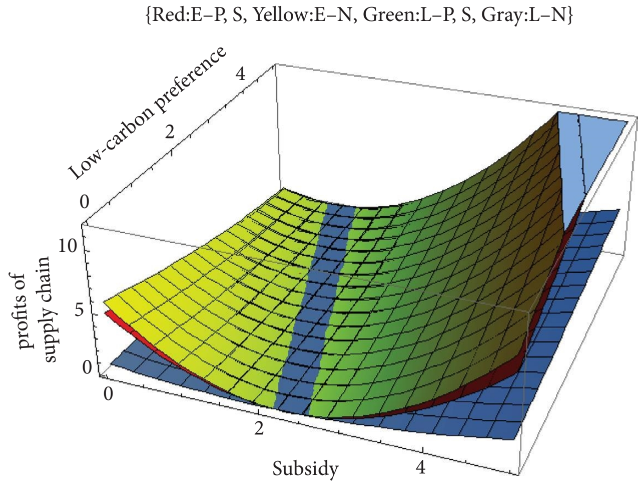

Figure 4: Profits of the supply chain.

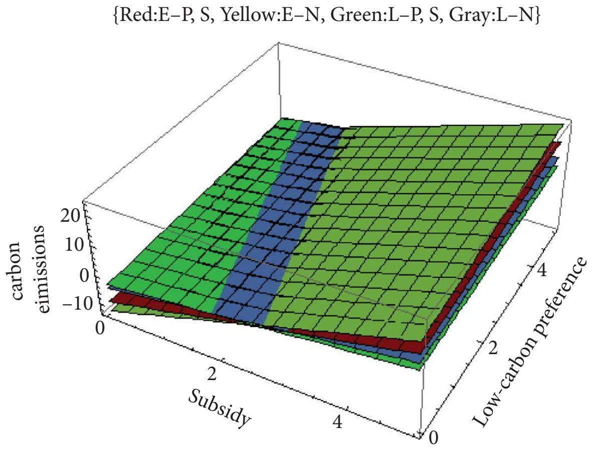

Figure 5: Total carbon emissions.

structures approach each other. With the subsidy and low-carbon preference increasing, the carbon emissions of using LSFO are higher than that of using SP. But when the subsidy increases to a threshold, the carbon emissions of using SP surpass that of using LSFO.

5. Managerial Insights and Practical Implications

In this section, according to the obtained results, the relevant managerial insights and practical implications are elaborated.

5.1. The Emission Control Technologies Decision of Port and Ship. According to Proposition 1 and 2, in the port supply chain, acting as leaders in the game always obtain more profits than the cases when they are followers, whether for port or ship. The supply chain's profits in the Nash game are the highest. In practice, ports always act as leaders in the port supply chain because of their own resources to obtain more benefits. If shipping companies want to achieve more profits in the supply chain, they should take a leadership position in the supply chain. Therefore, shipping companies have recently strived to gain more discourse rights through alliances, such as the world's three major ship alliances, 2M, THE, and OCEAN.

Proposition 3 shows when the subsidy is low, from the perspective of profits, LSFO is preferred. Otherwise, SP is the better choice. Therefore, when government subsidies and customers' low-carbon preferences are low, for port and ship, LSFO is preferred to SP. Otherwise, the supply chain should choose SP to reduce emissions.

5.2. The Subsidy Police and Management Measures of Government. According to Proposition 3, when the subsidy is low, from the perspective of profits, using LSFO is better than using SP for the supply chain. Although the government of China has promoted SP through subsidy policies, the current government's subsidy is relatively low concerning the high initial investment of SP, so ships prefer to use LSFO, which is one of the reasons why the willingness of ships in China to use SP is low under the government subsidy policies.

According to Proposition 4, the carbon emissions of the port supply chain in the Nash game are higher than that in the Stackelberg games. At the same time, Proposition 3 indicates the total supply chain profits in the Nash game are the highest. Therefore if the government is concerned about controlling emissions, encouraging the one-part dominant structure would be the better choice. But if the government is concerned with maximizing profits, supporting the Nash game would be preferred. The consumers' low carbon preferences can promote the supply chain to reduce emissions, so government should actively propagandize environmental protection and cultivate consumers' awareness of low carbon.

From Lemma 2, government subsidy has a positive relationship with the total emissions of the port supply chain. The increase of subsidies will lead to more emissions. Therefore, the government subsidy policy regarding emission reduction in port areas should be carefully considered.

According to Proposition 5, government and enterprises can achieve a win-win situation when the subsidy is within the appropriate range. So government should subsidize the supply chain moderately, not too high or too low. According to the literature [39], the current emissions of SP and LSFO in China satisfy. Therefore, for the Chinese government, subsidies within an appropriate range of $((c_L - c_E - c_s/e_E - e_L)- (\gamma/b) < \theta < \tau - (\gamma/b))$ are the better choice. In this situation, the port supply chain chooses SP to reduce carbon emissions, and the whole emissions are fewer than that of adopting LSFO.

6. Conclusion and Future Research

The supply chain included one port and one ship considering government subsidy and low-carbon preference is discussed in the paper under three power structures. Some significant results are obtained as follows.

In the port supply chain, being leaders always obtain more profits than acting as followers in the game, whether for port or ship. The supply chain's profits in the Nash game are higher than that in the other two Stackelberg games. So the equal relationships between port and ship should be the better choice from the perspective of the supply chain's overall profits. When port and shipping companies are in a relatively equal relationship, they are tended to price lowly to attract more customers and expand the market, thus generating more emissions. While in a Stackelberg game, the leader always limits the motivation of the other to provide services, leading to emissions reduction. Therefore the one part dominant relationship between port and ship should be the better choice from the perspective of emission control.

SP is a more expensive but effective emission reduction technology than LSFO. When subsidy and customers' low-carbon preferences are low, from the perspective of profits, LSFO is preferred in the advantage of low overall costs. When subsidies and customers' low-carbon preferences are high, SP is the better choice.

In the case that e satisfies $e_E < e < e_E + e_L$, when subsidy and low-carbon preference of customers within the appropriate range of $((c_L - c_E - c_s/e_E - e_L) < \theta + (\gamma/b) < \tau)$, using SP is the optimal decision for the supply chain to maximize profits, and at the same time, adopting SP produces less total emissions than that of using LSFO. In other words, government and enterprises can achieve a win-win situation when the subsidy is within the appropriate range of $((c_L - c_E - c_s/e_E - e_L) < \theta + (\gamma/b) < \tau)$.

In the case that e satisfies $e > e_E + e_L$, when subsidy and low-carbon preference of customers within the appropriate range of $\tau < \theta + (\gamma/b) < (c_L - c_E - c_s/e_E - e_L)$, using LSFO is the optimal decision for the supply chain to maximize profits, and at the same time, adopting LSFO produces less total emissions than that of using SP. In other words, government and enterprises can achieve a win-win situation when the subsidy is within the appropriate range of $(c_L - c_E - c_s/e_E - e_L) < \theta + (\gamma/b) < \tau$.

The obtained results give valuable insights for port and shipping companies to choose the appropriate emission reduction technologies, and the results also provide a reference for the government to formulate policies and management measures.

In practice, the emission reduction decisions of port and navigation enterprises are affected by many factors. The factors include the resource of ports, the feature of ships, the competitive relationship between the ports, the competitive relationship between the vessels, and the uncertainty of market demand. So the choice of emission control technologies of port and shipping enterprises is more complex. Therefore, a more realistic supply chain with multiple ports, multiple shipping companies, and the random order of the shipping market is the research direction in the future. Furthermore, other carbon emissions control policies, such as cap-and-trade schemes, and carbon taxes, can also be incorporated into the current study in the future. At last but not the least, different subsidy methods, such as port subsidy and ship subsidy, can also be considered in the current study.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The study was supported by Natural Science Foundation of Guangdong Province of China (2021A1515110213), Philosophy and Social Science Planning Project of Guangdong Province of China (Grant no. GD20CGL44).

References

[1] L. Yang, Y. Cai, and Y. Wei, H. Shuo, Choice of technology for emission control in port areas: a supply chain perspective," *Journal of Cleaner Production*, vol. 240, 2019.

[2] Q. Zhang and Z. Q. Zhen, "Study on the development and evolution of Ship emission control zone policy in China," *Journal of Dalian Maritime University*, vol. 19, no. 3, pp. 67–72, 2020.

[3] W. J. Hall, "Assessment of CO2 and priority pollutant reduction by installation of shoreside power," *Resources, Conservation and Recycling*, vol. 54, no. 7, pp. 462–467, 2010.

[4] K. Zhang, *New Regulations on the Using Of"shore Power" Will Impact the Water Transport Industry*, The first finance and economics, Beijing, China, 2019-08-06, https://www.yicai.com/news/100285256.html.

[5] L. Li, *Why Is it Difficult to Promote Shore Power*, China Energy News, China, 2019-01-14, http://www.escn.com.cn/news/show-702856.html.

[6] C. Che, Z. Zhang, X. Zhang, and Y Chen, "Two-stage pricing decision for low-carbon products based on consumer strategic behaviour," *Complexity*, vol. 2021, pp. 2021–2112, Article ID 6633893, 2021.

[7] Q. P. Wang and D. Z. Zhao, "Cooperative strategy of carbon emissions reduction and promotion in a two-echelon supply chain," *Control and Decision*, vol. 2014, no. 2, pp. 307–314, 2014.

[8] W. Liu, S. Wang, D. Zhu, D. Wang, and X. Shen, "Order allocation of logistics service supply chain with fairness concern and demand updating: model analysis and empirical examination," *Annals of Operations Research*, vol. 268, no. 1-2, pp. 177–213, 2017.

[9] Y. c Yang and P. y Nie, "Subsidy for clean innovation considered technological spillover," *Technological Forecasting and Social Change*, vol. 184, Article ID 121941, 2022.

[10] Q. Meng, Y. Wang, Z. Zhang, and Y He, "Supply chain green innovation subsidy strategy considering consumer heterogeneity," *Journal of Cleaner Production*, vol. 281, Article ID 125199, 2021.

[11] S. Huang, Z. P. Fan, and N. Wang, "Green subsidy modes and pricing strategy in a capital-constrained supply chain," *Transportation Research Part E: Logistics and Transportation Review*, vol. 136, Article ID 101885, 2020.

[12] X. Gu, L. Zhou, H. Huang, X. Shi, and P. Ieromonachou, "Electric vehicle battery secondary use under government subsidy: a closed-loop supply chain perspective,"

International Journal of Production Economics, vol. 234, pp. 108035–112021, 2021.

[13] Y. Wang, R. Fan, L. Shen, and W. Miller, "Recycling decisions of low-carbon e-commerce closed-loop supply chain under government subsidy mechanism and altruistic preference," *Journal of Cleaner Production*, vol. 259, Article ID 120883, 2020.

[14] Z. r Chen, X. Xiao, and P. y Nie, "Renewable energy hybrid subsidy combining input and output subsidies," *Environmental Science and Pollution Research*, vol. 28, no. 8, pp. 9157–9164, 2021.

[15] C. Mondal and B. C. Giri, "Investigating strategies of a green closed-loop supply chain for substitutable products under government subsidy," *Journal of Industrial and Production Engineering*, vol. 39, no. 4, pp. 253–276, 2022.

[16] W. Miao, G. Zhu, B. Shen, and D. Kong, "Emissions reduction and pricing of supply chain under cap-and-trade and subsidy mechanisms," *PLoS One*, vol. 17, no. 4, p. e0266413, Article ID e0266413, 2022.

[17] Z. Mu, Q. Li, G. Dai, K. Li, G. Zhang, and F. Zhang, "Government subsidy policy and online selling strategy in a platform supply chain with green R&D and DDM activities," *Sustainability*, vol. 14, no. 15, p. 9658, Article ID 9658, 2022.

[18] P. Liu, X. Cui, and Y. Li, *Subsidy Policies of a Fresh Supply Chain Considering the Inputs of Blockchain Traceability Service System"*, Science and Public Policy, Minnesota UK, 2022.

[19] X. Li, H. Kuang, and Y. Hu, "Using system dynamics and game model to estimate optimal subsidy in shore power technology," *IEEE Access*, vol. 8, pp. 116310–116320, 2020.

[20] C. Wang and Y. Jiao, "Shipping companies' choice of low sulfur fuel oil with government subsidy and different maritime supply chain power structures," *Maritime Policy & Management*, vol. 49, no. 3, pp. 323–346, 2022.

[21] H. Sun, Q. Zeng, H. Xiang, and C. Chen, "Competition model of cruise home ports based on the cruise supply chain–based on China cruise market," *Maritime Policy & Management*, vol. 46, no. 3, pp. 277–294, 2019.

[22] Y. Li and Y. Jiao, "How government subsidy impacts on the supply chain decision for LNG-fuelled ships," *Mathematical Problems in Engineering*, vol. 2022, pp. 1–13, 2022.

[23] S. Yu and Q. Hou, "Supply Chain Investment in Carbon Emission-Reducing Technology Based on Stochasticity and Low-Carbon Preferences," *Complexity*, vol. 2021, 2021.

[24] C. Su, X. Liu, and W. Du, "Green supply chain decisions considering consumers'low-carbon awareness under different government subsidies," *Sustainability*, vol. 12, no. 6, p. 2281, 2020.

[25] P. Cheng, G. Ji, G. Zhang, and Y. Shi, "A closed-loop supply chain network considering consumer's low carbon preference and carbon tax under the cap-and-trade regulation," *Sustainable Production and Consumption*, vol. 29, pp. 614–635, 2022.

[26] S. S. Sana, "Sale through dual channel retailing system—a mathematical approach," *Sustainability Analytics and Modeling*, vol. 2, Article ID 100008, 2022.

[27] S. Chen, J. Su, Y. Wu, and F Zhou, "Optimal production and subsidy rate considering dynamic consumer green perception under different government subsidy orientations," *Computers & Industrial Engineering*, vol. 168, Article ID 108073, 2022.

[28] Q. Long, X. Tao, Y. Chen et al., "Exploring combined effects of dominance structure, green sensitivity, and green preference on manufacturing closed-loop supply chains," *International Journal of Production Economics*, vol. 251, Article ID 108537, 2022.

[29] P. V. Thalis, "Prospects of cold ironing as an emissions reduction option," *Transportation Research Part A: Policy and Practice*, vol. 119, no. 7, pp. 82–95, 2019.

[30] A. Martínez López, A. Romero Filgueira, and M. Chica, "Specific environmental charges to boost Cold Ironing usein the European Short Sea Shipping," *Transportation Research Part D Transport and Environment*, vol. 94, pp. 52–63, 2021.

[31] C. A. Reusser and J. R. Perez, "Evaluation of the emission impact of cold-ironing power systems, using a Bi-directional power flow control strategy," *Sustainability*, vol. 13, no. 1, p. 334, 2020.

[32] A. Martínez-López, A. Romero, and J. A. Orosa, "Assessment of cold ironing and lng as mitigation tools of short sea shipping emissions in port: a Spanish case study," *Applied Sciences*, vol. 11, no. 5, pp. 2050–2061, 2021.

[33] T. Piccoli, M. Fermeglia, D. Bosich, P. Bevilacqua, and G. Sulligoi, "Environmental assessment and regulatory aspects of cold ironing planning for a maritime route in the adriatic sea," *Energies*, vol. 14, no. 18, p. 5836, 2021.

[34] N. N. A. Bakar, N. Bazmohammadi, H. Çimen, T. Uyanik, J. C. Vasquez, and J. M. Guerrero, "Data-driven ship berthing forecasting for cold ironing in maritime transportation," *Applied Energy*, vol. 326, Article ID 119947, 2022.

[35] I. Panasiuk and S. Lebedevas, "The assessment of the possibilities for the Lithuanian fleet to comply with new environmental requirements," *Transport*, vol. 29, no. 1, pp. 50–58, 2014.

[36] H. Xing, C. Stuart, S. Spence, and H. Chen, "Alternative fuel options for low carbon maritime transportation: pathways to 2050," *Journal of Cleaner Production*, vol. 297, p. 126651, Article ID 126651, 2021.

[37] C. Port, *Management Suggestions on the Development of China's Shore Power*, http://www.escn.com.cn/news/show-430111.html, 2017.

[38] X. L., W. Y. Qian, W. Liu, and J Yang, "Game theory analysis of technology adoption timing and pricing decision in supply chain system under asymmetric nash equilibrium," *Journal of Intelligent and Fuzzy Systems*, vol. 35, no. 3, pp. 3101–3111, 2018.

[39] L. Yang, Y. Cai, X. Zhong, Y. Shi, and Z. Zhang, "A carbon emission evaluation for an integrated logistics system—a case study of the port of Shenzhen," *Sustainability*, vol. 9, no. 3, pp. 462–485, 2017.