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Dynamic Incentive Contract of Government for Port Enterprises to Reduce Emissions in the Blockchain Era: Considering Carbon Trading Policy

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Abstract: Blockchain technology is very useful. This paper considers the application of blockchain technology to smart contracts, green certification, and market information disclosure, and introduces the carbon trading market price as a parameter to solve the dynamic incentive problem of the government for port enterprises to reduce emissions under the carbon trading policy. Based on the state change of port carbon emission reduction, this paper uses principal–agent theory to construct the dynamic incentive contract model of government without blockchain, with blockchain, and when carbon trading is considered under blockchain, respectively, and uses the optimal control method to solve and analyze the model. This paper finds that only when the opportunity cost of port enterprises is greater than a certain critical point and the fixed cost of blockchain is less than a certain critical point, the implementation of blockchain will help improve government efficiency. However, only when the critical value of carbon emission reduction of port enterprises and the unit operating cost of blockchain are small, the government should start the carbon trading market under blockchain technology. Through numerical simulation, this paper also finds that it is usually beneficial for the government to regulate and appropriately increase the carbon trading market price.

Keywords: blockchain technology; green port; emission reduction; carbon trading; optimal control theory

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1. Introduction

Ports are the gateway of international trade and play a vital role in global economic and social development. However, the carbon emission pollution generated by ports should not be underestimated [1]. According to the statistics of China's Ministry of Transport, China's port cargo throughput in 2022 is about 15.685 billion tons. However, the carbon emissions of fossil fuels consumed by port enterprises each year are nearly 100 million tons, accounting for about 3% of the global greenhouse gas emissions. Therefore, port enterprises are facing increasing pressure of decarbonization, and port emission reduction is imminent [2,3]. To this end, the Chinese government has provided subsidies to encourage port enterprises to invest in green energy-saving and emission reduction technologies, such as replacing oil with shore power, liquefied natural gas (LNG) terminals, and clean energy trucks, in order to speed up the construction of green ports and alleviate port carbon emission pollution. Some powerful evidence is provided as follows: from 2016 to 2018, China's Ministry of Transport awarded subsidies for the construction of port shore power facilities and the renovation of ship power receiving facilities; In September 2022, Guangzhou Port Authority issued the measures for the implementation of subsidy funds for ship emission control in Guangzhou port. In addition, governments of various countries have also begun to implement corresponding measures in the shipping industry, such as carbon emission trading policy. The evidence includes that the shipping industry will be included in the European Union Emission Trading System (EUETS) from 2024, and port enterprises such as Shanghai international port group and Shanghai Shengdong international container terminal have been included in the list of carbon emission quota management units of Shanghai in 2022. Therefore, under the government's subsidy incentives and carbon trading policy, how to control and reduce the carbon emission of port enterprises, accelerate the investment and construction of green ports, and help the sustainable development of the shipping industry is the first research motivation of this paper.

As a world-changing and disruptive technology, blockchain technology is gradually being applied to the shipping industry, and port enterprises are benefiting from it [4]. There is much evidence here. For example, International Business Machines Corporation (IBM) and Maersk jointly built a shipping blockchain solution (TradeLens) to realize the digital operation of ports and shipping. Shanghai Port Group and China Ocean Shipping (Group) Company (COSCO) realize transparent and paperless operations with the support of blockchain technology. In 2021, Guangzhou Port successfully completed the docking with the electronic cargo release platform of the port and shipping blockchain, and all the main terminals were connected to the chain. Since 2022, the blockchain electronic cargo release platform of Shanghai Port has released a total of 335,000 bills of lading, totaling about 1.03 million TEUs, which effectively realized the cost reduction and efficiency increase in the logistics of imported cargo, and during the "Double 11" period, it even made a new history and realized the rapid release of imported e-commerce goods. The main reason why blockchain technology is so popular is that compared with traditional technology, blockchain technology has unique advantages. Specifically, it is a decentralized, point-to-point distributed database system, which is traceable, tamper-proof, open, and transparent. The traditional common technologies such as bar codes and radio frequency identification (RFID) tags may be copied and forged, and cannot be compared with blockchain technology in trusting the authenticity of its information processing [5]. Therefore, the second research motivation of this paper is to introduce the application values of blockchain technology such as smart contracts, green certification, and market information disclosure (which will be explained in detail later) in port enterprises' emission reduction to improve the government's subsidy incentives and carbon trading policy to stimulate and regulate port emission reduction.

In addition, although the existing literature has considered the investment and application of blockchain technology in the shipping industry (e.g., [4,6,7]), there are few studies on the government's incentive contract design for port enterprises to reduce emissions by introducing the different application values of blockchain technology. Especially from the perspective of the principal–agent, based on the change in the status of port emission reductions and considering the carbon trading policy, there are even fewer studies on the dynamic incentive contract model of the government to port enterprises to reduce emissions. Therefore, based on the above realistic background of emission reduction of port enterprises in the shipping industry, three scenarios will be considered in this paper, namely, the scenario of no blockchain, the scenario where blockchain adoption without considering carbon trading policy, and the scenario where carbon trading policy is also considered under blockchain technology. Although there are many studies in the literature on different optimal control methods [8,9]. The advantage of this work is that we focus on the optimal control for carbon trading, and study the dynamic incentive of government for port emission reduction in the shipping industry from the perspective of the principal–agent.

The remainder of this paper is organized as follows. In Section 2, we present a review of the related literature. We give the model description and assumptions in Section 3. In Section 4, we develop three different analytical models of the government's dynamic incentive contracts for port enterprises to reduce emissions, including no blockchain, blockchain adoption, and blockchain adoption when considering carbon trading policy. Moreover, we obtain the equilibrium solutions for the government and port enterprise under different cases by solving hierarchically. In Section 5, we conduct the model analysis, including the analysis of a government dynamic incentive strategy for port emission reduction, parameter analysis, and the analysis of the effects and values of blockchain technology and carbon trading policy. Numerical analysis is performed in Section 6. Section 7 contains our conclusions and suggestions for future research. All proofs are placed in Appendix A.

2. Literature Review

This paper is closely related to the following three research streams: (1) blockchain technology in the shipping industry; (2) port emission reduction and government subsidy; (3) incentive contract design. Therefore, in the following subsections, we will summarize the relevant research in three aspects and clarify the differences between this study and the existing literature.

2.1. Blockchain Technology in the Shipping Industry

Blockchain technology has become increasingly popular in supply chain management in recent years, which has attracted the attention of many scholars (e.g., Choi [10], Sun et al. [11], Shen et al. [12], Liu et al. [13], Guo et al. [14], Xu et al. [15]). Meanwhile, as an important carrier of cross-border trade, the research of applying blockchain technology to the shipping industry has also gradually become a hot topic [6]. The relevant research mainly includes two aspects. First, some scholars focused on the analysis of the application status and future development prospects of blockchain technology in the shipping industry. For example, Ying et al. [16] pointed out that by promoting the digitalization of the shipping industry, blockchain technology can help improve the operational efficiency of relevant enterprises involved and reduce the risks and unnecessary time costs associated with trade activities. To analyze the potential impact of new technologies such as blockchain on the performance and sustainability of the shipbuilding industry, Ramirez et al. [17] developed a performance model of the shipbuilding supply chain from an Industry 4.0 perspective, explored lean, agile, resilient, and green supply chain management modes, and proposed two phases to achieve the overall visibility and connectivity required for Shipbuilding Supply Chain 4.0. In order to explore the potential application fields of blockchain technology in port logistics management, Ahmad et al. [4] further discussed blockchain applications and architectures for port operations and logistics management. In addition, Pu et al. [18] presented a conceptual framework for the application of blockchain technology in the maritime industry, and they argued that it is crucial that managers should fully understand blockchain and its own specific issues and needs before adopting the technology. Subsequently, Balci and Surucu [19] and Kapnissis et al. [7] conducted empirical analysis on the adoption of blockchain in the shipping industry. They investigated the relationship between barriers to blockchain adoption, identified the main stakeholders of blockchain adoption in international trade in containers, and described the intention of the shipping sector to adopt blockchain technology.

Some other scholars are concerned about using blockchain technology to optimize the decisions of relevant enterprises in the shipping industry. For example, Meng and Wang [20] used game theory and mathematical planning methods to construct a benefit allocation mechanism for shipping industry alliance members to rent each other's slots under blockchain technology, which optimized the allocation of slots among members and maximized the benefits of the alliance. Chen and Yang [21] used Stackelberg game theory to develop a mathematical model of a shipping logistics service supply chain consisting of shipping companies and freight forwarders, and found that the impact of freight rate competition on market evolution was reduced after blockchain application. Wang and Yin [22] constructed a pricing decision model for a secondary shipping supply chain under the traditional mode and blockchain technology mode, and explored the impact of different levels of information sharing on a private blockchain platform on the pricing and revenue of ports and carriers. In addition, Xin et al. [6] investigated the value of blockchain-based vertical cooperation dominated by ports or shipping companies in a one-to-two model of shipping service competition. They found that investments in blockchain technology can significantly increase the profits of shipping supply chain participants, and in particular, ports' investments in blockchain technology led to more consumer surplus and social welfare. Meanwhile, Zhao et al. [23] integrated the technical features of blockchain decentralization with the investment choices of port and shipping supply chain members, and explored the issue of whether to centralize and whether to invest in a portfolio strategy in terms of shipping market prices and volumes and the economic effects of its shipping market.

However, the existing studies mainly focused on the pricing decisions and benefit distribution of port and shipping enterprises under blockchain technology and blockchain investment strategies in the shipping industry. Differing from them, this paper focuses on the dynamic incentive strategy of the government and the emission reduction investment (ERI) decision of the port under blockchain technology, especially we analyze the value and effect of blockchain technology in the government's dynamic incentive contract.

2.2. Port Emission Reduction and Government Subsidy

Our study is closely related to port emission reduction and government subsidy in the shipping industry, which is one of the important research topics in the field of shipping at present. Regarding the research on port emission reduction strategies, Acciaro et al. [24] argued that active energy management in ports could improve their service efficiency, promote the development of new alternative sources of income, and ultimately enhance their competitive position. Innes and Monios [25] analyzed ship docking data to calculate energy demand and found that installing cold ironing technology in medium-sized ports is feasible, which will consume less energy than traditional ships connected to shore power. Poulsen and Sampson [26] confirmed the existence of idle time in ports, detailed the reasons for it, and pointed out some previously overlooked factors. Wang et al. [27] studied the development process of port emission reduction from early "environmental factors and energy scheduling" to "low-carbon and green ports" through system review and Citespace visual analysis. Zhou et al. [28], based on the field theory in physics, combined with the characteristics of ship emission trajectory data, analyzed the spatio-temporal aggregation law of ship carbon emissions in the Wuhan Port.

Moreover, some scholars have taken into account the government's regulatory and subsidy mechanisms in port emission reduction. Zhao et al. [29] considered a three-way evolutionary game model between the government, a port company, and another port company, and found that the environmental benefits can be maximized only if the government chooses passive regulation and the port company implements shore-side electricity. Zheng et al. [30] modeled two commonly used regulatory policies for port adaptation investments (minimum demand regulation and subsidies), making explicit the ambiguity in the probability of disasters and the policymaker's attitude towards risk. Meng et al. [31] explored the impact of government regulation on cooperative emission reduction between ports and shipping companies by establishing a differential game model. They found that when the government only provides incentives to ports, if the port subsidizes shipping companies and the decision-making power is dispersed among shipping companies, the emission reduction effect is best, but it is unfavorable for port revenue. Meng et al. [32] constructed an evolutionary game model with the participation of the government, port enterprises, and shipping enterprises, and analyzed the evolutionary process of the selection of carbon reduction strategies among the three parties. Wang et al. [33] considered the interaction between governments, ports, and ships to develop a Stackelberg model to optimize government subsidy schemes to maximize the environmental benefits of unit currency subsidies. They found that in an optimal government subsidy structure, subsidies for ships should take precedence over subsidies for ports. Song et al. [34] constructed a Nash game between two shipping companies on shore rights usage decisions and analyzed the effect of government intervention on the equilibrium that can be achieved between the two shipping companies. Tan et al. [35] argued that the use of both environmental incentives and infrastructure subsidies mechanisms by the government influences port authorities to change the capacity decisions of port-specific terminals, which in turn affects the total emission reductions.

In addition, in order to further manage the emission reduction of port enterprises, some other scholars have considered the government's implementation of carbon emission policies for the shipping industry, such as carbon trading and carbon tax policies. Zhong et al. [36] studied the specific impacts of the carbon trading mechanism on the optimal emission reduction strategies of container terminals by taking Nansha Terminal in China as an example. Yang et al. [37] analyzed the choice problem of ports and shipping companies for low-sulfur oils and on-shore power under the carbon trading mechanism. Zhong et al. [38] found that a carbon tax policy is a relatively direct and effective incentive to drive multi-modal transportation in the port hinterland towards greening. Li et al. [39] explored the impact of government intervention on the carbon emissions trading market, and suggested that excessive government intervention would lead to the failure of the carbon market mechanism. Wang et al. [40] analyzed the relationship between digital trade and carbon emissions, as well as the moderating role of industrial agglomeration and carbon emission trading mechanisms on the effect of digital trade in reducing carbon emissions.

Although the existing research on port emission reduction and government subsidy in the shipping industry has yielded important results and progress, this paper considers smart contracts, green certification, and market information disclosure of blockchain technology, studies the government's dynamic incentive problem for port enterprises to reduce emissions from the perspective of the principal–agent, and analyzes the value and effect of carbon trading policy under blockchain technology, which has not been covered in the related studies cited above.

2.3. Incentive Contract Design

Our study is also related to the research of incentive contract design in operations management, which is a hot issue of academic concern and has a wider scope of research. Holmstrom and Milgrom [41] first proposed the principal–agent model and laid the foundation for the study of incentive contracts and incentive mechanisms. Subsequently, many scholars began to design contracts such as linear and commission to resolve conflicts of interest between principals and agents in different industries. For example, in the past, Zhou and Swan [42] investigated the optimality of piecewise linear incentive contracts and found evidence of the role of performance thresholds by examining Chief Executive Officer (CEO) compensation data. Yu and Kong [43] considered the ambiguity in the distribution of effort-related outputs and demonstrated that piecewise linear incentive contracts are uniquely optimal among salesperson compensation contracts. Gao and Tian [44] extended the single-period incentive contract model to the multi-period incentive contract model to constrain the behavior of the firms and motivate the firms to make greater efforts. Gao et al. [45] considered outsourcing a manufacturer to a supplier and proposed a quality incentive contract with asymmetric product manufacturability information. With the rise of the live-streaming industry, Zhang and Xu [46] discussed proportional incentive contracts based on target sales volume in the context of the live commerce supply chain and studied the optimization of contract design based on principal generation theory. They found that the optimal solution of the proportional incentive contract exists and is optimal under certain conditions. Meanwhile, Zhang et al. [47] further considered the moral hazard and adverse selection issues in contract design, studied incentive contracts in the live-streaming supply chain under the information asymmetry of streaming influence and recommendation efforts, and revealed that equilibrium contracts depend on the priori beliefs of Pinbo suppliers about streamer influence.

Since changes in the market environment are often dynamic, the design of the contract between the principal and the agent may not always be static, so some scholars have carried out research on the dynamic incentive contract. For example, Barbos [48] carved out the optimal contract realized under stochastic monitoring in a stochastic dynamic setting where the type of agent cost varies over time. Hori and Osano [49] explored how the timing of compensation payments and contract termination are jointly determined in a continuous-time principal–agent model when the agent has loss aversion preferences and the principal has a discretionary termination policy. Szydlowski and Yoon [50] studied a continuous-time principal–agent model in which the subject is ambiguous and unwilling to influence the agent's cost of effort, and this robust contract produces a pay performance that appears to be overly sensitive. Zhu et al. [51] proposed a dynamic incentive and reputation mechanism to improve energy efficiency and training performance in federated learning. Xie et al. [52] analyzed the optimal contract in continuous time under the principal–multi-agent moral hazard environment based on the behavioral relationship between agents, and gave the optimal contract for the generalized principal–agent dynamic problem based on the stochastic optimal control theory, analyzed the optimal behavioral choices of the agents and incentive mechanisms. Tan et al. [53], motivated by information asymmetry that makes it difficult for recycling companies to determine incentive strategies for collectors, formulated a dynamic moral hazard model and found that collectors are always motivated to voluntarily maintain a high-quality supply of C&D waste under the optimal mechanism.

Unlike the above research, this paper follows the relevant research on dynamic decision models (e.g., Ma et al. [54], Meng et al. [31]), considers that the port emission reduction market is uncertain, and based on the dynamic equation of port emission reductions, studies the dynamic incentive contract design of the government (principal) for port enterprise (agent) to reduce emissions in the blockchain era.

2.4. Research Gap

In order to illustrate the research gap between the literature review and this study, and highlight the contributions of this paper, some representative articles are summarized and compared in Table 1, as follows.

Table 1. Summary of some existing related literature.

References	Blockchain Adoption	Shipping Industry	Port Emission Reduction	Government Subsidy		Carbon Trading Policy
				Dynamic Incentive	Static Incentive	
[27,28]	No	No	Yes	No	No	No
[29,33]	No	No	Yes	No	Yes	No
[20–23]	Yes	Yes	No	No	No	No
[10–14]	Yes	No	No	No	No	No
[51,52]	No	No	No	Yes	No	No
[39]	No	No	Yes	No	Yes	Yes
[36,37,40]	No	No	Yes	No	No	Yes
[31,32]	No	No	Yes	Yes	No	No
This paper	Yes	Yes	Yes	Yes	Yes	Yes

After defining the literature gap, we attempt to address the following new research questions.

RQ1: What is the optimal dynamic incentive strategy of the government for port enterprises to reduce emissions under blockchain technology and carbon trading policy?

RQ2: How can we sort out the effects and values of blockchain technology and carbon trading policy in the government's dynamic incentive to port enterprises' emission reduction?

RQ3: How do key parameters such as blockchain-related costs, market uncertainty, and carbon trading market price affect the government's dynamic incentive strategy and the optimal emission reduction investment decision of port enterprises?

The main contributions of this work are threefold.

First, we introduce the method of combining principal–agent theory and optimal control theory in the research of dynamic incentive contracts of governments to promote emission reduction of port enterprises. Our findings can contribute to government subsidy incentives and port emission reduction investment decisions in the shipping industry. We identify the optimal dynamic trajectory change rules of the government's incentive strategy for port emission reduction. We find that with the passage of time, the dynamic incentive contract of the government can not only promote the emission reduction of port enterprises in the early stage, but also improve the expected revenue of the government. However, in the later stage, the emission reductions of port enterprises under the government's dynamic incentive contract will maintain a steady value. In addition, a surprising finding is that the adoption of blockchain technology and the launch of a carbon trading policy will actually affect the government's dynamic incentive strategy due to the role of blockchain unit operating cost and carbon trading market price.

Second, our findings provide new contributions to the effects and values of blockchain technology and carbon trading policy in government dynamic incentives for port enterprises to reduce emissions. We compare the equilibrium solutions in different cases, and clarify the effects of blockchain technology and carbon trading policy on port emission reduction investment level and government dynamic incentive contract decisions. In addition, we identify the values of blockchain technology and carbon trading policy in promoting port emissions reduction and improving social benefit under meeting relevant critical conditions. We find that it is beneficial to realize the value of blockchain technology if the opportunity cost of investment in emission reduction for port enterprises is large, while it is beneficial to enhance the value of carbon trading policy if the threshold value of emission reduction for the port is small.

Third, we conduct parameter analysis and numerical analysis on equilibrium solutions in different scenarios, which provide important contributions to the strategic adjustments regarding the government's dynamic incentive contract and port enterprise's emission reduction investment decision. We find that the unit operating cost of the blockchain is usually unfavorable for port emissions reduction, but the carbon trading market price is usually favorable. An interesting proposal is to facilitate the landing and implementation of blockchain technology by appropriately increasing the carbon trading market price.

To the best of our knowledge, this is the first paper to examine the values of blockchain technology's smart contracts, green certification, and market information disclosure in the dynamic incentive contract of the government for port emission reduction when considering the carbon trading policy. This is the core innovation of this article. The research implications of this paper are twofold: (1) Theoretical significance. Our findings enrich the literature on port emission reduction, blockchain adoption, government subsidy incentives, and carbon trading policy; (2) Practical significance. Our managerial insights provide important lessons for port enterprises and government managers in the construction of green ports.

3. Problem Formulation and Assumptions

Ports, as core enterprises in the shipping industry, play an important role in promoting green port construction. As shown in Figure 1, we consider that a port enterprise (e.g., Shanghai International Port Group) in the t period actively invests in green energy-saving and emission reduction technologies (e.g., "oil-to-power" shore power, LNG, etc.) under the government's dynamic incentive contract $S(t)$ and strives to improve carbon emission reduction $G(t)$, which generates certain social benefits $R_g(t)$ in terms of reducing carbon emissions and improving the environment.

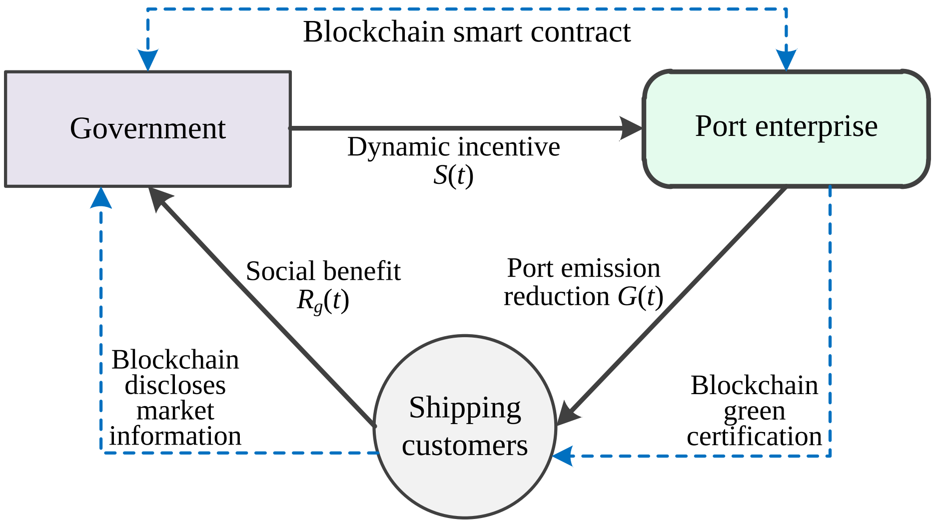


Figure 1. Model structure of government's dynamic incentives for port emission reduction under blockchain technology.

In addition, we consider government investment to build a port blockchain technology platform. The main values of blockchain technology are as follows: First, the government realizes the automatic execution of dynamic incentive contracts for emission reduction of port enterprises through the blockchain smart contract mechanism, which not only can ensure the execution of contracts and improve efficiency, but also can reduce the execution cost of contracts. Second, the blockchain can achieve green certification for port emission reduction. Specifically, based on blockchain technology, carbon emission data management, carbon emission traceability, carbon footprint tracking and verification of the emission reduction process of port enterprises will be carried out, and the authenticity and credibility of green energy conservation and emission reduction will be confirmed to shipping customers, so as to improve customers' green trust in the port service process and consolidate the investment results of port energy conservation and emission reduction. Third, the government can capture the historical transaction data of port enterprises based on the blockchain distributed database system, disclose the green energy-saving and emission reduction information of the port service process through "big data analysis", and reduce the uncertainty of the port emission reduction market, so as to more effectively implement dynamic incentives and realize the precise subsidies of the government to relevant port enterprises.

Based on the above description, the basic assumptions of this paper are as follows:

1. We assume that the investment level of the port enterprise in emission reduction in the t period is $I(t)$, which indicates the investment in energy-saving and emission reducing technologies such as "oil-to-electricity" shore-side power and LNG terminals by port enterprises to build green ports, and assume that the carbon emission reductions (*CERs*) of the port in period t is:

$$G(t) = \int_0^t (\beta \cdot I(t) - \sigma \cdot G(t))dt + v \tag{1}$$

where $\beta > 0$ refers to the impact factor of the port's *ERI* level $I(t)$ on the port's *CERs*; $s > 0$ indicates the attenuation rate of the port's *CERs*, which indicates that the emission reduction effect caused by port *ERI* before time t becomes worse (e.g., due to backward emission reduction technology, aging of shore power equipment, etc.), which makes it that there is a attenuation term in the cumulative emission reduction $G(t)$ at time t; and v represents the exogenous uncertainty with the mean value of 0 and the variance of δ^2, which reflects the uncertainty of port emission reduction market.

2. Referring to existing relevant literature (e.g., Hong and Guo [55], Chai et al. [56]), we assume that the social benefit brought by the port enterprise to the government through efforts to improve carbon emission reductions in the period t is $R_g(t) = h{\cdot}G(t)$, and h is the monetary expression of the social benefit generated by unit port emission reduction. In addition, based on the dynamic changes of the port's *CERs*, we propose a linear dynamic incentive contract for the government to implement subsidy to the port enterprise in the t period is:

$$S(t) = s_0(t) + s_1(t) \cdot G(t) \tag{2}$$

where $s_0(t)$ and $s_1(t)$, respectively, refer to the fixed subsidy and unit subsidy paid by the government to the port enterprise. In addition, we assume that the government will incur a contract execution cost c (such as information cost and supervision cost) in determining contract terms, fulfilling contracts, and resolving disputes during the t period.
3. As port emission reduction helps to attract green customers and promote shipping demand, it is assumed that the shipping customer demand caused by the port enterprise's *CERs* in the t period is $D(t) = \gamma{\cdot}G(t)$. $\gamma > 0$ is the impact of port emission reduction on shipping customer demand, which depends on shipping customers' awareness of green environmental protection. In addition, we also assume that the revenue of the port enterprise consists of two parts: one part is the revenue $R_p(t) = \xi \cdot D(t)$, and $\xi > 0$ is the service price of the port. The other part is the revenue $W(g_0,\ S(t)) = g_0{\cdot}S(t)$ brought to the port enterprise by the government's dynamic incentive contract $S(t)$, and $0 < g_0 < 1$ is the execution efficiency of the contract, which reflects the sensitivity of port enterprise to the government contract.
4. Considering that both the government and port enterprise are risk averse to their revenues [57], we define the degree of risk aversion θ using the Arrow–Pratt absolute risk aversion measure, and assume that the government's risk avoidance cost for social benefit $R_g(t)$ is $CR_g(t) = \theta{\cdot}Var(R_g(t))/2 = \theta{\cdot}h^2\delta^2/2$, and the port enterprise's risk avoidance cost for its revenue is $CR_p(t) = \theta{\cdot}Var(R_p(t) + W(t))/2 = \theta{\cdot}(g_0{\cdot}s_1(t) + \gamma\xi)^2\delta^2/2$.
5. Suppose that the investment cost function of emission reduction for the port enterprise is $\eta{\cdot}I^2(t)/2$ (such as the cost of equipment purchase, human input, technological innovation, and shore power maintenance), where $\eta > 0$ is the corresponding cost coefficient. The setting of the cost function meets the general convexity assumption in economics, and the economic implication behind it is that the investment cost of port emission reduction meets the law of marginal cost increase. In addition, we assume that the revenue of the port enterprise without emission reduction investment while maintaining the traditional operation mode is Φ, which reflects the opportunity cost of the port enterprise's green transformation investment in shore power and other emission reduction technologies. In addition, it is assumed that the government will provide dynamic incentives to the port enterprise's emission reduction within time $t \in [0, +\infty)$, ρ is used to express the discount rate of the port service market.

Based on the basic assumptions 1 to 5 above, combined with the values of blockchain technology, the following describes the relevant assumptions under blockchain technology:

(1) According to the value of blockchain smart contracts, it is assumed that the execution efficiency of government dynamic incentive contracts under blockchain technology is g_1 and meets $0 < g_0 < g_1 < 1$. At the same time, without losing generality, let the contract execution cost $c = 0$.
(2) According to the value of blockchain green certification, this paper introduces the green trust coefficient r of customers on the port's *ERI* level, which is reflected in

the accumulation of the port enterprise's effort to reduce emissions. Therefore, it is assumed that the port's *CERs* in the t period under blockchain technology is:

$$G(t) = \int_0^t (\beta \cdot I(t) - \sigma \cdot G(t) + r \cdot I(t))dt + v^* \quad (3)$$

where the green trust coefficient $0 < r < 1$ reflects the impact of blockchain green certification on port emission reduction, and v^* represents the uncertainty of the port emission reduction market under blockchain technology, which is different from v in Equation (1) (explained in (3) below).

(3) According to the value of blockchain disclosure of market information on green energy efficiency and emission reduction in ports, this paper introduces the disclosure degree ω of blockchain for port emission reduction uncertain information [58]. We assume that the random disturbance factor of port emission reduction under blockchain technology is v^* (see Equation (3)) with mean 0 and variance $(1 - \omega) \cdot \delta^2$, where $0 < \omega < 1$ denotes the degree of information disclosure. It reduces the variance of random disturbance factor without blockchain, and reduces the uncertainty of the port emission reduction market.

Moreover, it is assumed that the fixed cost for the government to invest in the construction of an energy blockchain technology platform is F_b, while the unit operating cost for the port enterprise to participate in and apply blockchain technology is C_b.

4. Models

In this section, the dynamic incentive contract models of the government for the port enterprise's emission reduction under the traditional mode without blockchain (Case *N*), with the adoption of blockchain (Case *B*) and considering carbon trading policy under blockchain technology (Case *TB*), is constructed, respectively. Moreover, we will solve for the optimal dynamic incentive contract of the government, the optimal *ERI* level and verified emission reductions (*VERs*) of the port, and the discounted value of the government's expected benefit under different cases. The basis for the model used in the article includes two aspects: (1) Theoretical basis. This article follows relevant literature such as principal–agent and optimal control to further study the dynamic incentive model of government for port emission reduction in the shipping industry. (2) Realistic basis. The model in this paper is based on the realistic background of the government encouraging port enterprises to strive for green investment construction and emission reduction, as well as the application of shipping blockchain. The theoretical and practical basis has been explained in detail in the Literature Review section (Section 2) as well as in the Problem Formulation and Assumptions section (Section 3).

4.1. No Blockchain (Case N)

As a benchmark model, this subsection considers the case of N in which the government dynamically encourages the port enterprise to reduce emissions in the traditional mode without blockchain. According to the basic assumptions in Section 3, we can obtain the *VERs* of the port enterprise certified by the government in period t; that is, the expected emission reductions $EG^N(t)$ is:

$$EG^N(t) = E(G^N(t)) = \int_0^t (\beta \cdot I^N(t) - \sigma \cdot EG^N(t))dt \quad (4)$$

The state equation of the port's *VERs* can be constructed by differentiating the two ends of Equation (4):

$$dEG^N(t) = \beta \cdot I^N(t)dt - \sigma \cdot EG^N(t)dt \quad (5)$$

This state equation reflects the state of port *VERs* at time *t*. Since the government cannot observe the effort of port enterprise in emission reduction investment (which is private information), the port enterprise may have the moral hazard problem of hidden action. Therefore, in order to induce the port enterprise to choose the emission reduction action beneficial to the government from its own interest, this paper, based on the state change of port *VERs*, considers the income and cost expenditure of the government and port enterprises, and uses the principal–agent theory to construct a dynamic incentive contract model for the government to reduce the emission of the port enterprise under the traditional mode without blockchain:

$$\max_{s_0{}^N(t),\, s_1{}^N(t)} \left\{ \pi_g{}^N = \int_0^{+\infty} e^{-\rho \cdot t} [E(R_g{}^N(t)) - E(S^N(t)) - CR_g{}^N(t) - c \cdot E(S^N(t))] dt \right\} \quad (6)$$

$$s.t. \begin{cases} IR: \; E(R_p{}^N(t)) + E(W^N(t)) - \frac{1}{2}\eta I^{N^2}(t) - CR_p{}^N(t) \geq \Phi \\ IC: \; I^N(t) \in arg\max(\pi_p{}^N) = \int_0^{+\infty} e^{-\rho \cdot t} \quad [E(R_p{}^N(t)) + E(W(t)) - \frac{1}{2}\eta I^{N^2}(t) \\ \qquad\qquad -CR_p{}^N(t)] dt \\ SE: \; dEG^N(t) = \beta \cdot I^N(t) dt - \sigma \cdot EG^N(t) dt \end{cases} \quad (7)$$

Among them, $\pi_g{}^N$ in the objective function formula (6) represents the discounted value of the total expected benefit of the government in the time of [0, +∞] under the case of *N*, which includes four parts: $E(R_g{}^N(t))$ denotes the expected social benefit to the government from the port's *CERs* in period *t*, $E(S^N(t))$ refers to the dynamic incentive contract expected to be paid by the government to port enterprise in period *t*, $CR_g{}^N(t)$ refers to the risk aversion cost of the government to social benefit, and $c \cdot E(S^N(t))$ refers to the contract execution cost expected by the government in the period *t*. In Equation (7), *IR* refers to the individual rational constraint of port enterprise, which ensures that the expected return of the port enterprise's green transformation and active emission reduction investment is not lower than that of the traditional operation mode. *IC* is the incentive compatibility constraint of port enterprise; that is, after signing the contract, the port enterprise determines its *ERI* level $I^N(t)$ based on maximizing its own expected revenue $\pi_p{}^N$. *SE* is the state equation of port *VERs*.

Next, we first solve the optimal *ERI* level of port enterprise under the government dynamic incentive contract. According to the constraints *IC* and *SE*, the expected revenue of port enterprise is transformed into the following continuous dynamic optimal control problem:

$$\max_{I^N(t)} \left\{ \begin{aligned} \pi_p{}^N &= \int_0^{+\infty} e^{-\rho \cdot t} \quad [E(R_p{}^N(t)) + E(W^N(t)) - \tfrac{1}{2}\eta I^{N^2}(t) - CR_p{}^N(t)] dt \\ &= \int_0^{+\infty} e^{-\rho \cdot t} \quad [\gamma\xi \cdot EG^N(t) + g_0 \cdot (s_0{}^N(t) + s_1{}^N(t) \cdot EG^N(t)) \\ &\qquad - \tfrac{1}{2}\eta I^{N^2}(t) - \tfrac{1}{2}\theta(g_0 \cdot s_1{}^N(t) + \gamma\xi)2\delta^2] dt \end{aligned} \right\} \quad (8)$$

$$s.t. \;\; dEG^N(t) = \beta \cdot I^N(t) dt - \sigma \cdot EG^N(t) dt$$

In order to solve the dynamic optimal control problem of the port enterprise objective function (8), let the optimal expected value function of the port enterprise be $V_p{}^N(EG^N)$, which represents the discounted value of the total expected revenue in the period from time *t* to +∞. $V_p{}^{N\prime}(EG^N)$, be the first derivative of the optimal expected value function with respect to the port EG^N, which represents the marginal contribution of the unit port *VERs* to the discounted value of the total expected revenue of the port enterprise. According to the continuous dynamic optimal control theory, the optimal expected value function ${V_p}^N(EG^N)$ satisfies the following Hamilton–Jacobi–Bellman (HJB) equation:

$$\rho \cdot {V_p}^N(EG^N) = \max_{I^N(t)} \left\{ \begin{array}{l} [\gamma\xi \cdot EG^N(t) + g_0 \cdot ({s_0}^N(t) + {s_1}^N(t) \cdot EG^N(t)) - \frac{1}{2}\eta {I^N}^2(t) - \frac{1}{2}\theta(s_0 \\ \cdot {s_1}^N(t) + \gamma\xi)^2\delta^2] + {V_p}^{N\prime}(EG^N)[\beta \cdot I^N(t) - \sigma \cdot EG^N(t)] \end{array} \right\} \tag{9}$$

Lemma 1. *In Case N, the optimal response to the ERI level of port enterprise in the government's dynamic incentive contract is:*

$$I^{N^*}(t) = \frac{\beta(g_0 {s_1}^N(t) + \gamma\xi)}{\eta(\rho + \sigma)} \tag{10}$$

Under the constraint of incentive compatibility, the port enterprise will always choose the action to maximize its expected return; that is, it will always choose the corresponding *ERI* level $I^{N^*}(t)$ when maximizing its own interests. Therefore, according to Lemma 1, the incentive compatibility constraint condition *IC* of port enterprise can be expressed equivalently by Equation (10). For port enterprise's individual rationality constraint *IR*, it is a tight constraint when the government objective function is maximized. The reason is that if *IR* is not equal, the government in the model will always increase its expected benefit by reducing the fixed subsidy ${s_0}^N(t)$ without affecting the establishment of the port enterprise's *IR* condition. Therefore, the government dynamic incentive contract model in the *N* case can be transformed into the following optimal control problem:

$$\max_{{s_0}^N(t),\, {s_1}^N(t)} \left\{ \begin{array}{lll} {\pi_g}^N & = \int_0^{+\infty} e^{-\rho \cdot t} & [E({R_g}^N(t)) - E(S^N(t)) - C{R_g}^N(t) - c \cdot E(S^N(t))]dt \\ & = \int_0^{+\infty} e^{-\rho \cdot t} & [h \cdot (EG^N(t)) - ({s_0}^N(t) + {s_1}^N(t) \cdot EG^N(t)) - \frac{1}{2}\theta h^2\delta^2 \\ & & -c \cdot ({s_0}^N(t) + {s_1}^N(t) \cdot EG^N(t))]dt \end{array} \right\} \tag{11}$$

$$s.t. \left\{ \begin{array}{l} IR: \left[\begin{array}{l} \gamma\xi \cdot E \quad G^N(t) + g_0 \cdot ({s_0}^N(t) + {s_1}^N(t) \cdot EG^N(t)) - \frac{1}{2}\eta {I^{N^*}}^2(t) - \\ \qquad \frac{1}{2}\theta(g_0 \cdot {s_1}^N(t) + \gamma\xi)2\delta^2 \end{array} \right] = \Phi \\ IC: \ I^{N^*}(t) = \frac{\beta(g_0 {s_1}^N(t) + \gamma\xi)}{\eta(\rho+\sigma)} \\ SE: \ dEG^N(t) = \beta \cdot I^{N^*}(t)dt - \sigma \cdot EG^N(t)dt \end{array} \right. \tag{12}$$

According to the incentive compatibility constraint *IR* in the above formula, the optimal fixed subsidy for port enterprise in the government dynamic incentive contract should meet the following requirement:

$${s_0}^{N^*}(t) = \frac{1}{g_0}(\Phi + \frac{1}{2}\eta I^{N^*2}(t) + \frac{1}{2}\theta(g_0 \cdot {s_1}^N(t) + \gamma\xi)^2\delta^2 - \gamma\xi \cdot EG^N(t)) - {s_1}^N(t) \cdot EG^N(t) \tag{13}$$

Furthermore, the individual rational constraint *IR* and incentive-compatible constraint *IC* of port enterprise are substituted into the government objective function and the state change equation of port *VERs*. The above optimization problem can be reformulated as:

$$\max_{{s_1}^N(t)} \left\{ \begin{array}{ll} {\pi_g}^N = \int_0^{+\infty} e^{-\rho \cdot t} & [h \cdot (EG^N(t)) - \frac{1+c}{g_0} \cdot (\Phi + \frac{\beta^2(g_0 {s_1}^N(t) + \gamma\xi)^2}{2\eta(\rho+\sigma)^2} + \frac{1}{2}\theta(g_0 \cdot \\ & {s_1}^N(t) + \gamma\xi)^2\delta^2 - \gamma\xi \cdot EG^N(t) - \frac{1}{2}\theta h^2\delta^2]dt \end{array} \right\} \tag{14}$$

$$s.t.\ dEG^N(t) = \frac{\beta^2(g_0 {s_1}^N(t) + \gamma\xi)}{\eta(\rho+\sigma)}dt - \sigma \cdot EG^N(t)dt$$

To solve the continuous dynamic optimal control problem in Equation (14), let the optimal expected value function of the government be ${V_g}^N(EG^N)$, which satisfies the following HJB equation:

$$\rho \cdot {V_g}^N(EG^N) = \max_{{s_1}^N(t)} \left\{ \begin{array}{l} [h \cdot (EG^N(t)) - \frac{1+c}{g_0} \cdot (\Phi + \frac{\beta^2 (g_0 {s_1}^N(t) + \gamma\xi)^2}{2\eta(\rho+\sigma)^2} + \frac{1}{2}\theta(g_0 \cdot \\ {s_1}^N(t) + \gamma\xi)^2\delta^2 - \gamma\xi \cdot EG^N(t) - \frac{1}{2}\theta h^2 \delta^2] + {V_g}^{N\prime}(EG^N) \\ [\frac{\beta^2 (g_0 {s_1}^N(t) + \gamma\xi)}{\eta(\rho+\sigma)} - \sigma \cdot EG^N(t)] \end{array} \right\} \tag{15}$$

By solving the HJB equation, Theorem 1 can be obtained.

Theorem 1. *In the case of traditional mode N without blockchain, the optimal ERI level of port enterprise is:*

$$I^{N*} = \frac{\beta^3 (c\gamma\xi + g_0 h + \gamma\xi)}{(c+1)\eta(\rho+\sigma)\left(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2\right)} \tag{16}$$

the optimal unit subsidy for emission reduction of the port enterprise in the government dynamic incentive contract is:

$${s_1}^{N*} = \frac{1}{g_0} \cdot \left[\frac{\beta^2 (c\gamma\xi + g_0 h + \gamma\xi)}{(c+1)\left(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2\right)} - \gamma\xi \right] \tag{17}$$

According to Theorem 1, Corollary 1 can be obtained.

Corollary 1. *In the case of traditional mode N without blockchain, the optimal dynamic trajectory of port VERs is:*

$$EG^{N*}(t) = \frac{\beta^4 (c\gamma\xi + g_0 h + \gamma\xi)(1 - \mathrm{e}^{-\sigma \cdot t})}{\sigma(c+1)\eta(\rho+\sigma)\left(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2\right)} \tag{18}$$

the optimal fixed subsidy for the port enterprise in the government dynamic incentive contract is:

$${s_0}^{N*}(t) = \frac{1}{2g_0} \cdot \left[\frac{\beta^2 (c\gamma\xi + g_0 h + \gamma\xi)\left((c+1)\left(\beta^2\gamma\xi - 2EG^{N*}(t)\eta(\rho+\sigma)^2\right) + \beta^2 g_0 h\right)}{(c+1)^2\eta(\rho+\sigma)^2\left(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2\right)} + 2\Phi \right] \tag{19}$$

the optimal dynamic trajectory of the discounted value of government expected benefit is:

$${V_g}^{N*}(t) = \frac{c\gamma\xi + g_0 h + \gamma\xi}{g_0\rho + g_0\sigma} \cdot EG^{N*}(t) + \frac{1}{2g_0\rho} \cdot \left[\begin{array}{l} \frac{\beta^2 (c\gamma\xi + g_0 h + \gamma\xi)^2}{(c+1)\eta(\rho+\sigma)^2} - \frac{\beta^2\delta^2\theta(c\gamma\xi + g_0 h + \gamma\xi)^2}{(c+1)\left(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2\right)} \\ -\delta^2 g_0 h^2 \theta - 2\Phi(1+c) \end{array} \right] \tag{20}$$

4.2. Blockchain Adoption (Case B)

In this subsection, we consider Case *B*, in which the government dynamically encourages port enterprises to reduce emissions under blockchain technology. According to the values and relevant assumptions of blockchain technology in Section 3, considering the impacts of blockchain smart contracts, green certification, information disclosure, and blockchain-related costs, the dynamic incentive contract model of government for the port enterprise's emission reduction under blockchain technology is established as follows:

$$\max_{s_0{}^B(t),\, s_1{}^B(t)} \left\{ \begin{aligned} \pi_g{}^B &= \int_0^{+\infty} e^{-\rho \cdot t}[E(R_g{}^B(t)) - E(S^B(t)) - CR_g{}^B(t)]dt - F_b \\ &= \int_0^{+\infty} e^{-\rho \cdot t}[E(R_g{}^B(t)) - E(S^B(t)) - CR_g{}^B(t) - \rho F_b]dt \end{aligned} \right\} \tag{21}$$

$$s.t. \begin{cases} IR: \; E(R_p{}^B(t)) + E(W^B(t)) - \frac{1}{2}\eta I^{B^2}(t) - CR_p{}^B(t) - C_b \cdot E(G^B(t)) \geq \Phi \\ IC: \; I^B(t) \in arg\max(\pi_p{}^B) = \int_0^{+\infty} e^{-\rho \cdot t} \quad [E(R_p{}^B(t)) + E(W^B(t)) - \frac{1}{2}\eta I^{B^2}(t) \\ \qquad\qquad -CR_p{}^B(t) - C_b \cdot E(G^B(t))]dt \\ SE: \; dEG^B(t) = \beta \cdot I^B(t)dt - \sigma \cdot EG^B(t)dt + r \cdot I^B(t)dt \end{cases} \tag{22}$$

Compared with the traditional mode N without blockchain, in this blockchain model, there is no contract execution cost c in the government objective function (21) under blockchain technology, but there is a fixed cost F for establishing blockchain, and the government's risk aversion cost for its social benefit is updated to $CR_g{}^B(t) = \theta \cdot Var(R_g{}^B(t))/2 = \theta \cdot h^2(1-\omega)\delta^2/2$. In the individual rational constraint IR and incentive compatibility constraint IC, the revenue that the government dynamic incentive contract $S^B(t)$ brings to port enterprise is updated to $W^B(t) = g_1 \cdot S^B(t)$, the risk aversion cost of port enterprise's revenue is updated to $CR_p{}^B(t) = \theta \cdot Var(R_p{}^B(t) + W^B(t))/2 = \theta \cdot (g_1 \cdot s_1{}^B(t) + \gamma\xi)^2(1-\omega)\delta^2/2$, and the port enterprise needs to bear certain operating costs of blockchain $C_b \cdot E(G^B(t))$.

In addition, in the state change equation SE of port emission reduction, a customer's green trust item for port ERI, namely $r \cdot I^B(t)$, is designed. As mentioned above, blockchain green certification helps the port enterprise to prove the authenticity and credibility of its green energy conservation and emission reduction to customers, and relevant customers will generate an additional green trust item for the emission reduction process of blockchain-supported port enterprise out of low-carbon preference. Moreover, the cumulative change of port $EG^B(t)$ will also directly affect the social benefit $E(R_g{}^B(t)) = h \cdot EG^B(t)$ of the government and the income $E(R_p{}^B(t)) = \gamma\xi \cdot EG^B(t)$ of port enterprise·

Similarly, we first convert the expected revenue of port enterprise into the corresponding continuous dynamic optimal control problem according to the incentive compatibility constraint IC and the state change equation SE in Equation (22). By constructing and solving the HJB equation, Lemma 2 can be obtained.

Lemma 2. *Under blockchain technology, the optimal response of the ERI level of port enterprise to the government dynamic incentive contract is:*

$$I^{B^*}(t) = \frac{(r+\beta)\left(g_1 s_1{}^B(t) + \gamma\xi - C_b\right)}{\eta(\rho+\sigma)} \tag{23}$$

According to Lemma 2, by substituting $I^{B^*}(t)$ into the personal rational constraint IR and tightening the constraint, the optimal fixed subsidy for port enterprise in the government dynamic incentive contract can be obtained as follows:

$$\begin{aligned} s_0{}^{B^*}(t) = \; & \tfrac{1}{g_1}(\Phi + \tfrac{1}{2}\eta I^{B^{*2}}(t) + \tfrac{1}{2}\theta(g_1 \cdot s_1{}^B(t) + \gamma\xi)^2(1-\omega)\delta^2 + C_b \cdot EG^B(t) - \gamma\xi \cdot EG^B(t)) \\ & - s_1{}^B(t) \cdot EG^B(t) \end{aligned} \tag{24}$$

Further, according to $I^{B^*}(t)$ and ${s_0}^{B^*}(t)$, the objective function and state change equation of the government are updated, and the optimization problem of the original model can be transformed into:

$$\max_{{s_1}^B(t)}\left\{\begin{array}{lll} {\pi_g}^B & = \int_0^{+\infty} e^{-\rho\cdot t} & [E({R_g}^B(t)) - E(S^B(t)) - C{R_g}^B(t) - \rho F_b]dt \\ & = \int_0^{+\infty} e^{-\rho\cdot t} & [h\cdot(EG^B(t)) - \frac{1}{g_1}(\Phi + \frac{1}{2}\eta {I^{B^*}}^2(t) + \frac{1}{2}\theta(g_1\cdot {s_1}^B(t) + \gamma\xi)2(1-\omega \\ & &)\delta^2 + C_b\cdot EG^B(t) - \gamma\xi\cdot EG^B(t)) - \frac{1}{2}\theta h^2(1-\omega)\delta^2 - \rho F_b]dt \end{array}\right\} \tag{25}$$

$$s.t.\ dEG^B(t) = (\beta + r)\cdot\frac{(r+\beta)\left(-C_b + g_1 {s_1}^{TB}(t) + \gamma\xi\right)}{\eta(\rho+\sigma)}dt - \sigma\cdot EG^B(t)dt$$

Furthermore, by constructing and solving the HJB equation containing the control variable ${s_1}^B(t)$, Theorem 2 can be obtained.

Theorem 2. *Under blockchain technology, the optimal ERI level of port enterprise is:*

$$I^{B^*} = \frac{(\beta + r)}{\eta(\rho+\sigma)}\cdot\left[\frac{(\beta+r)^2(g_1 h + \gamma\xi)}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2} - C_b\right] \tag{26}$$

the optimal unit subsidy for port emission reduction in the government dynamic incentive contract is:

$${s_1}^{B^*} = \frac{g_1 h(\beta+r)^2 - \delta^2\eta\theta\gamma\xi(1-\omega)(\rho+\sigma)^2}{g_1\left(\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2\right)} \tag{27}$$

Corollary 2. *Under blockchain technology, the optimal dynamic trajectory of port VERs is:*

$$EG^{B^*}(t) = \frac{(\beta+r)^2(1-\mathrm{e}^{-\sigma\cdot t})}{\eta(\rho+\sigma)}\cdot\left[\frac{(\beta+r)^2(g_1 h + \gamma\xi)}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2} - C_b\right] \tag{28}$$

the optimal fixed subsidy for port emission reduction in the government dynamic incentive contract is:

$${s_0}^{B^*}(t) = \frac{1}{2g_1}\left[\begin{array}{l} 2C_b EG^{B^*}(t) + \frac{(\beta+r)^2}{\eta(\rho+\sigma)^2}\left(C_b - \frac{(\beta+r)^2(g_1 h+\gamma\xi)}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2}\right)^2 + \delta^2\theta\gamma^2\xi^2 \\ (1-\omega) - \frac{\left(2\delta^2\theta\gamma\xi(1-\omega) - 2EG^{B^*}(t)\right)\left(g_1 h(\beta+r)^2 - \delta^2\eta\theta\gamma\xi(1-\omega)(\rho+\sigma)^2\right)}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2} \\ -2EG^{B^*}(t)\gamma\xi + \frac{\delta^2\theta(1-\omega)\left(g_1 h(\beta+r)^2 - \delta^2\eta\theta\gamma\xi(1-\omega)(\rho+\sigma)^2\right)^2}{\left(\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2\right)^2} + 2\Phi \end{array}\right] \tag{29}$$

the optimal dynamic trajectory of the discounted value of government expected benefit is:

$${V_g}^{B^*}(t) = \frac{g_1 h + \gamma\xi - C_b}{g_1(\rho+\sigma)}\cdot EG^{B^*}(t) + \frac{1}{2g_1\rho}\left[\begin{array}{l} \frac{(\beta+r)^2(g_1 h + \gamma\xi - C_b)^2}{\eta(\rho+\sigma)^2} - g_1\left(2F_b\rho + \delta^2 h^2\theta(1-\omega)\right) \\ -\frac{\delta^2\theta(1-\omega)(\beta+r)^2(g_1 h+\gamma\xi)^2}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2} - 2\Phi \end{array}\right] \tag{30}$$

4.3. Blockchain Adoption When Considering Carbon Trading Policy (Case TB)

Carbon emissions trading (i.e., carbon trading) refers to the trading of greenhouse gas emissions such as carbon dioxide (CO_2) as commodities, which is a market mechanism used to reduce global greenhouse gas emissions. This subsection will further discuss the dynamic incentive contract of the government for the port enterprise's emission reduction when the carbon trading market mechanism is introduced under blockchain technology.

On the basis of the research in Section 4.2, considering the mandatory carbon quota (i.e., carbon emission permit) imposed by the government on port enterprise, it is assumed that in order to meet its own carbon emission demand, the revenue or expenditure that port enterprise can obtain from selling or purchasing carbon quota in the carbon trading market is $T(t) = \tau \cdot (G(t) - \psi)$, where τ refers to the carbon trading market price, and ψ indicates that the port enterprise meets the critical value of *CERs* required by the government carbon quota. Specifically, when the port enterprise makes efforts to carry out *ERI* and thus promotes carbon emission reduction, if the port's *CERs* are less than the critical value ψ (i.e., $G(t) < \psi$), the port enterprise's carbon emissions will be higher than the government's carbon quota limit, and it needs to purchase carbon quota in the carbon trading market to meet the carbon emission demand, at which time we have $T(t) < 0$. However, when the port's *CERs* are greater than the critical value ψ (i.e., $G(t) > \psi$), the carbon emissions of the port enterprise will be lower than the government carbon quota limit, and it can benefit from selling excess carbon quota in the carbon trading market, at which time we have $T(t) > 0$. In short, the critical value ψ is related to the government's carbon quota. The smaller the carbon quota, the more emission reductions the port needs to achieve, and the larger the ψ; otherwise, the result is just the opposite. It can be seen that when considering the carbon trading mechanism, the design of the carbon reduction threshold certified by the government carbon quota can balance the carbon emissions of port enterprises. Therefore, considering the carbon trading policy, the dynamic incentive contract model of the government for port enterprise's emission reduction under blockchain technology is constructed as follows:

$$\max_{s_0{}^{TB}(t),\, s_1{}^{TB}(t)} \left\{ \pi_g = \int_0^{+\infty} e^{-\rho \cdot t} [E({R_g}^{TB}(t)) - E(S^{TB}(t)) - {CR_g}^{TB}(t) - \rho F_b] dt \right\} \tag{31}$$

$$s.t. \begin{cases} IR: \ E({R_p}^{TB}(t)) + E(W^{TB}(t)) + E(T^{TB}(t)) - \frac{1}{2}\eta {I^{TB}}^2(t) - {CR_p}^{TB}(t) - C_b \cdot E(G^{TB}(t)) \geq \Phi \\ IC: \ I^{TB}(t) \in arg\max({\pi_p}^{TB}) = \int\limits_0^{+\infty} e^{-\rho \cdot t} \quad [E({R^{TB}}_p(t)) + E(W^{TB}(t)) + E(T^{TB}(t)) - \\ \qquad \frac{1}{2}\eta {I^{TB}}^2(t) - {CR_p}^{TB}(t) - C_b \cdot E(G^{TB}(t))] dt \\ SE: \ dEG^{TB}(t) = \beta \cdot I^{TB}(t) dt - \sigma \cdot EG^{TB}(t) dt + r \cdot I^{TB}(t) dt \end{cases} \tag{32}$$

Lemma 3. *In the TB case where blockchain is used when considering carbon trading policy, the optimal response of the ERI level of port enterprise to the government dynamic incentive contract is:*

$$I^{TB^*}(t) = \frac{(r+\beta)\left(g_1 {s_1}^{TB}(t) + \gamma\xi + \tau - C_b\right)}{\eta(\rho+\sigma)} \tag{33}$$

According to Lemma 3, Theorem 3 can be obtained by further solving the blockchain-carbon trading model.

Theorem 3. *Under blockchain technology and carbon trading policy, the optimal ERI level of the port enterprise is:*

$$I^{TB^*}(t) = \frac{(r+\beta)\left(g_1 {s_1}^{TB}(t) + \gamma\xi + \tau - C_b\right)}{\eta(\rho+\sigma)} \tag{34}$$

the optimal unit subsidy for port emission reduction in the government dynamic incentive contract is:

$${s_1}^{TB^*} = \frac{g_1 h(\beta+r)^2 - \delta^2\eta\theta\gamma\xi(1-\omega)(\rho+\sigma)^2}{g_1\left(\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2 + (\beta+r)^2\right)} \tag{35}$$

Corollary 3. *In the TB case, the optimal dynamic trajectory of port VERs is:*

$$EG^{TB*}(t) = \frac{(\beta+r)^2(1-\mathrm{e}^{-\sigma\cdot t})}{\eta(\rho+\sigma)} \cdot \left[-C_b + \frac{(\beta+r)^2(g_1h+\gamma\xi)}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2+(\beta+r)^2} + \tau\right] \tag{36}$$

the optimal fixed subsidy for port emission reduction in the government dynamic incentive contract is:

$$s_0{}^{TB*}(t) = \frac{1}{2g_1}\left[\begin{array}{l} 2C_bEG^{TB*}(t) + \frac{(\beta+r)^2}{\eta(\rho+\sigma)^2}\left(\tau - C_b + \frac{(\beta+r)^2(g_1h+\gamma\xi)}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2+(\beta+r)^2}\right)^2 \\ -\frac{\left(2\delta^2\theta\gamma\xi(1-\omega)-2EG^{TB*}(t)\right)\left(g_1h(\beta+r)^2-\delta^2\eta\theta\gamma\xi(1-\omega)(\rho+\sigma)^2\right)}{\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2+(\beta+r)^2} \\ +\frac{\delta^2\theta(1-\omega)\left(g_1h(\beta+r)^2-\delta^2\eta\theta\gamma\xi(1-\omega)(\rho+\sigma)^2\right)^2}{\left(\delta^2\eta\theta(1-\omega)(\rho+\sigma)^2+(\beta+r)^2\right)^2} + \delta^2\theta\gamma^2\xi^2(1-\omega) \\ -2EG^{TB*}(t)(\tau+\gamma\xi) + 2\Phi + 2\tau\psi \end{array}\right] \tag{37}$$

the optimal dynamic trajectory of the discounted value of government expected benefit is:

$$\begin{aligned} V_g{}^{TB*}(t) = \; & \frac{g_1h+\tau+\gamma\xi-C_b}{g_1(\rho+\sigma)} \cdot EG^{TB*}(t) + \frac{(\beta+r)^2\left(s_1{}^{TB*}g_1-C_b+\tau+\gamma\xi\right)(-C_b+g_1h+\tau+\gamma\xi)}{\rho\eta g_1(\rho+\sigma)^2} \\ & -\frac{1}{2g_1\rho}\left[\begin{array}{l} s_1{}^{TB*2}\delta^2 g_1{}^2\theta(1-\omega) + \frac{(\beta+r)^2\left(g_1s_1{}^{TB*}-C_b+\tau+\gamma\xi\right)^2}{\eta(\rho+\sigma)^2} + 2s_1{}^{TB*}\delta^2g_1\theta\gamma\xi \\ (1-\omega) + \delta^2\theta\gamma^2\xi^2(1-\omega) + 2\Phi + 2\tau\psi + 2g_1F_b\rho + \delta^2h^2g_1\theta(1-\omega) \end{array}\right] \end{aligned} \tag{38}$$

5. Model Analysis

This section will systematically study the equilibrium solutions of the government and port enterprise in the traditional mode without blockchain (Case *N*), blockchain adoption (Case *B*), and blockchain adoption under carbon trading policy (Case *TB*). We first explore the optimal dynamic trajectory change rules of the government's incentive strategy for port emission reduction under different cases, and then analyze the impacts of relevant parameters on the optimal decisions of the government and port enterprise. Finally, we reveal the effects and values of blockchain and carbon trading policy by comparing the equilibrium solutions under different cases.

5.1. Government's Dynamic Incentive Strategy for Port Emission Reduction

The government's dynamic incentive strategy refers to the optimal dynamic trajectories of port *VERs* $EG^*(t)$, fixed subsidy $s_0{}^*(t)$, incentive contract $S^*(t)$, and the government's expected benefit discount value $V_g{}^*(t)$. This subsection will analyze the optimal dynamic trajectory change rules of the government's incentive strategy. The purpose is to study how the government should dynamically adjust the incentive contract for port enterprises to reduce emissions, and how the port *VERs* and the government's expected benefit discount value will evolve under the influence of the government's optimal contract. At the same time, it provides a reference and theoretical basis for relevant government decision-makers to adjust and control the optimal state of dynamic changes in port enterprises' emission reduction incentive strategies before and after the adoption of blockchain and the launch of the carbon trading market.

Proposition 1. *In the case N, analysis of the government's dynamic incentive strategy for port emission reduction is as follows:*

(i) *When* $t < t_{th}{}^N$, *then* $\frac{\partial EG^{N*}(t)}{\partial t} > 0$, $\frac{\partial s_0{}^{N*}(t)}{\partial t} < 0$, $\frac{\partial S^{N*}(t)}{\partial t} < 0$, $\frac{\partial V_g{}^{N*}(t)}{\partial t} > 0$;

(ii) *When* $t \geq t_{th}{}^N$, *then* $\frac{\partial EG^{N*}(t)}{\partial t} = 0$, $\frac{\partial s_0{}^{N*}(t)}{\partial t} = 0$, $\frac{\partial S^{N*}(t)}{\partial t} = 0$, $\frac{\partial V_g{}^{N*}(t)}{\partial t} = 0$;

where $t_{th}{}^N$ *is the time threshold in* $(0, +\infty)$.

As a reference, it can be seen from Proposition 1 that in the traditional mode without blockchain, the optimal dynamic trajectory change rules of the government incentive strategy are related to the time when the government implements dynamic incentives to the port enterprise. Specifically, in the early stage of the government's implementation of dynamic incentives for port emission reduction, that is, when $t < t_{\text{th}}{}^{N}$, the port *VERs* $EG^{N^*}(t)$ and the government's expected benefit discount value $V_g{}^{N^*}(t)$ monotonically increased with time t, while the government's fixed subsidy $s_0{}^{N^*}$ and incentive contract $S^{N^*}(t)$ monotonically decreased with time t. This means that the government dynamic incentive contract not only promotes the emission reduction of the port enterprise, but also improves the expected benefit of the government. This is because the utilization rate of green equipment such as port electricity increases with the increase in emission reduction, while the carbon emissions decrease over the same period. The government has achieved economic growth and social benefit in the process of carbon emission reduction and environmental improvement. At the same time, the government's investment in incentive subsidies for port enterprise in the early stage is large, and with the passage of time and the improvement of the emission reduction incentive effect, the government's incentive subsidies for port enterprise will gradually decrease. When the government's dynamic incentive time exceeds a critical point, that is, $t \geq t_{\text{th}}{}^{N}$, the optimal dynamic trajectories of the government's emission reduction incentive strategy will not change with time. At this time, $EG^{N^*}(t)$, $V_g{}^{N^*}(t)$, $s_0{}^{N^*}(t)$, and $S^{N^*}(t)$ all reach steady-state values.

Proposition 2. *In Case B, analysis of the government's dynamic incentive strategy for port emission reduction is as follows:*

(i) When $t < t_{th}{}^{B}$, then $\frac{\partial EG^B(t)}{\partial t} > 0, \begin{cases} if\ C_b = 0,\ then\ \frac{\partial s_0{}^B(t)}{\partial t} < 0 \\ if\ C_b > 0, \begin{cases} and\ C_b < C_b{}^{th1},\ then\ \frac{\partial s_0{}^B(t)}{\partial t} < 0 \\ and\ C_b \geq C_b{}^{th1},\ then\ \frac{\partial s_0{}^B(t)}{\partial t} \geq 0 \end{cases} \end{cases},$

$$\begin{cases} if\ C_b = 0,\ then\ \frac{\partial S^B(t)}{\partial t} < 0 \\ if\ C_b > 0, \begin{cases} and\ C_b < \gamma\xi,\ then\ \frac{\partial S^B(t)}{\partial t} < 0 \\ and\ C_b \geq \gamma\xi,\ then\ \frac{\partial S^B(t)}{\partial t} \geq 0 \end{cases} \end{cases},$$

$$\begin{cases} if\ C_b = 0,\ then\ \frac{\partial V_g{}^B(t)}{\partial t} > 0 \\ if\ C_b > 0, \begin{cases} and\ C_b < g_1 h + \gamma\xi,\ then\ \frac{\partial V_g{}^B(t)}{\partial t} > 0 \\ and\ C_b \geq g_1 h + \gamma\xi,\ then\ \frac{\partial V_g{}^B(t)}{\partial t} \leq 0 \end{cases} \end{cases};$$

(ii) When $t \geq t_{th}{}^{B}$, then $\frac{\partial EG^B(t)}{\partial t} = 0, \frac{\partial s_0{}^B(t)}{\partial t} = 0, \frac{\partial S^B(t)}{\partial t} = 0, \frac{\partial V_g{}^B(t)}{\partial t} = 0$;

where $C_b{}^{th1} = \frac{(r+\beta)^2(g_1 h+\gamma\xi)}{(r+\beta)^2+\delta^2\eta\theta(\rho+\sigma)^2(1-\omega)}$; $t_{th}{}^{B}$ *is the time threshold in (0, +∞).*

Proposition 2 shows that under Case *B*, when $C_b = 0$ [10,59], the optimal dynamic trajectory change rules of the government incentive strategy are the same as the traditional model without blockchain, which is only related to time t. However, when $C_b > 0$, the change rules of the fixed subsidy $s_0{}^{B^*}(t)$, incentive contract $S^{B^*}(t)$ and the government expected benefit discount value $V_g{}^{B^*}(t)$ are not only related to time t, but also related to cost C_b. Specifically, even in the early stage, that is, when $t < t_{\text{th}}{}^{B}$, the government's fixed subsidy $s_0{}^{B^*}(t)$ and incentive contract $S^{B^*}(t)$ may increase over time, while the government's expected benefit discount value $V_g{}^{B^*}(t)$ may decrease over time, which is different from Proposition 1. The reason is that if the cost C_b of the blockchain is large, the port enterprise will have to bear large costs when participating in the implementation of the blockchain, and its enthusiasm for emission reduction investment may be reduced. The government will have to provide more incentive subsidies to promote port emission reduction, which is often unfavorable to the expected benefit of the government. Therefore, Proposition 2 means that the implementation of blockchain will not affect the optimal dynamic trajectory change rule of port *VERs* $EG^{B^*}(t)$. However, in a period of time before the government's emission reduction incentive strategy reaches a steady state, the size of the blockchain's unit operating cost will directly affect the optimal dynamic trajectory change rules of the government's fixed subsidy ${s_0}^{B^*}(t)$, incentive contract $S^{B^*}(t)$ and the government's expected benefit discount value ${V_g}^{B^*}(t)$.

Proposition 3. *In the case TB, analysis of the government's dynamic incentive strategy for port emission reduction is as follows:*

(i) *When* $t < {t_{th}}^{TB}$, *then* $\frac{\partial EG^{TB}(t)}{\partial t} > 0$,

$$\begin{cases} if\ 0 \le C_b < {C_b}^{th1},\ then\ \frac{\partial {s_0}^{TB}(t)}{\partial t} < 0 \\ if\ C_b \ge {C_b}^{th1},\ \begin{cases} and\ \tau \le \left(C_b - {C_b}^{th1}\right),\ then\ \frac{\partial {s_0}^{TB}(t)}{\partial t} \ge 0 \\ and\ \tau > \left(C_b - {C_b}^{th1}\right),\ then\ \frac{\partial {s_0}^{TB}(t)}{\partial t} < 0 \end{cases} \end{cases},$$

$$\begin{cases} if\ 0 \le C_b < \gamma\xi,\ then\ \frac{\partial S^{TB}(t)}{\partial t} < 0 \\ if\ C_b \ge \gamma\xi, \\ \begin{cases} and\ \tau \le (C_b - \gamma\xi),\ then\ \frac{\partial S^{TB}(t)}{\partial t} \ge 0 \\ and\ \tau > (C_b - \gamma\xi),\ then\ \frac{\partial S^{TB}(t)}{\partial t} < 0 \end{cases} \end{cases},$$

$$\begin{cases} if\ 0 \le C_b < g_1 h + \gamma\xi,\ then\ \frac{\partial {V_g}^{TB}(t)}{\partial t} > 0 \\ if\ C_b \ge g_1 h + \gamma\xi, \\ \begin{cases} and\ \tau \le (C_b - g_1 h - \gamma\xi),\ then\ \frac{\partial {V_g}^{TB}(t)}{\partial t} \le 0 \\ and\ \tau > (C_b - g_1 h - \gamma\xi),\ then\ \frac{\partial {V_g}^{TB}(t)}{\partial t} > 0 \end{cases} \end{cases};$$

(ii) *When* $t \ge {t_{th}}^{TB}$, *then* $\frac{\partial EG^{TB}(t)}{\partial t} = 0, \frac{\partial {s_0}^{TB}(t)}{\partial t} = 0, \frac{\partial S^{TB}(t)}{\partial t} = 0, \frac{\partial {V_g}^{TB}(t)}{\partial t} = 0$; *where* ${t_{th}}^{TB}$ *is the time threshold in (0, +∞).*

Proposition 3 reveals that when considering carbon trading policy under blockchain technology (i.e., *TB* case), the optimal dynamic trajectories of the government incentive strategy not only depend on time t, but also is related to the unit operating cost C_b of the blockchain and the market price τ of carbon trading. Compared with Proposition 2, when the government starts the carbon trading market, in the early stage of the government dynamic incentive, that is, $t < {t_{\text{th}}}^{TB}$, even if the unit operating cost C_b of the blockchain is large, and if the carbon trading market price τ is also large, the fixed subsidy ${s_0}^{TB^*}(t)$ and incentive contract $S^{B^*}(t)$ in the government incentive strategy for port emission reduction will still decrease with time, while the government expected benefit discount value ${V_g}^{TB^*}(t)$ will still increase with time. This means that carbon trading policy can weaken the impact of the unit operating cost brought by the implementation of blockchain on the change rules of the government's dynamic incentive strategy for port emission reduction to a certain extent. The reason is that the government's opening of the carbon trading market helps to improve the motivation of the port enterprise's effort to invest in emission reduction, especially the size of the carbon trading market price directly affects the enthusiasm of the port enterprise's investment in emission reduction. Therefore, even if the unit operation cost of port enterprise participating in the implementation of blockchain is large, under the positive effect of carbon trading, the government may not need to increase the incentive subsidies for port enterprise, the port emission reduction can still be improved, and the expected benefit of the government will also be continuously improved.

5.2. Parameter Analysis

Based on the optimal solutions of the model under different cases in Section 4, this subsection will investigate the impacts of emission-reduction-related parameters (β, h, ξ, γ), emission reduction uncertainty-related parameters (δ^2, θ), contract execution efficiency (g_0, g_1) and execution cost c, and blockchain and carbon trading-related parameters (C_b, r, ω, τ) on the port enterprise's optimal *ERI* level, the government's optimal unit subsidy, and the port *VERs*. The results of the study are summarized in Propositions 4 to 7. According to the analysis in Section 5.1, the port *VERs* under different cases converge to steady state and no longer vary over time. Therefore, this subsection provides a parametric analysis of port *VERs* at steady state, which helps to provide some insights into the long-term dynamics of government incentives for port enterprises to reduce emissions.

Proposition 4. *Under different cases, the impacts of emission-reduction-related parameters (i.e., β, h, ξ, γ) on the optimal decisions of government and port enterprise are analyzed as follows:*

(i) $\frac{\partial I^{i^*}}{\partial \beta} > 0, \frac{\partial s_1{}^{i^*}}{\partial \beta} > 0, \frac{\partial EG^{i^*}}{\partial \beta} > 0;$

(ii) $\frac{\partial I^{i^*}}{\partial h} > 0, \frac{\partial s_1{}^{i^*}}{\partial h} > 0, \frac{\partial EG^{i^*}}{\partial h} > 0;$

(iii) $\frac{\partial I^{i^*}}{\partial \xi} > 0, \frac{\partial s_1{}^{i^*}}{\partial \xi} < 0, \frac{\partial EG^{i^*}}{\partial \xi} > 0;$

(iv) $\frac{\partial I^{i^*}}{\partial \gamma} > 0, \frac{\partial s_1{}^{i^*}}{\partial \gamma} < 0, \frac{\partial EG^{i^*}}{\partial \gamma} > 0;$

where $i = N, B, TB$.

Proposition 4 gives the impacts of the influence factor β of port *ERI* on *CERs*, monetary expression h of social benefits generated by unit *CERs*, service price ξ of port, and the impact γ of port's *CERs* on shipping customer demand on the optimal solutions of the government and port enterprise in different cases. The results show that when the parameter β increases, the optimal solutions in different cases, namely, the optimal *ERI* level I^{i^*} of port enterprise, the optimal unit subsidy $s_1{}^{i^*}$ of government and port *VERs* EG^{i^*} will increase. This is consistent with intuition. The reason is that the increase in parameter β will help port enterprises improve their *ERI* level to significantly promote port emission reduction, and the government will also enhance the unit subsidy incentives for port enterprises. According to Proposition 4 (*ii*), the optimal solutions I^{i^*}, $s_1{}^{i^*}$, and EG^{i^*} in different cases are positively correlated with parameter h. This implies that when port emission reduction becomes more important and has greater social benefits, port enterprises will have greater motivation to improve their *ERI* enthusiasm, the government will also increase unit subsidies to port enterprises, and port emission reduction will also be positively affected. Proposition 4 (*iii*) and (*iv*) show that the optimal solutions I^{i^*} and EG^{i^*} in different cases are both positively related to the parameters ξ and γ, while $s_1{}^{i^*}$ is negatively related to the parameters ξ and γ. This means that when the service price of the port increases or customers become more aware of environmental protection, port enterprises will make more efforts to improve the *ERI* level of the port, and the government will appropriately reduce the unit subsidy incentives for port enterprises in order to balance the income of port enterprises.

Proposition 5. *Under different cases, the impacts of emission reduction uncertainty-related parameters (i.e., δ^2, θ), contract execution efficiency (i.e., g_0, g_1), and execution cost (i.e., c) on the optimal decisions of government and port enterprise are analyzed as follows:*

(i) $\frac{\partial I^{i^*}}{\partial \delta^2} < 0, \frac{\partial s_1{}^{i^*}}{\partial \delta^2} < 0, \frac{\partial EG^{i^*}}{\partial \delta^2} < 0;$

(ii) $\frac{\partial I^{i^*}}{\partial \theta} < 0, \frac{\partial s_1{}^{i^*}}{\partial \theta} < 0, \frac{\partial EG^{i^*}}{\partial \theta} < 0;$

(iii) $\frac{\partial I^{N^*}}{\partial g_0} > 0, \frac{\partial s_1{}^{N^*}}{\partial g_0} > 0, \frac{\partial EG^{N^*}}{\partial g_0} > 0, \frac{\partial I^{j^*}}{\partial g_1} > 0, \frac{\partial s_1{}^{j^*}}{\partial g_1} > 0, \frac{\partial EG^{j^*}}{\partial g_1} > 0;$

(iv) $\frac{\partial I^{N^*}}{\partial c} < 0, \frac{\partial s_1{}^{N^*}}{\partial c} < 0, \frac{\partial EG^{N^*}}{\partial c} < 0;$

where $i = N, B, TB$; $j = B, TB$.

The emission reduction uncertainty-related parameters include the variance δ^2 of market random disturbance factor v and the degree θ of risk aversion of the government and port enterprise to their respective benefits due to the uncertainty of emission reduction. From Proposition 5 (*i*) and (*ii*), it can be seen that the optimal *ERI* level I^{i^*} of port enterprise, the optimal government unit subsidy ${s_1}^{i^*}$, and port *VERs* EG^{i^*} are negatively correlated with parameters δ^2 and θ. This implies that when the uncertainty of port emission reduction increases, such as the difference in customers' preferences for green ports, the competition between traditional facility ports, and emission reduction investment facility ports, the enthusiasm of port enterprises' emission reduction investment will be hit, port *VERs* will also be reduced, and the government's unit subsidy incentive to port enterprises will also be weakened. At the same time, when the degree of risk aversion increases, the cost of risk aversion of the government and port enterprises to their respective benefits increases. At this time, port enterprises are unwilling to make more efforts to reduce costs, and the government is also unwilling to provide more unit subsidies and incentives. Accordingly, the *VERs* of port enterprises will also be reduced. Proposition 5 (*iii*) uncovers that when the contract execution efficiency increases, the optimal solutions in different cases will increase. This means that blockchain smart contracts to improve the efficiency of contract execution will help improve the emission reduction investment ability of port enterprises, promote port emission reduction, and enhance the government's subsidy incentives for port enterprises. Proposition 5 (*iv*) confirms that the increase in contract execution cost c is not conducive to the emission reduction investment of port enterprises, and will reduce the unit subsidy incentive of the government and the *VERs* of ports.

Proposition 6. *Under different cases, the impacts of blockchain-related parameters (i.e., C_b, r, ω) on the optimal decisions of government and port enterprise are analyzed as follows:*

(i) $\frac{\partial I^{j^*}}{\partial C_b} < 0, \frac{\partial {s_1}^{j^*}}{\partial C_b} = 0, \frac{\partial EG^{j^*}}{\partial C_b} < 0;$

(ii) $\frac{\partial I^{j^*}}{\partial r} > 0, \frac{\partial s^{j^*}}{\partial r} > 0, \frac{\partial EG^{j^*}}{\partial r} > 0;$

(iii) $\frac{\partial I^{j^*}}{\partial \omega} > 0, \frac{\partial {s_1}^{j^*}}{\partial \omega} > 0, \frac{\partial EG^{j^*}}{\partial \omega} > 0;$

where j = B, TB.

Proposition 6 shows that the optimal *ERI* level I^{j^*} and *VERs* EG^{j^*} of port enterprise are negatively correlated with the unit operating cost C_b of blockchain, but the optimal unit subsidy ${s_1}^{j^*}$ of government is independent of the parameter C_b. This implies that the increase in the unit operating cost of the blockchain is unfavorable to the emission reduction of port enterprises, but the government's unit subsidy incentive has not been reduced. The reason may be that the government is optimizing its dynamic incentive contract by adjusting the fixed subsidies to port enterprises at this time while keeping the unit subsidies unchanged helps to maintain the enthusiasm of port enterprises' emission reduction investment to a certain extent. From Proposition 6, it is clear that the optimal solutions for both the government and port enterprise are positively related to the parameters r and ω. This means that if blockchain technology enhances customers' green trust in port *ERI*, port enterprises' enthusiasm to participate in the implementation of blockchain and invest in emission reduction will increase. The more port emission reductions are expected to be achieved, the more motivated the government will be to increase subsidies and incentives for port enterprises. At the same time, the higher the disclosure of port emission reduction information by the blockchain, the lower the uncertainty of the market, and the greater the optimal solutions of the government and port enterprises.

Proposition 7. *In the TB case of considering carbon trading under blockchain technology, the impacts of carbon trading market price (i.e., τ) on the optimal decisions of government and port enterprise are analyzed as follows:* $\frac{\partial I^{TB^*}}{\partial \tau} > 0$, $\frac{\partial {s_1}^{TB^*}}{\partial \tau} = 0$, $\frac{\partial EG^{TB^*}}{\partial \tau} > 0$.

Proposition 7 reveals that when considering carbon trading policy under blockchain technology (i.e., *TB* case), the optimal *ERI* level I^{TB^*} of port enterprise and port *VERs* EG^{TB^*} are positively correlated with the parameter τ, while the optimal unit subsidy ${s_1}^{TB^*}$ of the government to port enterprise is independent of the parameter τ. This implies that when the government starts the carbon emissions trading market for port enterprises, the increase in the carbon trading market price will help to stimulate the port enterprises' emission reduction efforts and improve the *VERs* of ports, but the unit subsidy in the government dynamic incentive contract should remain unchanged. The reason may be that the government is optimizing its dynamic incentive contract by adjusting the fixed subsidies to port enterprises. At the same time, port enterprises have benefited from the carbon trading market, and the government does not need to provide additional unit subsidy incentives for their emission reductions.

5.3. Effects of Blockchain Technology and Carbon Trading Policy

This subsection compares and analyzes the optimal *ERI* level of port enterprise, the government's optimal unit subsidy and port *VERs* in different cases, and studies the effects of blockchain implementation and carbon trading policy on the port enterprise's emission reduction investment and the government's dynamic incentive contract.

Proposition 8. *Effects of blockchain technology on the optimal decisions of government and port enterprise are as follows:*

(i) $\begin{cases} if\ C_b = 0, then\ I^{B^*} > I^{N^*} \\ if\ C_b > 0, \begin{cases} and\ C_b \le {C_b}^{th2}, then\ I^{B^*} \ge I^{N^*} \\ and\ {C_b}^{th2} < C_b, then\ I^{B^*} < I^{N^*} \end{cases} \end{cases};$

(ii) $s^{B^*} > s^{N^*}$;

(iii) $\begin{cases} if\ C_b = 0, then\ EG^{B^*} > EG^{N^*} \\ if\ C_b > 0, \begin{cases} and\ C_b \le {C_b}^{th3}, then\ EG^{B^*} \ge EG^{N^*} \\ and\ {C_b}^{th3} < C_b, then\ EG^{B^*} < EG^{N^*} \end{cases} \end{cases};$

where

$${C_b}^{th2} = \frac{1}{\beta + r}\left[\frac{(r+\beta)^3(g_1 h + \gamma\xi)}{(r+\beta)^2 + \delta^2\eta\theta(\rho+\sigma)^2(1-\omega)} - \frac{\beta^3(g_0 h + \gamma\xi + c\gamma\xi)}{(1+c)(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2)}\right] > 0,$$

$${C_b}^{th3} = \frac{1}{\beta + r}\left[\frac{(r+\beta)^4(g_1 h + \gamma\xi)}{(r+\beta)^2 + \delta^2\eta\theta(\rho+\sigma)^2(1-\omega)} - \frac{\beta^4(g_0 h + \gamma\xi + c\gamma\xi)}{(1+c)(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2)}\right] > 0.$$

According to Proposition 8, the government's optimal unit subsidy under blockchain technology is higher than that of the traditional mode without blockchain (i.e., $s^{B^*} > s^{N^*}$). This implies that after the implementation of blockchain, the government needs to improve the unit subsidy incentives for port enterprises to increase the marginal income of port enterprises, and indirectly share a certain unit operating cost of blockchain for port enterprises, so as to encourage port enterprises to participate in the implementation of blockchain. Proposition 8 also shows that when the government's dynamic incentive contract for the port enterprise is changed from the traditional mode to the blockchain technology mode, if the unit operating cost of the blockchain is ignored, that is, $C_b = 0$, the optimal *ERI* level of port enterprise and port *VERs* will increase. At this time, the implementation of blockchain is completely beneficial to the government's incentive for the port enterprise's emission reduction. However, if the unit operation cost of blockchain is considered, that is, $C_b > 0$, the implementation of blockchain is not necessarily beneficial to the port emission reduction investment. When C_b is large, the marginal income of port enterprises participating in the implementation of blockchain will be reduced, its *ERI* level will be reduced, and the expected port emission reduction will also be reduced. At this time, the implementation of blockchain is unfavorable.

Proposition 9. *Effects of carbon trading policy on the optimal decisions of government and port enterprise are as follows:* $I^{TB^*} > I^{B^*}$; $s^{TB^*} = s^{B^*}$; $EG^{TB^*} > EG^{B^*}$.

Proposition 9 shows that when the government starts the carbon emission trading market for the port enterprise under blockchain technology, the optimal *ERI* level of the port enterprise and port *VERs* will increase, while the optimal unit subsidy of the government will remain unchanged. This means that carbon trading policy helps to stimulate port enterprises' investment in emission reduction and promote port emission reduction to a certain extent, but the government does not need to change the existing unit subsidy incentives.

5.4. Values of Blockchain Technology and Carbon Trading Policy

The government's expected benefit in this paper mainly includes the social benefit (benefit term) and contractual and related cost expenditures (expenditure term) resulting from the port emission reductions. Among them, "benefit term" reflects that the government plans to achieve the "double carbon" goal by encouraging port enterprises to actively invest in emission reduction technologies and facilities to improve port emissions reduction and reduce carbon emissions, but at the same time, there should be relevant costs. Here, this subsection compares and analyzes the discount value of the expected benefit of the government in the steady state under different cases, and studies the values of blockchain technology and carbon trading policy on the expected benefit of the government, so as to determine the influencing factors and specific conditions for the government to implement blockchain and start the carbon trading market in the process of encouraging port enterprises to reduce emissions.

Proposition 10. *Value of blockchain technology on the expected benefit of the government is analyzed as follows:*

(i) *When ignoring the fixed cost of establishing the blockchain (as a sunk cost), i.e.,* $F_b = 0$, *we have*

$$\begin{cases} if\ \Phi \le \frac{(Y(\cdot)-X(\cdot))g_0 g_1 \rho}{(g_1(1+c)-g_0)},\ then\ V_g B^* \le V_g N^* \\ if\ \Phi > \frac{(Y(\cdot)-X(\cdot))g_0 g_1 \rho}{(g_1(1+c)-g_0)},\ then\ V_g B^* > V_g N^* \end{cases};$$

(ii) *when considering the fixed cost of establishing the blockchain, that is,* $F_b > 0$, *we have*

$$\begin{cases} if\ \Phi \le \frac{(Y(\cdot)-X(\cdot))g_0 g_1 \rho}{(g_1(1+c)-g_0)},\ then\ V_g B^* < V_g N^* \\ if\ \Phi > \frac{(Y(\cdot)-X(\cdot))g_0 g_1 \rho}{(g_1(1+c)-g_0)},\ \begin{cases} and\ F_b \le \frac{(g_1(1+c)-g_0)\Phi}{g_0 g_1 \rho} - (Y(\cdot)-X(\cdot)),\ then\ V_g B^* \ge V_g N^* \\ and\ F_b > \frac{(g_1(1+c)-g_0)\Phi}{g_0 g_1 \rho} - (Y(\cdot)-X(\cdot)),\ then\ V_g B^* < V_g N^* \end{cases} \end{cases};$$

where

$$X(\cdot) = \frac{1}{2g_1}\left[\begin{array}{c} \frac{1}{\rho}\left(\frac{(r+\beta)^2(g_1 h+\gamma\xi-C_b)^2}{\eta(\rho+\sigma)^2}\right) + \frac{2(r+\beta)^2}{\eta(\rho+\sigma)^2} \\ \left(\frac{(r+\beta)^2(g_1 h+\gamma\xi)^2}{(r+\beta)^2+\delta^2\eta\theta(\rho+\sigma)^2(1-\omega)} + {C_b}^2\right) \end{array}\right] + \frac{\theta\delta^2}{2\rho g_0}\left(\begin{array}{c} \frac{\beta^2(g_0 h+\gamma\xi+c\gamma\xi)^2}{(1+c)\left(\beta^2+\delta^2\eta\theta(\rho+\sigma)^2\right)} \\ +g_0 h^2 \end{array}\right),$$

$$Y(\cdot) = \frac{1}{2g_1}\left[\begin{array}{l} \frac{2(r+\beta)^2 C_b(g_1h+\gamma\xi)}{\eta(\rho+\sigma)^2}\left(1+\frac{(r+\beta)^2}{(r+\beta)^2+\delta^2\eta\theta(\rho+\sigma)^2(1-\omega)}\right) \\ +\frac{1}{\rho}\left(\frac{(r+\beta)^2\delta^2\theta(g_1h+\gamma\xi)^2(1-\omega)}{(r+\beta)^2-\delta^2\eta\theta(\rho+\sigma)^2(-1+\omega)}+g_1h^2\delta^2\theta(1-\omega)\right)\end{array}\right]+\frac{1}{2g_0}\left(\frac{\beta^2(g_0h+\gamma\xi+c\gamma\xi)^2}{\rho(1+c)\eta(\rho+\sigma)^2}+.\right.$$
$$\left.\frac{2\beta^4(g_0h+\gamma\xi+c\gamma\xi)^2}{(1+c)\eta\sigma(\rho+\sigma)^2\left(\beta^2+\delta^2\eta\theta(\rho+\sigma)^2\right)}\right)$$

Proposition 10 analyzes the value of blockchain technology by comparing the discounted value of the government's expected benefit before and after blockchain adoption. According to the research of Choi et al. [10,59] and Shen et al. [12], we first consider the scenario where the fixed cost of establishing the blockchain is ignored. From Proposition10 (*i*) and in conjunction with Figure 2a, we find that if and only if the opportunity cost R_0 of the port enterprise *ERI* is greater than a certain critical point (corresponding to Region II in Figure 2a), the government's expected benefit under blockchain technology is higher than that without blockchain; Otherwise, the result is the opposite. This implies that if the fixed cost of blockchain is taken as a sunk cost and not considered in the relevant decisions of the government, the opportunity cost of port enterprises to invest in emission reduction and actively build green ports determines whether the establishment of blockchain in the government's dynamic incentive contract is beneficial. This finding is interesting and non-intuitive, and the reason can be explained as follows: according to the optimal solution of the model, it is known that there exists $\partial V_g{}^N/\partial\Phi = -(1+c)/g_0 \cdot \rho < 0$ in the absence of blockchain, while there exists $\partial V_g{}^B/\partial\Phi = -1/g_1 \cdot \rho < 0$ under blockchain technology, and the system satisfies $|\partial V_g{}^N/\partial\Phi| > |\partial V_g{}^B/\partial\Phi|$. Thus, although the parameter Φ is detrimental to the government's expected benefit when the government dynamically incentivizes the port enterprise to reduce emissions, interestingly, blockchain can reduce this detrimental effect. Thus, the implementation of blockchain technology is beneficial when Φ is greater than a certain threshold.

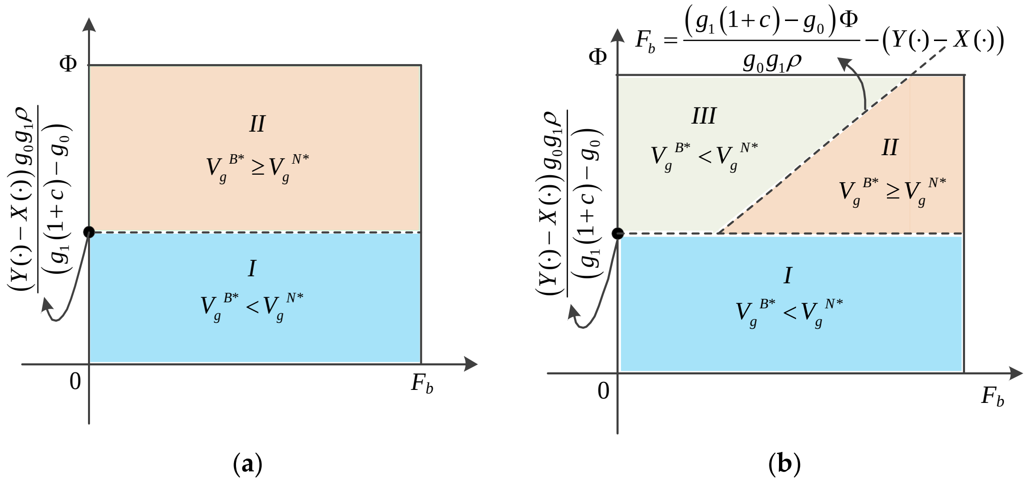


Figure 2. Comparison of expected benefit of the government before and after the adoption of blockchain: (**a**) $F_b = 0$; (**b**) $F_b > 0$.

Different from Proposition 10, when considering the fixed cost of establishing the blockchain, it can be seen from Proposition 10 and Figure 2b, if and only if the parameter Φ is greater than a critical point and the cost F_b is less than a critical point, corresponding to Region II in Figure 2b, the expected benefit of the government under blockchain technology is higher than that without blockchain; Otherwise, the result is opposite. This means that if the fixed cost of blockchain is taken into account in the government dynamic incentive contract, the conditions for the government to implement blockchain to improve the expected benefit are related not only to the opportunity cost of the *ERI* of port enterprises, but also to the fixed cost of blockchain.

Proposition 11. *Value of carbon trading policy on the expected benefit of the government under blockchain technology is analyzed as follows:*

(i) When the unit operation cost of implementing blockchain is ignored, that is, $C_b = 0$, we have

$$\begin{cases} if\ \psi \leq g_1\rho Z(\cdot), then\ V_gTB^* \geq V_gB^* \\ if\ \psi > g_1\rho Z(\cdot), then\ V_gTB^* < V_gB^* \end{cases};$$

(ii) When considering the unit operation cost of implementing the blockchain, that is, $C_b > 0$, we have

$$\begin{cases} if\ \psi \leq g_1\rho Z(\cdot), \begin{cases} and\ C_b \leq \frac{(g_1\rho Z(\cdot)-\psi)g_1\eta\rho\sigma(\rho+\sigma)^2}{g_1\rho(2\rho+\sigma)(r+\beta)^2}, then\ V_gTB^* \geq V_gB^* \\ and\ C_b > \frac{(g_1\rho Z(\cdot)-\psi)g_1\eta\rho\sigma(\rho+\sigma)^2}{g_1\rho(2\rho+\sigma)(r+\beta)^2}, then\ V_gTB^* < V_gB^* \end{cases} \\ if \psi > g_1\rho Z(\cdot), then\ V_gTB^* < V_gB^* \end{cases};$$

where

$$Z(\cdot) = \frac{(r+\beta)^2}{g_1\eta\sigma(\rho+\sigma)^2}(g_1h+\gamma\xi+2\tau+\frac{\sigma(g_1h+\gamma\xi+\tau)}{\rho}+\frac{(r+\beta)^2(g_1h+\gamma\xi)}{(r+\beta)^2-\delta^2\eta\theta(\rho+\sigma)^2(-1+\omega)}).$$

Proposition 11 analyzes the value of carbon trading policy by comparing the discount value of the expected benefit of the government before and after the start of carbon trading policy under blockchain technology. The results show that when the unit operation cost of implementing the blockchain is ignored, that is, $C_b = 0$, if the critical value ψ of carbon emission reduction of the port enterprise is small, corresponding to Region I in Figure 3a, the expected benefit of the government under the carbon trading policy is higher than that without carbon trading. If ψ is large, it corresponds to Region II in Figure 3a, and the result is opposite. This implies that after the launch of the carbon trading market, the government can appropriately increase the carbon quota of port enterprises, reduce the critical value of carbon emission reduction of port enterprises so that port enterprises have more opportunities to sell excess carbon quota in the carbon trading market, and drive port enterprises to actively invest in emission reduction, so as to improve social benefits and realize the positive value of carbon trading policy. According to Proposition 11, when considering the unit operation cost of implementing the blockchain, that is, $C_b > 0$, as shown in Figure 3b, if and only if the parameter ψ is small and C_b is also small, corresponding to Region I in Figure 3b, the expected benefit of the government under the carbon trading policy is higher than that of the carbon-free trading; Otherwise, the result is opposite. This finding is non-intuitive. When the carbon trading market is launched under blockchain technology, the unit operating cost C_b of the blockchain will affect the value of carbon trading policy. The reason is that the parameter C_b directly affects the *ERI* level of port enterprises. If the parameter C_b is large, it is difficult for port enterprises to make more efforts to improve the carbon emission reduction generated by emission reduction investment, and port enterprises will have little opportunity to sell carbon credits from carbon trading. At this time, the government's carbon trading policy will not be conducive to encouraging port enterprises to reduce emissions.

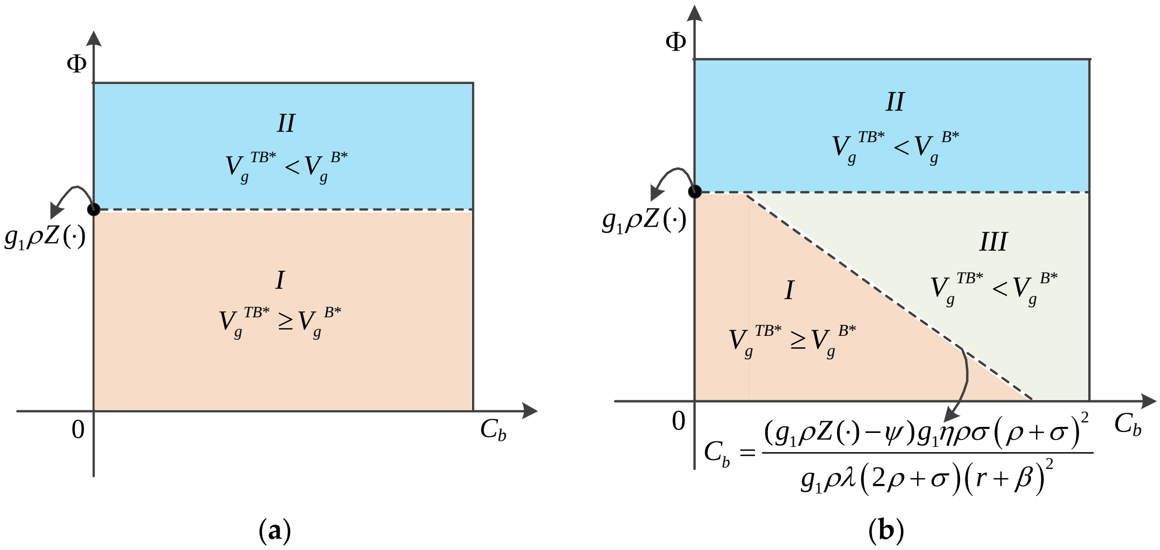


Figure 3. Comparison of government expected benefit before and after the start of carbon trading policy under blockchain technology: (**a**) $C_b = 0$; (**b**) $C_b > 0$.

6. Numerical Analysis

The equilibrium results in different cases have been analyzed in detail above, but it is difficult to obtain an intuitive conclusion because the optimal expressions of variables such as the fixed subsidy for port enterprise and the government expected discounted benefit in the government's dynamic incentive contract are complex. Therefore, this section will conduct numerical research through MATLAB R2023a software to further compare and analyze the dynamic trajectory changes of the government's incentive strategy under different cases, and reveal the impact of key parameters in the model on the government's incentive strategy, so as to provide some new insights for the government's dynamic incentive to port enterprise's emission reduction. Referring to the existing research on incentive contract [60], differential game [54] and blockchain technology [12,61], and combining with the specific background of this paper, the basic parameters are assigned as $\delta^2 = 1$; $\eta = 0.15$; $\theta = 0.2$; $\sigma = 0.3$; $\rho = 0.1$; $\beta = 0.4$; $g_0 = 0.6$; $h = 1.501$; $\gamma = 1.2$; $\xi = 1$; $\Phi = 23.1$; $g_1 = 0.8$; $c = 0.02$; $C_b = 0.72$; $F_b = 1.9$; $r = 0.1$; $\omega = 0.2$; $\psi = 5.1$; $\tau = 0.004$.

6.1. The Optimal Dynamic Trajectories of Government Incentive Strategy

The simulation results in Figures 4–6 show the optimal dynamic trajectories of port emission reductions, government fixed subsidy and dynamic incentive contracts, and government expected benefit discount over time in the *N* case of the traditional mode without blockchain, the *B* case with blockchain technology, and the *TB* case considering carbon trading policy with blockchain technology, respectively. It can be observed from Figures 4–6 that the port's emission reductions $EG^*(t)$ under different cases increases with time and then tends to be stable, while the government's fixed subsidy $s_0{}^*(t)$ and dynamic incentive contract $S^*(t)$ both decrease with time and then tend to be stable. At the same time, in a period of time after the implementation of the government dynamic incentive contract, the discount value of the government expected benefit $V_g{}^*(t)$ under different cases increases with time and then tends to be stable. This is consistent with the relevant conclusions of Propositions 1–3 in the previous sections.

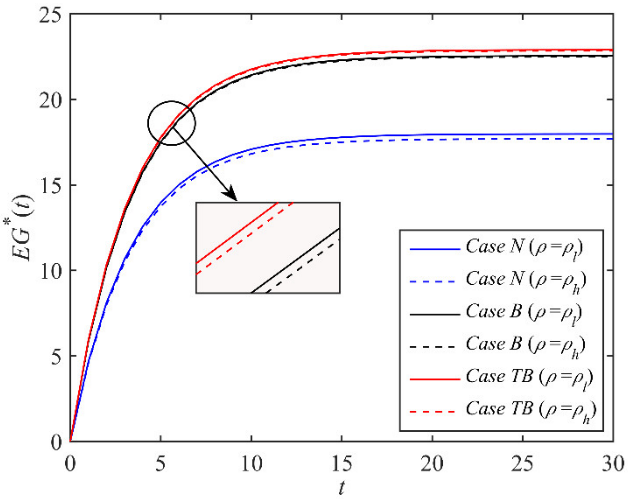
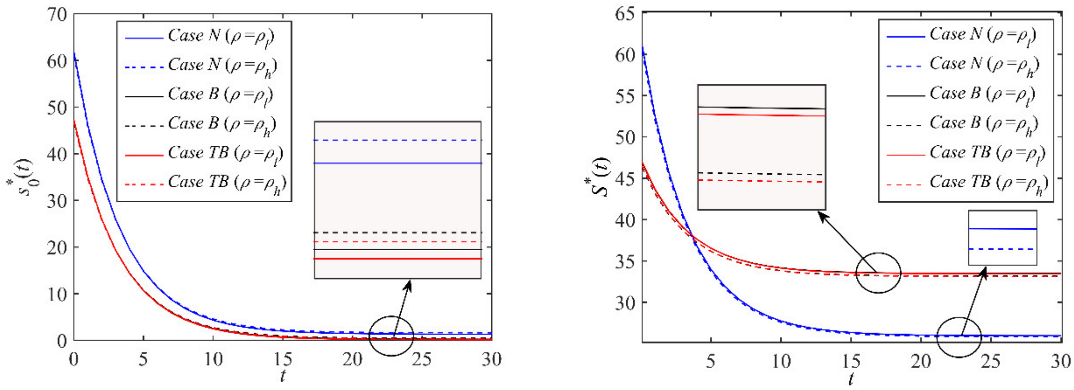


Figure 4. Optimal dynamic trajectories of port emission reduction over time under different cases.



(**a**) (**b**)

Figure 5. Time variation trajectories of government's optimal dynamic incentive contract under different cases: (**a**) s_0^{N*}, s_0^{B*} and s_0^{TB*}; (**b**) S^{N*}, S^{B*} and S^{TB*}.

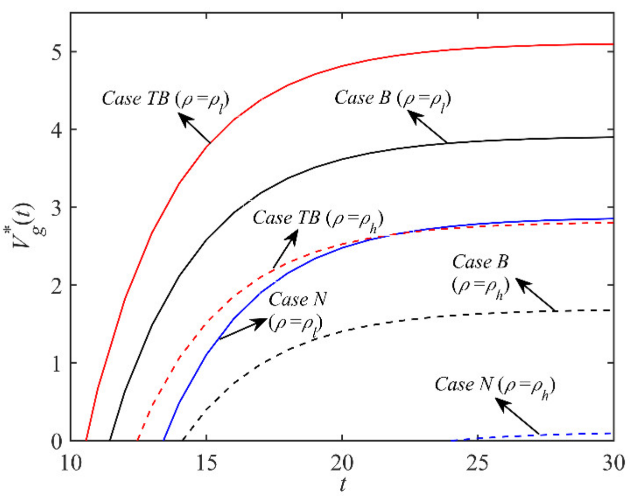


Figure 6. Optimal dynamic trajectories of the discount value of government expected benefit over time under different cases.

It can also be seen from Figures 4–6 that as time goes on, the port's emission reductions, government dynamic incentive contract, and government expected benefit discount value under blockchain technology will be higher than that under the traditional mode without blockchain, while the government's carbon trading under blockchain technology will further improve the port's emission reductions, government dynamic incentive contract, and government expected benefit discount value in the same period. This implies that the reasonable implementation of blockchain technology and carbon trading policy is beneficial to the government's rapid improvement of port emission reduction, and is also beneficial to the expected benefit generated by the government's dynamic incentives for emission reduction. In addition, it can be seen from Figure 5a that in the same period, the government's fixed subsidy is the largest without blockchain traditional mode, the next is blockchain technology mode, and the smallest is carbon trading mode under blockchain technology, which is just the opposite of the relationship between the government's dynamic incentive contract in Figure 5b under different cases. This means that although the reasonable implementation of blockchain technology and carbon trading policy will urge the government to reduce the fixed subsidies for port enterprises, in fact, the dynamic incentive contract of the government for port enterprises is increased. The reason is that blockchain and carbon trading have promoted the emission reduction of port enterprises, and the government will provide port enterprises with more unit subsidy incentives based on the amount of port emission reduction.

6.2. Impacts of Key Parameters on the Government Dynamic Incentive Strategy

In order to further study the effects of key parameters on the government's dynamic incentive strategy, especially the impact on the dynamic incentive contract and the expected benefit of the government under different cases, sensitivity analyses are conducted in this subsection for the relevant parameters of emission reductions (β, h, ξ, γ), market uncertainty parameters (δ^2, θ), contract execution efficiency (g_0, g_1) and execution cost c, and blockchain and carbon trading-related parameters (C_b, r, ω, τ).

Table 2 shows that port *VERs* and the discounted value of government expected benefit in different scenarios increase when the influence factor β of port *ERI* on *CERs* increases, while the government fixed subsidy all decrease. This means that the parameter β is beneficial to promote port emission reduction and also helps to improve government efficiency. However, the effect of the parameter β on the dynamic incentive contract of the government under different cases is different. Specifically, the government dynamic incentive contract without blockchain traditional mode is negatively related to the parameter β, while the government dynamic incentive contract under blockchain technology and when carbon trading policy is considered under blockchain technology are both positively related to the parameter β. This suggests that blockchain and carbon trading policy affect the sensitivity of the government's dynamic incentive contract to parameter β to some extent. The reason is that the government's dynamic incentive contract is composed of fixed subsidy and unit subsidy, and blockchain and carbon trading policy increase the *VERs* of the port, and port enterprise will receive more unit subsidies. From Table 2, we also find that with the increase in h, the monetary expression of social benefit generated by unit *CERs* is also beneficial to promoting port emission reduction and the expected benefit of the government.

Table 2. Effects of parameters β and h on the government's dynamic incentive strategy ($t \to +\infty$).

Parameters	β / h	**0.39925** / **1.495**	**0.3995** / **1.495**	**0.39975** / **1.495**	**0.4** / **1.495**	**0.4** / **1.4975**	**0.4** / **1.5**	**0.4** / **1.5025**
Case N	EG^{N*}	17.876	17.899	17.922	17.945	17.958	17.971	17.983
	${s_0}^{N*}$	1.590	1.541	1.491	1.441	1.389	1.336	1.284
	S^{N*}	25.980	25.964	25.948	25.932	25.939	25.947	25.955
	${V_g}^{N*}$	0.015	0.525	1.034	1.544	2.097	2.651	3.206
Case B	EG^{B*}	22.705	22.728	22.751	22.774	22.802	22.829	22.856
	${s_0}^{B*}$	0.487	0.457	0.426	0.396	0.327	0.258	0.189
	S^{B*}	33.399	33.403	33.407	33.412	33.438	33.465	33.492
	${V_g}^{B*}$	1.312	1.617	1.921	2.226	2.929	3.633	4.338

Table 2. *Cont.*

Parameters	β h	0.39925 1.495	0.3995 1.495	0.39975 1.495	0.4 1.495	0.4 1.4975	0.4 1.5	0.4 1.5025
Case *TB*	EG^{TB*}	22.760	22.783	22.807	22.830	22.857	22.885	22.912
	${s_0}^{TB*}$	0.370	0.340	0.309	0.279	0.210	0.140	0.071
	S^{TB*}	33.362	33.367	33.371	33.375	33.402	33.429	33.456
	${V_g}^{TB*}$	2.503	2.809	3.115	3.421	4.126	4.832	5.538

Table 3 reveals that when the port service price ξ or the impact γ of the port's *CERs* on shipping customer demand increases, the port *VERs* (i.e., data in Rows 3, 7, and 11 of Table 3) and the government expected benefit discount value (i.e., data in Rows 6, 10 and 14 of Table 3) under different cases increase, while the government fixed subsidy (i.e., data in Rows 4, 8, and 12 of Table 3) and government dynamic incentive contract (i.e., data in Rows 5, 9, and 13 of Table 3) decrease. This implies that with the popularization of people's awareness of port green environmental protection, the impact of port emission reduction on the demand of the shipping market will increase. It is beneficial to further improve the enthusiasm for port emission reduction by increasing the price of port services. Port enterprises can obtain more profits from the shipping market. The government can reduce the Incentive subsidies for port enterprises and increase the expected benefit of the government. The results in Table 4 are intuitive. When the variance δ^2 of market random disturbance factor v and the degree θ of risk aversion of the government and port enterprise to their respective revenues increase, the port *VERs* (i.e., data in Rows 3, 7, and 11 of Table 4) and the discount value of government expected benefit (i.e., data in Rows 6, 10 and 14 of Table 4) in different cases decrease, while the government fixed subsidy (i.e., data in Rows 4, 8 and 12 of Table 4) and government dynamic incentive contract (i.e., data in Rows 5, 9 and 13 of Table 4) increase. This implies that market uncertainty is unfavorable for port emission reduction and the expected benefit of the government. At the same time, in order to reduce the impact of market uncertainty on port enterprises, the government will increase the dynamic incentive contract for port enterprises, so as to enhance the anti-risk ability of port enterprises and promote port emission reduction.

Table 3. Effects of parameters ξ and γ on the government's dynamic incentive strategy ($t \to +\infty$).

Parameters	ξ γ	0.9975 1.1970	0.998 1.1970	0.9985 1.1970	0.9990 1.1970	0.9990 1.1975	0.9990 1.198	0.9990 1.1985
Case *N*	EG^{N*}	17.924	17.929	17.934	17.940	17.944	17.948	17.952
	${s_0}^{N*}$	1.529	1.507	1.486	1.465	1.447	1.429	1.411
	S^{N*}	26.098	26.083	26.068	26.054	26.041	26.029	26.017
	${V_g}^{N*}$	0.587	0.815	1.043	1.271	1.462	1.652	1.843
Case *B*	EG^{B*}	22.758	22.766	22.774	22.783	22.789	22.796	22.803
	${s_0}^{B*}$	0.437	0.416	0.396	0.375	0.358	0.341	0.323
	S^{B*}	33.566	33.557	33.548	33.539	33.532	33.524	33.517
	${V_g}^{B*}$	1.784	1.997	2.209	2.422	2.599	2.777	2.955
Case *TB*	EG^{TB*}	22.814	22.822	22.830	22.838	22.845	22.852	22.859
	${s_0}^{TB*}$	0.320	0.299	0.279	0.258	0.241	0.223	0.206
	S^{TB*}	33.530	33.521	33.512	33.503	33.495	33.488	33.480
	${V_g}^{TB*}$	2.979	3.192	3.405	3.618	3.796	3.974	4.152

Table 4. Effects of parameters δ^2 and θ on the government's dynamic incentive strategy ($t \to +\infty$).

Parameters	δ^2 θ	**1.025²** **0.19**	**1.05²** **0.19**	**1.075²** **0.19**	**1.1²** **0.19**	**1.1²** **0.1925**	**1.1²** **0.195**	**1.1²** **0.1975**
Case *N*	EG^{N*}	17.977	17.951	17.925	17.898	17.890	17.882	17.874
	$s_0{}^{N*}$	1.310	1.450	1.592	1.738	1.780	1.823	1.865
	S^{N*}	25.949	25.967	25.986	26.004	26.010	26.015	26.021
	$V_g{}^{N*}$	2.899	2.218	1.522	0.811	0.604	0.396	0.189
Case *B*	EG^{B*}	22.841	22.817	22.791	22.766	22.758	22.751	22.743
	$s_0{}^{B*}$	0.226	0.323	0.421	0.521	0.550	0.580	0.609
	S^{B*}	33.4757	33.4860	33.4966	33.507	33.510	33.514	33.517
	$V_g{}^{B*}$	3.937	3.356	2.761	2.153	1.975	1.798	1.620
Case *TB*	EGT^{B*}	22.897	22.872	22.847	22.821	22.814	22.807	22.799
	s_0T^{B*}	0.109	0.205	0.304	0.404	0.433	0.463	0.492
	S^{TB*}	33.4391	33.4495	33.4601	33.471	33.474	33.477	33.480
	V_gT^{B*}	5.137	4.555	3.960	3.352	3.174	2.996	2.818

Figures 7 and 8 visualize the impacts of contract execution efficiency g_0 and unit execution cost c on government incentive strategy for the case N of no blockchain. As can be seen from Figure 7, the port *VERs* and the discount value of the government's expected benefit are both positively correlated with the parameter g_0, while the government's fixed subsidy and dynamic incentive contract are both negatively correlated with the parameter g_0. This indicates that the government should actively improve the contract execution efficiency of port enterprises, which will not only reduce the government's contract expenditure, but also promote the emission reduction power of port enterprises and improve the government's expected benefit. However, according to the observation in Figure 8, we find that the port's *VERs* and the discount value of government expected benefit are negatively correlated with parameter c, while government fixed subsidy is positively correlated with parameter c, and parameter c has a weak impact on government dynamic incentive contract. This is consistent with intuition. When the government's information cost and supervision cost to implement the contract increase, the government will increase the fixed subsidy to port enterprise and maintain the dynamic incentive contract unchanged. However, according to Proposition 5, the government's unit subsidy and the investment level of port enterprise's emission reduction will both decrease, which is unfavorable for port emission reduction and government benefit.

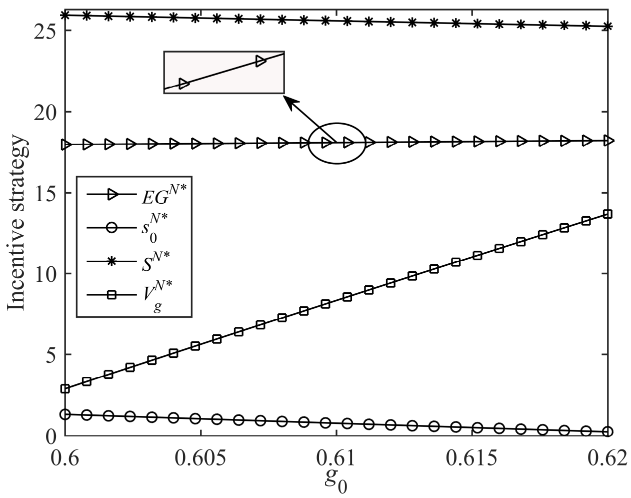


Figure 7. Effect of contract execution efficiency g_0 on the government's dynamic incentive strategy in Case N.

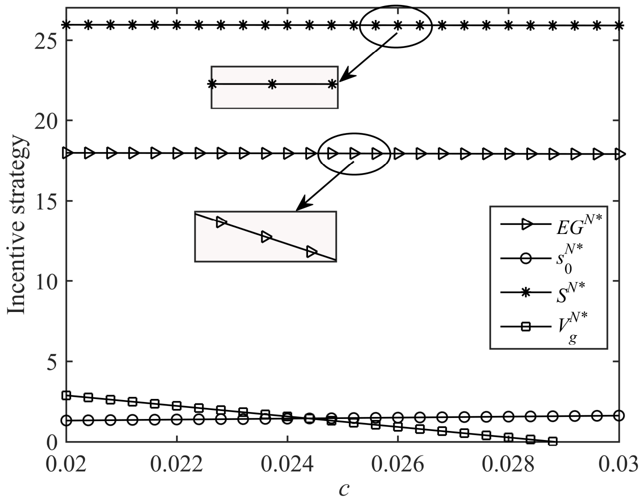


Figure 8. Effect of the unit execution cost c of the contract on the government's dynamic incentive strategy in Case N.

Figure 9 provides the following insights for government managers. In the case of blockchain technology B and the case TB of carbon trading policy under blockchain technology, when the green trust coefficient r of shipping customers increases, the port *VERs* in Figure 9a, and the dynamic incentive contract in Figure 9c, as well as the expected benefit discounted value of the government in Figure 9d all increase in both cases, while the government's fixed subsidy in Figure 9b decreases. This reveals that providing port emission reduction green certification for shipping customers through blockchain technology helps to stimulate port enterprises' emission reduction and improve government efficiency. However, the increase in the unit operating cost C_b of the blockchain is generally unfavorable to the emission reduction of port enterprise and the government.

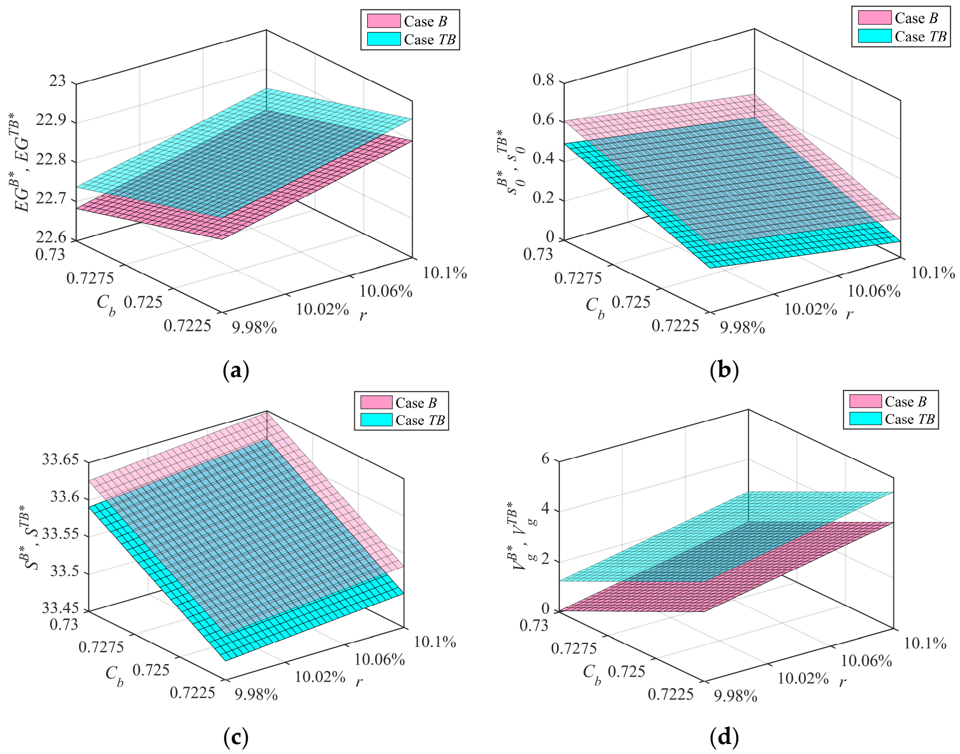


Figure 9. Effects of the parameters r and C_b on the government's dynamic incentive strategy in the B and TB cases: (**a**) EG^{B*} and EG^{TB*}; (**b**) ${s_0}^{B*}$ and ${s_0}^{TB*}$; (**c**) S^{B*} and S^{TB*}; (**d**) V^{B*} and ${V_g}^{TB*}$.

Figure 10a–d depict the effect of the contract execution efficiency g_1 on the government's dynamic incentive strategy in Case *B* of blockchain technology and in the case *TB* of considering carbon trading policy under blockchain technology. The result is similar to the effect of parameter g_0 in Figure 7, and will not be repeated here. In addition, it can be seen from Figure 10 that the effect of blockchain on the degree ω of disclosure of port emission reduction information on the government incentive strategy is similar to the effect of parameter r. The reason is that the information disclosure effect of blockchain reduces the uncertainty of the market, reduces the risk avoidance cost of the government and port enterprises, promotes the emission reduction of port enterprises, and improves the expected benefit of the government.

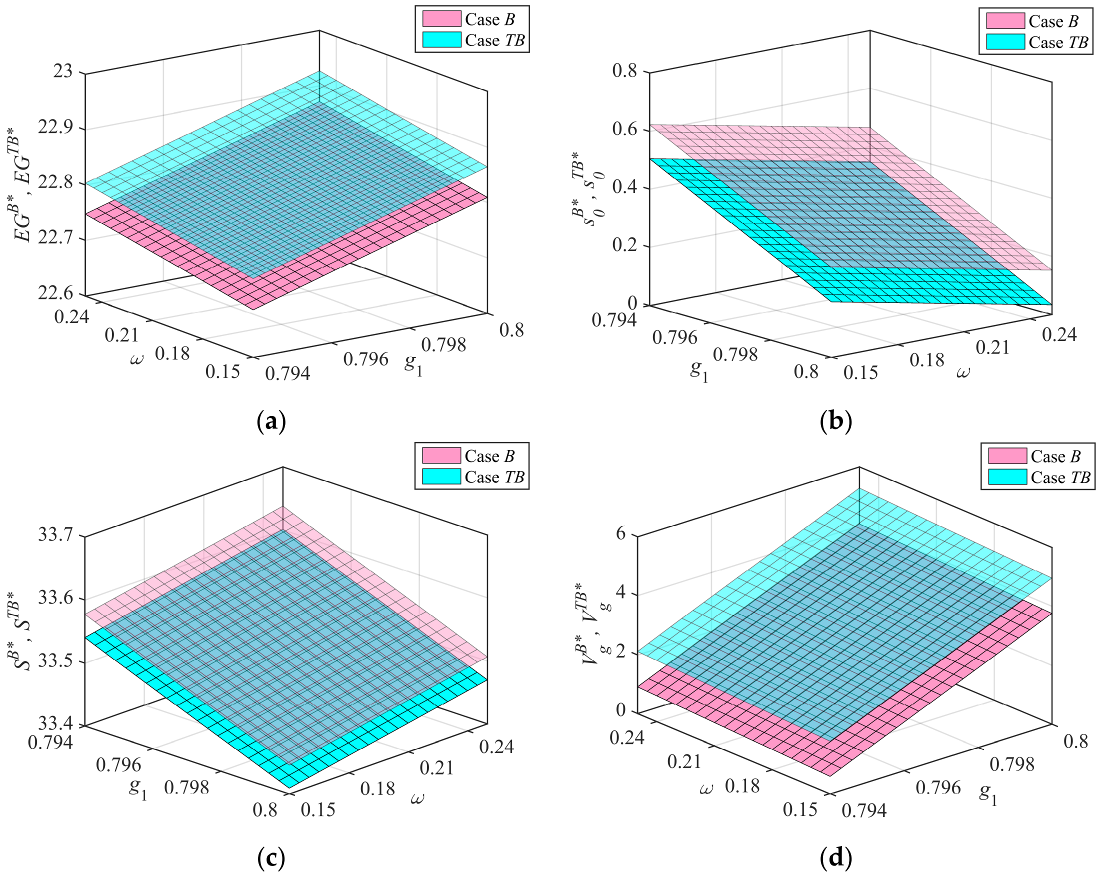


Figure 10. Effects of the parameters g_1 and ω on the government's dynamic incentive strategy in the *B* and *TB* cases: (**a**) EG^{B^*} and EG^{TB^*}; (**b**) ${s_0}^{B^*}$ and ${s_0}^{TB^*}$; (**c**) S^{B^*} and S^{TB^*}; (**d**) V^{B^*} and ${V_g}^{TB^*}$.

Figure 11 uncovers the effect of the carbon trading market price τ on the government's dynamic incentive strategy for port emission reduction under blockchain technology. We find that as the parameter τ increases, both EG^{TB^*} in Figure 11a and ${V_g}^{TB^*}$ in Figure 11d increase, while both ${s_0}^{TB^*}$ in Figure 11b and S^{TB^*} in Figure 11c decrease, but the relative decrease in STB* is not significant. This finding confirms that an increase in the price τ is usually beneficial to the reduction of emissions by port enterprises and the desired benefits to the government, and therefore, it is beneficial for the government to further exploit the value of carbon trading policy by regulating and appropriately increasing the price τ.

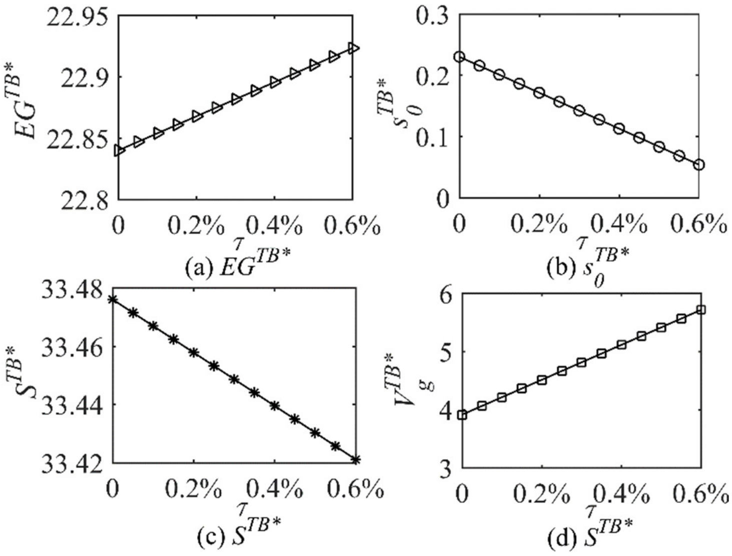


Figure 11. Effect of the carbon trading market price τ on the government's dynamic incentive strategy in Case *B*.

7. Conclusions

This paper studies the dynamic incentive of the government for green investment and the emission reduction of port enterprises, and considers the application value of blockchain technology in port emission reduction, including blockchain smart contracts, green certification, and market information disclosure. We also consider the government's carbon emission trading policy and construct a government dynamic incentive contract model based on the state change of port *VERs* for three cases of port enterprise without blockchain traditional mode (*N*), with blockchain technology (*B*), and with blockchain technology considering carbon trading policy (*TB*), respectively. Firstly, the principal–agent theory and optimal control theory are applied to obtain the optimal *ERI* level of emission reduction of port enterprises, the optimal incentive contract of the government, and the optimal dynamic trajectories of port *VERs* and the discounted value of the expected benefit of the government in different cases. Then, based on the equilibrium solutions in different cases, the model is systematically analyzed and compared, and the effects and values of blockchain and carbon trading policy on the equilibrium solutions are revealed. Finally, numerical simulation is used to further compare and analyze the sensitivity of government incentive strategy.

7.1. Key Findings

This paper obtains the following main research conclusions.

(1) This paper determines the optimal dynamic trajectory change rules of the government's incentive strategy for port emission reduction under different cases (see Propositions 1–3). We find that under the government dynamic incentive contract, the optimal dynamic trajectory of port *VERs* in different cases will first monotonously increase and then tend to steady state with the passage of time. However, the optimal dynamic trajectories of the government's fixed subsidy for port enterprises, the incentive contract, and the discount value of the government's expected benefit are different in different cases. Especially after the implementation of the blockchain, the government's dynamic incentive strategy for port emission reduction is related to the unit operating cost of the blockchain. After the carbon trading policy is launched, the government's dynamic incentive strategy is not only related to the unit operating cost of the blockchain, but also related to the price of the carbon trading market.

(2) This paper reveals the impacts of relevant parameters on the equilibrium solutions of the government and port enterprise in different cases (see Propositions 4–7). We

find that the equilibrium solutions in different cases are positively correlated with the influencing factor of the investment level of port emission reduction on its emission reductions, the monetary expression of the social benefit generated by unit emission reduction, and the contract execution efficiency, while they are negatively correlated with the variance of market random disturbance factor, the degree of risk aversion and the contract execution cost. In addition, when the port service price increases, the optimal *ERI* level and *VERs* of port enterprises in different cases will increase, while the optimal unit subsidy in the government dynamic incentive contract will decrease. Under blockchain technology, the equilibrium solutions of the government and port enterprise are positively correlated with the green trust coefficient of shipping customers to port *ERI* level and the disclosure degree of blockchain to market information. Moreover, the optimal *ERI* level and *VERs* of port enterprises are negatively correlated with the unit operating cost of blockchain, while the government's optimal unit subsidy has nothing to do with the unit operating cost of blockchain. When considering carbon trading policy, the increase in carbon trading market price will positively affect the optimal *ERI* level and *VERs* of port enterprises, but will not affect the optimal unit subsidy of the government.

(3) This paper compares and analyzes the equilibrium solutions in different cases, and gives the effects of blockchain and carbon trading policy on the optimal decisions of the government and port enterprises (see Propositions 8–9). We find that compared with the traditional mode without blockchain, the government's optimal unit subsidy under blockchain technology will increase. Moreover, if the unit operation cost of blockchain is ignored, the optimal *ERI* level and *VERs* of port enterprises will also increase. However, if the unit operation cost of blockchain is considered, the optimal *ERI* level and *VERs* of port enterprises will not necessarily increase. In addition, compared with Case *B* of blockchain technology, the optimal *ERI* level and *VERs* of port enterprises will increase under the *TB* case of considering carbon trading under blockchain technology, while the optimal unit subsidy of the government will remain unchanged.

(4) This paper determines the influencing factors and specific conditions for the government to implement the blockchain and start the carbon trading policy (see Propositions 10–11). We find that when the fixed cost of establishing blockchain is ignored, only if the opportunity cost Φ of port enterprise is greater than a critical point, the expected benefit of the government under blockchain technology will be higher than that under the traditional mode without blockchain. However, when the fixed cost of blockchain is considered, only if the opportunity cost Φ is greater than a certain threshold and the fixed cost of blockchain is less than a certain threshold are simultaneously satisfied, the expected benefit of the government under blockchain technology will be higher than that under the traditional mode without blockchain. In addition, when the unit operation cost of implementing the blockchain is ignored, only if the critical value of carbon emission reduction of port enterprises is small, the expected benefit of the government under the carbon trading policy is higher than that under the carbon-free trading policy. However, when the unit operation cost of blockchain is considered, only if the critical value is small and the unit operation cost of the blockchain is small, the expected benefit of the government under the carbon trading policy is higher than that of the carbon-free trading.

(5) Through the numerical simulation, we confirm that the reasonable implementation of blockchain technology and carbon trading policy will help to improve the *VERs* of port enterprise and the expected benefit of the government, and the government's incentive strategy for port emission reduction is sensitive to the changes of relevant parameters under different cases, especially the increase in carbon trading market price is usually conducive to promoting the enthusiasm of port emission reduction and improving the expected benefit of the government.

Overall, the above conclusions in this paper have certain generality. On the one hand, these conclusions can directly provide some references for the design of incentive contracts for the government to port enterprises to reduce emissions in the shipping industry. On the other hand, the design and analysis of dynamic incentive contract models in this paper can provide some theoretical basis for relevant enterprises with principal–agent relationships.

7.2. Managerial Insights

Based on the above main conclusions, the corresponding management insights can be obtained as follows:

First, government managers can refer to the research in this paper to design dynamic incentive contracts for port enterprises to optimize and promote green technology investments (e.g., LNG terminals, shore-side power) for port enterprises, improve the carbon emission reduction of port enterprises, and accelerate the realization of the "double carbon" goal.

Second, the introduction of blockchain technology and the launch of carbon trading policy will affect the optimal dynamic trajectory change rules of government incentive strategy and the emission reduction investment decisions of port enterprises, and managers can make judgments based on the relevant conclusions in this paper.

Third, the change of relevant parameters means that the port market environment will change, and managers should make timely optimization and adjustment to the government's dynamic incentive contract to maximize the incentive for port enterprises to reduce emissions and improve government efficiency.

Fourth, managers should also optimize the government's dynamic incentive contract after the implementation of blockchain and carbon trading. In addition, an important insight is that the establishment of blockchain and the initiation of carbon trading policy do not always help to improve government effectiveness, and managers should carefully consider and make sound decisions based on the relevant conditions.

7.3. Limitations and Future Research

This paper can be extended from the following aspects: First, this paper considers the scenario that the government establishes the blockchain and port enterprises participate in the implementation of the blockchain, and further consider the case that port enterprises independently establish the blockchain technology platform. Second, this paper only studies the dynamic incentives between the government and port enterprises, and further considers the dynamic incentives of the government for shipping enterprises. Third, we can further use the game analysis framework of bounded rationality to build a dynamic evolutionary game model between the government and port enterprises.

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Abbreviations

Symbol	Description
ERI	Emission reduction investment
CERs	Carbon emission reductions
VERs	Verified emission reductions
v	Market random disturbance factor, $v \sim N(0, \delta^2)$
δ^2	Variance of random disturbance factor v
η	The investment cost coefficient of port enterprise
θ	Degree of risk aversion
σ	Attenuation rate of port emission reduction
ρ	Discount rate
β	Influence factor of port *ERI* on *CERs*
g	Contract execution efficiency
c	Unit execution cost of contract
C_b	Unit operation cost of blockchain
F_b	Fixed cost of blockchain
r	Green trust coefficient of customers on port *ERI*
h	Monetary expression of social benefits generated by unit *CERs*
γ	Impact of port's *CERs* on shipping customer demand
ξ	Service price of port
Φ	Opportunity cost of *ERI* in port enterprise
τ	Carbon trading market price
ψ	A critical value of carbon emission reduction to achieve carbon trading
ω	Disclosure degree of blockchain for port emission reduction market information
I	The port's *ERI* level (decision variable)
s_0	Fixed subsidy paid by the government to port enterprise (decision variable)
s_1	Unit subsidy paid by the government to port enterprise (decision variable)
G	*CERs* of port enterprise
EG	*VERs* of port enterprise
S	Dynamic incentive contract of government ($S = s_0 + s_1 \cdot G$)
π_p	Expected revenue of port enterprise
π_g	Government expected benefit
V_p	Expected discounted profit of port enterprise
V_g	Discount value of government expected benefit

Appendix A. Proofs

Proof of Lemma 1. According to the first-order optimal condition of the right end of HJB Equation (9) with respect to the control variable I^N, we obtain:

$$I^{N*}(t) = \frac{\beta}{\eta} \cdot V_p{}^{N\prime}(EG^N) \tag{A1}$$

Substituting Equation (A1) into HJB Equation (9) can obtain:

$$\begin{aligned} \rho \cdot V_p{}^N(EG^N) = \quad & [\gamma\xi \cdot EG^N(t) + g_0 \cdot (s_0{}^N(t) + s_1{}^N(t) \cdot EG^N(t)) - \tfrac{1}{2}\eta I^{N*^2}(t) - \tfrac{1}{2}\theta \\ & (g_0 \cdot s_1{}^N(t) + \gamma\xi)2\delta^2] + V_p{}^{N\prime}(EG^N)[\beta \cdot I^{N*}(t) - \sigma \cdot EG^N(t)] \end{aligned} \tag{A2}$$

According to the structure of HJB Equation (A2), let the port enterprise's optimal expected value function $V_p{}^N(EG^N) = l_{p1}{}^N \cdot EG^N + l_{p2}{}^N$, where $l_{p1}{}^N$ and $l_{p2}{}^N$ are undetermined constant coefficients. In order to obtain the undetermined constant coefficient, the optimal expected value function $V_p{}^N(EG^N)$ and its derivative $V_p{}^{N\prime}(EG^N) = l_{p1}{}^N$ are substituted into the HJB Equation (A2), and according to the identity relationship, $l_{p1}{}^N = (s_1 \cdot g_0 + \gamma\xi)/(\rho + \sigma)$ can be obtained, which is substituted into Equation (A1), and Equation (10) in Lemma 1 can be obtained. □

Proof of Theorem 1. Referring to the proof of Lemma 1, the HJB equation in Equation (15) can be similarly solved by using the continuous dynamic optimization control theory, and s_1^{N*} in Theorem 1 can be obtained. By introducing it into Equation (10) in Lemma 1, Equation (16) in Theorem 1 can be obtained. □

Proof of Corollary 1. According to Theorem 1, substituting the optimal decisions I^{N*} and s_1^{N*} of the government and port enterprise into the port *VERs* state equation of Equation (5), we can obtain:

$$dEG^N(t) = \frac{\beta^4(c\gamma\xi + g_0 h + \gamma\xi)}{(c+1)\eta(\rho+\sigma)\left(\beta^2 + \delta^2\eta\theta(\rho+\sigma)^2\right)}dt - \sigma \cdot EG^N(t)dt \tag{A3}$$

Equation (A3) can be solved according to the first-order linear differential equation to obtain the optimal trajectory $EG^{N^*}(t)$ of port *VERs*, that is, Equation (18) in Corollary 1. Further, $EG^{N^*}(t)$ and Equation (13) are combined with Equation (15) to deduce Equations (18)–(20) in Corollary 1. □

Proof of Lemma 2. Similar to the proof of Lemma 1, the continuous dynamic optimal control problem of the *ERI* level of port enterprise in Case *B* is similarly solved, and Equation (23) can be obtained. □

Proof of Theorem 2. Similar to the proof of Theorem 1, Theorem 2 can be obtained by solving the continuous dynamic optimization problem of the discount value of the government expected benefit with respect to the control variable $s_1^B(t)$ in Case *B*. □

Proof of Corollary 2. According to Theorem 2 and with reference to the proof of Corollary 1, Equations (28)–(30) in Corollary 2 can be deduced. □

Proof of Lemma 3. Similar to the proof of Lemma 1 and thus omitted. □

Proof of Theorem 3. Similar to the proof of Theorem 1 and thus omitted. □

Proof of Corollary 3. Similar to the proof of Corollary 1 and thus omitted. □

Proof of Proposition 1. According to the emission reductions $EG^{N^*}(t)$ of port enterprise approved by the government, the fixed subsidy $b_0^{N^*}(t)$ of the government for port enterprises, the discount value of government expected benefit $V_g^{N^*}(t)$ and the government dynamic incentive contract $S^{N^*}(t) = s_0^{N^*}(t) + s_1^{N^*} \cdot EG^{N^*}(t)$, we can derive that when $t \to +\infty$, $e^{-\sigma \cdot t} \to 0$, then $EG^{N^*}(t) = EG^{N^*} = \beta^4(c\gamma\xi + g_0 h + \gamma\xi)/(\sigma(1+c)\eta(\rho+\sigma)(\beta^2 + \delta^2\eta\theta\,(\rho+\sigma)^2))$, $s_0^{N^*}(t) = s_0^{N^*}(EG^{N^*})$, $S^{N^*}(t) = S^{N^*}(EG^{N^*})$, $V_g^{N^*}(t) = V^{N^*}(EG^{N^*})$. Thus, there is $t = t_{th}^N$ ($t_{th}^N \to +\infty$), and when $t \geq t_{\mathrm{th}}^N$, then $\partial EG^{N^*}(t)/\partial t = 0$, $\partial s_0^{N^*}(t)/\partial t = 0$, $\partial S^{N^*}(t)/\partial t = 0$, $\partial V_g^{N^*}(t)/\partial t = 0$; when $t < t_{th}^N$, $EG^{N^*}(t)$, $s_0^{N^*}(t)$, $S^{N^*}(t)$ and $V_g^{N^*}(t)$ are respectively calculated for the first derivative of time t and judged positive or negative, then Proposition 1 can be obtained. □

Proofs of Propositions 2 and 3. According to Corollary 2 and 3, and with reference to Proposition 1, the results in Propositions 2 and 3 can be obtained similarly. □

Proofs of Propositions 4–7. According to the optimal solutions, the optimal *ERI* level of port enterprise, the optimal fixed subsidy of the government and the port *VERs* in the steady state under different scenarios are first-order derived for each basic parameter and judged positive or negative to obtain Propositions 4–7 respectively. □

Proof of Proposition 8. Based on whether to consider the unit operating cost of blockchain, i.e., Cb = 0 and Cb > 0, the optimal decisions in Case B are subtracted from the corresponding optimal decisions in Case N and determine the positive or negative to obtain Proposition 8. □

Proof of Proposition 9. The optimal decisions in the *TB* case are subtracted from the optimal decisions in the *B* case and the positive or negative are determined to obtain Proposition 9. □

Proof of Proposition 10. By subtracting ${V_g}^{B*}$ from ${V_g}^{N*}$ at steady state (i.e., $t \rightarrow +\infty$) and judging the positive or negative according to whether or not to consider the fixed cost of the blockchain (i.e., $F_b = 0$ and $F_b > 0$), we can obtain Proposition 10. □

Proof of Proposition 11. By subtracting ${V_g}^{TB*}$ from ${V_g}^{B*}$ at steady state (i.e., $t \rightarrow +\infty$) and judging the positive and negative depending on whether the unit operating cost of the blockchain (i.e., $C_b = 0$ and $C_b > 0$) is considered, we can obtain Proposition 11. □

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