The Impact of Green Finance on the Penetration of Alternative-Fuel Vessels and Associated Greenhouse Gas Emissions Reduction

Pei Liu[1,*] and Dong-Ping Song[2]

[1]Department of Supply Chain Management, Business School, Shandong University, Weihai 264209, China

[2]Department of Operations and Supply Chain Management, School of Management, University of Liverpool, Liverpool L69 7ZH, UK

Abstract: The renewal of vessel fleet with the penetration of alternative- and green-fuel vessels is critical for the maritime transport sector to meet the net-zero greenhouse gas (GHG) emission target around 2050. However, the high upfront investment of alternative-fuel vessels is a major barrier to their market penetration. This study proposes a system dynamics method to investigate the impact of green credit and carbon trading on the penetration of alternative-fuel vessels and associated GHG emissions reduction. This framework consists of two interrelated models: a maritime transport model, which simulates freight transport processes, including freight demand, traffic flow, fleet evolution, and GHG emissions, and a green finance support model, which quantifies the mechanism of green credit and carbon trading on increasing shipping companies' intention to use alternative-fuel vessels. The proposed model is applied to a feeder vessel fleet serving a major seaport in China. The results show that the implementation of green credit significantly accelerates the penetration of alternative-fuel vessels and reduces GHG emissions from the vessel fleet. In contrast, carbon trading shows a weaker effect on mitigating GHG emissions than green credit primarily due to its low price. The sensitivity analysis reveals that other factors, such as vessel price, the pace of the greening of methanol, and price of conventional fuels also significantly influence GHG emissions from the vessel fleet. These results indicate that a combination of multiple green financial instruments can facilitate the decarbonization of maritime transport sectors.

Keywords: Maritime transport, alternative fuels, green credit, carbon trading, GHG emission.

1. INTRODUCTION

Maritime transport plays an indispensable role in world trade and globalization. Although shipping is the most carbon-efficient mode of freight transport, compared with other transport modes, such as road, railway, and airway, it remains heavily reliant on fossil fuel use and contributes substantially to global greenhouse gas (GHG) emissions. Data from the International Maritime Organization (IMO) ship fuel oil consumption database show that in 2023, 28,620 reported ships consumed 211 million tonnes of fuel, 93.52% of which included conventional fuels, such as heavy fuel oil, light fuel oil or diesel/gas oil [1]. In response, the IMO has set ambitious targets, suggesting reducing GHG emissions per transport work by at least 40% by 2030 (relative to 2008 levels) and achieving net-zero GHG emissions from international shipping by approximately 2050 [2].

Fleet renewal for alternative- and green-fuel vessels is critical for meeting these GHG mitigation goals. Liquefied natural gas (LNG) is currently a major alternative fuel, cutting carbon emission intensity by approximately 20% compared with that of conventional fuels [3], but it is typically regarded as a transitional fuel for ships. In contrast, methanol is a promising alternative energy source, especially green methanol or E-methanol, which is produced from renewable energy, such as wind and photovoltaic power, and achieves a 90% reduction in carbon emission intensity [4]. In addition, emerging electric and hydrogen-powered vessels have high GHG reduction potential. However, the diffusion of these alternative-fuel vessels still faces multiple barriers, among which economic barriers are primary. According to the DNV's report, a large 20,000 twenty-foot equivalent unit (TEU) container ship powered by LNG requires approximately 10% higher capital investment (CAPEX) than a conventional vessel does [5]. Research by Xu *et al*. (2024) [6] on small container ships on China's Yangtze River shows that LNG-fueled and methanol-fueled vessels cost 4.5 and 3 times more, respectively, than conventional diesel-powered ships do in terms of CAPEX. It is therefore likely that emerging electric- and hydrogen-powered vessels would carry even higher upfront costs.

Green finance provides a promising solution for alleviating the financial pressure linked to the renewal of alternative-fuel vessels and facilitating the green transition in maritime transport sectors. It provides multiple instruments to address the high price of purchasing environmentally friendly products and the high investment in renewable energy infrastructures and facilities [7]. In maritime transport sectors, shipping companies can apply for green credit with low interest rates to purchase new alternative-fuel vessels or to retrofit conventional-fuel vessels [8]. Large shipping or

*Address correspondence to this author at the Department of Supply Chain Management, Business School, Shandong University, Weihai 264209, China; E-mail: liupei@sdu.edu.cn

Received on 28-05-2026 Accepted on 03-07-2026 Published on 08-07-2026

port groups with sound cash flow and credit records can issue green bonds to fund the construction of alternative fuel facilities [9]. Carbon cap-and-trading is also regarded as a green finance instrument in some existing studies [10, 11]; in the freight market, it facilitates the shift of freight flow to more environmentally friendly transport modes and vehicles. In fact, according to the DNV's estimation of the total cost of ownership (TCO) of containerships, fuel-related carbon costs (GHGEX) have increased to a non-negligible portion—approximately 6% (for 5,500 TEU container ships) [12].

Despite the significant potential of green finance in facilitating the green transition of the shipping industry, academic research in this field—particularly quantitative studies—remains very limited. Most studies either offer qualitative discussions on the suitability of green finance in the shipping industry or undertake literature reviews on broader topics, such as the decarbonization of the shipping industry and related economic incentives. One of the major obstacles to quantitative studies is data availability. The mainstream methods in the field of finance, such as regression models and econometric models, require either time series data that span decades or panel data that contain specific cross-sector records. However, the application of green finance in maritime transport sectors is still in its infancy. Statistical data in this specific field are insufficient, which limits the use of those established methods in the field of finance.

In view of this, this study proposes a system dynamics framework to quantify the effect of green finance on the penetration of alternative-fuel vessels and associated GHG emissions reduction. The proposed framework is composed of two interrelated models. The first is a maritime transport model. We adopt an econometric model to estimate maritime freight demand and convert freight demand into vessel fleet traffic flow. Next, we introduce a scrap-and-sales model to simulate the turnover dynamics of conventional-fuel vessels and various alternative-fuel vessels. The second model is a green finance support model, which quantifies the effect of green finance on increasing shipping companies' intention to use alternative-fuel vessels. By connecting these two models, we estimate the effects of green finance on the renewal of vessel fleets and on the GHG emissions from vessel fleets. This study contributes to the literature by investigating the application of green finance in the field of maritime transport and by proposing an alternative method to project the long-term impact of green finance on the decarbonization of maritime transport. It demonstrates how the application of green finance alters the structural transition of vessel fleets, thus providing insights into the formulation of more targeted financing instruments and policies to facilitate the decarbonization of the maritime transport sector.

The remainder of the paper is organized as follows. Section 2 presents a literature review. Section 3 introduces the proposed framework and explains the development of the constituent subsystems. Section 4 applies the proposed framework to a regional maritime transport case in China and estimates the impact of green finance on the greening of vessel fleets and the mitigation of GHG emissions. Section 5 provides implications for more targeted financing mechanisms for the decarbonization of maritime transport. Section 6 draws conclusions and suggests directions for future work.

2. LITERATURE REVIEW

The maritime transport sector is responsible for 3% of global GHG emissions. With the increase in global trade, the decarbonization of maritime transport has become one of the key challenges in the mitigation of global climate change. Song (2024) [8] summarizes measures for the decarbonization of maritime transport, including operational measures, technical measures, fuel and energy measures, infrastructure measures, digitalization measures, and policy and collaboration measures. Similarly, Anantharaman *et al*. (2025) [13] conclude that reducing GHG emissions associated with shipping requires efforts in multiple areas, such as vessel design, operational optimization, alternative fuels, technological innovation, and policy and regulatory frameworks. Among these decarbonization measures, the renewal of vessel fleets with alternative fuels is widely recognized as an effective method, but it faces major economic barriers. Both Camargo-Díaz *et al*. (2022) and Anantharaman *et al*. (2025) [13, 14] identify the high price of alternative-fuel vessels and the high investments in related infrastructures as major barriers to the decarbonization of maritime transport.

These economic barriers have led to research on the application of green finance to the decarbonization of maritime transport sectors. However, generally, research in this emerging field is very limited. Thus, we expand our literature survey to more general financing mechanisms related to the decarbonization of maritime transport. Some studies have investigated the carbon finance market and its impact on the shipping industry. For example, Christodoulou and Cullinane (2024) [10] report the necessity of introducing an emissions trading system (ETS) into the shipping industry and report that the ETS can incentivize greater investment in green technologies, which can reduce the carbon footprint of the shipping industry. Meng *et al*. (2023) [15] utilize data from both the EU ETS and the Baltic dry index (BDI) and explore the relationship between the carbon finance market and the shipping industry. Other studies investigate the economic incentives for the decarbonization of maritime transport. For example, in their literature review on this topic, Camargo-Díaz *et al.* (2022) [14] classified economic incentives into three categories: project financing, differentiated port tariffs, and incentives to cover onshore power service fees.

With respect to methods, most studies that explicitly include green finance applied in maritime transport sectors are qualitative case studies and literature reviews. For example, Morchio *et al.* (2024) [16] investigate the application of green finance to 29 bulk shipping companies and reveal the role of green finance in the shipping industry via this multiple case comparison. Gavalas (2025) [11] reviews the green finance frameworks for the sustainable shipping industry and the blue economy. Regression analysis is the primary method adopted among the very few quantitative studies, and it is the main method used to investigate the application of green finance to more general freight transport sectors. This method is typically employed to analyze the relationship between financial indices and shipping-related indices on the basis of sufficient historical data. For example, Mnif *et al.* (2026) [17] use this method to explore the relationships among crude oil prices, green bonds, the AI market index, and the BDI. Sigalas and Gerakoudi (2026) [18] conduct regression analysis on 1,470 debt transactions by 564 shipping companies and explore the difference between ESG-linked and conventional financing instruments. In contrast, analytical methods have lower requirements for statistical data. For example, Ziakas and Boile (2026) [19] develop a financing analytical model to calculate market returns, stock volatility, loan duration, interest rates and financing risk related to investments in fleet renewal. However, this study focuses on financial indicators and does not extend to the evolution of vessel fleets and GHG emissions.

In summary, studies have discussed the current state and suitability of green finance in the maritime transport sector and have investigated the relationship between the financial market and the development of the shipping industry. However, the effects of specific green finance instruments on the renewal of vessel fleets and on the reduction in GHG emissions remain unclear. Since the application of green finance in the field of maritime transport is still in its infancy, statistical data are not sufficient; this limits the use of established methods in the field of finance. Thus, an alternative method is needed to quantitatively assess the impact of green financing on the renewal of vessel fleets and associated GHG emissions reduction.

3. METHODOLOGY

3.1. Model Hypotheses

The proposed model aims to explore the turnover dynamics of a vessel fleet and the associated reduction in GHG emissions with the support of green finance. The hypotheses of the proposed model are explained below.

(1) This study presents long-term projections of the proportions of various alternative-fuel containerships. The proposed model cannot forecast the emergence of new vessel types in the future. It refers to the DNV's report on alternative-fuel containerships and considers the alternative fuels mentioned in this report, including natural gas (including LNG and LGP), methanol, biofuel, battery, and hydrogen [5, 20]. Furthermore, since electric and hydrogen-fueled ships account for a very small proportion, these two categories are classified into the "others" category in this study.

(2) Green finance is implemented in the form of a variety of green financial instruments (GFIs). This study considers two widely implemented GFIs. One is green credit, which alleviates the financial pressure placed on shipping companies in terms of their ability to purchase alternative-fuel vessels at a reduced interest rate. The other is carbon trading, which alters the TCO of vessels and shifts the purchasing intention to more environmentally friendly vessels. Other forms of GFIs, such as green bond, green insurance, and green fund, are not included.

(3) This study employs scenario comparisons to evaluate the effect of green credit on the renewal of alternative-fuel vessels and the associated reduction in GHG emissions. This work does not consider the impact of energy-efficient improvements in alternative fuels. For one alternative fuel, all the scenarios refer to the same benchmark of its life-cycle GHG emission factor.

3.2. Model Overview

The overall model framework is illustrated in Figure **1**. It consists of two interrelated models: a maritime transport model and a green finance support model. These two models can be further divided into four subsystems. The first is the maritime freight demand

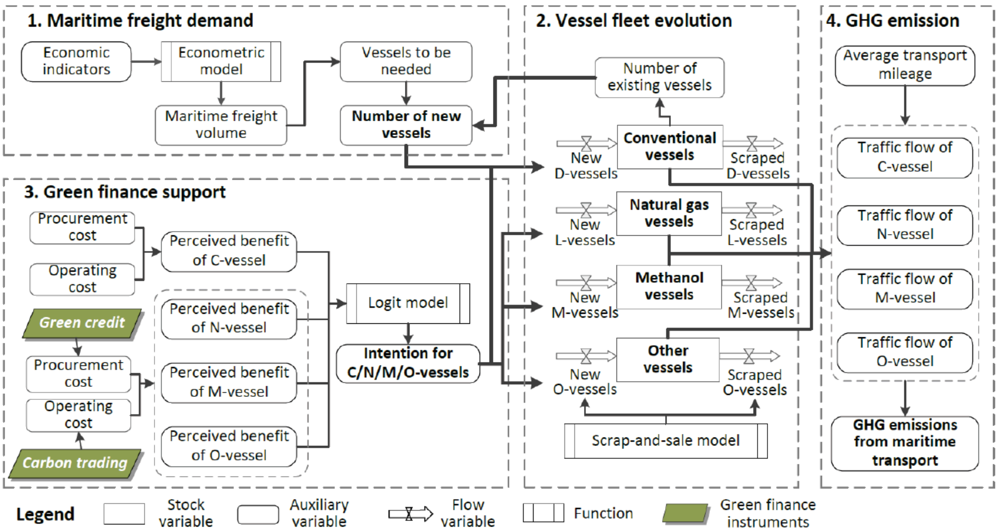

Figure 1: Schematic illustration of the model framework.

Notes: C-, N-, M-, and O-vessels refer to conventional, natural gas, methanol, and other vessels, respectively.

subsystem, which introduces an econometric model to project maritime freight volume in terms of the TEU of containers and estimate the number of new vessels. The second is the vessel fleet evolution subsystem, which introduces “stocks” and “flows” in system dynamics to simulate the coevolutionary dynamics of various alternative-fuel vessel fleets [21]. “Stocks” represent the number of vessels in operation. “Flows”, including inflow and outflow, represent the newly delivered and decommissioned vessels. Third, for the green finance support subsystem, we use a classic logit model to estimate the effect of green credit on the purchasing intention of various alternative-fuel vessels. Finally, for the GHG emission subsystem, we calculate the GHG emissions from various alternative-fuel vessels and compare the difference in GHG emissions with and without the implementation of green credit.

3.3. Model Development

3.3.1. Maritime Freight Demand Subsystem

Multiple methods have been used to forecast maritime freight demand, such as time series analysis [22] and machine learning approaches [23]. Since this study applies the model to a container feeder vessel fleet for a seaport, an econometric model is introduced to forecast the container throughput of the port [24]. The freight demand via feeder vessels is obtained according to both the total container throughput and the mode share of the feeder vessels. The econometric model for container throughput forecasting is specified as follows.

$$y_t = \beta_0 + \beta_1 y_{t-1} + \cdots + \beta_m y_{t-m} + \alpha_0 e_t + \alpha_1 e_{t-1} + \cdots + \alpha_n e_{t-n} + \varepsilon_t \quad (1)$$

Eq. (1) is an autoregressive distributed lag (ARDL) model, denoted as $\mathrm{ARDL}(m,n)$. y_t is the container throughput of a port. It is explained by the lagged values of itself (with maximum lags of m) and successive lags of the economic indicator, e (with maximum lags of n). ε_t is the error term with a normal distribution.

Maritime freight demand (f_t) is subsequently derived via Eq. (2):

$$f_t = y_t \times r_t^M \quad (2)$$

where y_t is the container throughput estimated by Eq. (1). r_t^M is the share of the container throughput transported via feeder vessels, which can be estimated using the classic logit model [25].

3.3.2. Vessel Fleet Evolution Subsystem

This subsystem uses the maritime freight demand provided by the previous subsystem, converts it into the number of vessels to be needed, and simulates the stock turnovers of various alternative-fuel vessels. It introduces the classic scrap-and-sales model to calculate the annual numbers of newly delivered and decommissioned vessels [26]. Specifically, the dynamics of the stock of vessels using fuel type i can be expressed as follows:

$$S_{i,t+1} = S_{i,t} + v_{i,t}^{+} - v_{i,t}^{-} \quad (3)$$

where $S_{i,t+1}$ is the number of vessels using fuel type i in year $t+1$. It depends on its value in year t ($S_{i,t}$) and both the number of newly delivered vessels ($v_{i,t}^{+}$) and the number of decommissioned vessels ($v_{i,t}^{-}$) in year t. Here, $v_{i,t}^{-}$ is determined by the ship service life. Large containerships generally have a longer service life than smaller ships. $v_{i,t}^{+}$ is related to the total number of newly delivered vessels (N_t) and the shipping companies’ intention or willingness to purchase vessel type i ($w_{i,t}$). Specifically, N_t is estimated according to freight demand (f_t), the average utilization rate of vessels (U), and vessels' operating days in a year (O). $w_{i,t}$ is estimated using a classic logit model according the TCO of different types of vessels. The above calculations are summarized in Eq. (4).

$$\begin{cases} v_{i,t}^{+} = N_t \times w_{i,t} \\ N_t = \max(\frac{f_t}{U\times O} - S_{i,t-1}, 0) \\ w_{i,t} = \frac{EXP(\alpha\times TCO_{i,t-1})}{\sum_i EXP(\alpha\times TCO_{i,t-1})} \end{cases} \quad (4)$$

where $TCO_{i,t}$ is the total cost of ownership for vessel type i, which is calculated in the subsequent green finance support subsystem. α is the spread parameter.

3.3.3. Green Finance Support Subsystem

The green finance support subsystem introduces the implementation of green credit and carbon trading and estimates their impact on the renewal of the vessel fleet by embedding them into the TCO of vessels. The DNV's report provides a detailed breakdown of the TCO, including capital expenditures, financing expenditures, operational expenditures excluding fuel, expenditures for fuel and fuel-related GHG costs [12]. In this study, these detailed cost items are categorized into two major groups: capital costs and operational costs. Thus, $TCO_{i,t}$ is expressed as follows:

$$TCO_{i,t} = CAPEX_{i,t} + OPEX_{i,t} \quad (5)$$

where $CAPEX_{i,t}$ are the capital costs for purchasing vessel type i, including the investment cost, that is, the price of vessel type i (P_i), and the interest expenses on bank loans. Generally, the price of vessels using alternative fuels is higher than that of conventional vessels, but interest expenses can be reduced by applying for green credit (the interest rates of regular credit and green credit are denoted as k_R and k_G, respectively). $OPEX_{i,t}$ are the operational costs of vessel type i, including expenditures for fuel (FuelEX), other operational costs, and the GHG-related cost (GHGEX). Specifically, $GHGEX_{i,t}$ is the GHG-related cost of vessel type i in year t, which is calculated based on the GHG emissions from vessel type i ($GHG_{i,t}$, calculated in the subsequent GHG emission subsystem) and the price of carbon trading h. Note that the above costs are normalized into unit cost (per ton of cargo) according to the capacity of container vessels and the average payload of containers.

3.3.4. GHG Emission Subsystem

For this subsystem, we use the stocks of various alternative-fuel vessels, which are $S_{i,t}$ provided by the vessel fleet evolution subsystem, and calculate the total GHG emissions from the vessel fleet (GHG_t) according to the volume of vessel traffic and the emission factors of alternative fuels. The equation is specified as follows.

$$GHG_t = \sum_i GHG_{i,t} = \sum_i (S_{i,t} \times U \times O \times M \times E_{i,t}) \quad (6)$$

where U, O, and M represent the average utilization rate, operating days in a year, and transport mileage of the vessel fleet, respectively. $E_{i,t}$ is the GHG emission factor of fuel type i in year t. Note that this is a life-cycle emission factor that is designed to better reflect the potential for reducing GHG emissions when alternative fuels are used, particularly the fuels produced by green energies, such as green methanol produced by solar or wind power.

4. RESULTS AND DISCUSSION

4.1. Case Profile and Model Validation

4.1.1. Case Profile

The proposed model is applied to the feeder vessel fleet of Qingdao Port for empirical demonstration. Qingdao Port is located on the southern coast of the Shandong Peninsula and is the world's 5th largest port in terms of container throughput, handling more than 30 million TEU of containers by 2024. Containers are transported via road, railway, and feeder vessels from the port to the hinterland and vice versa, from the hinterland to the port. The feeder vessel fleet operates mainly between Qingdao Port and smaller ports around the Shandong Peninsula, such as Rizhao Port, Yantai Port, and Weihai Port. Alternative fuels for feeder vessels include primarily natural gas and methanol. Other fuel types, such as biofuel and hydrogen, have not yet been deployed.

With respect to Qingdao Port, the equation for estimating container throughput (Eq. (1)) is estimated in the form of $\mathrm{ARDL}(1,2)$, as specified in Eq. (7) [27]:

$$L(y_t) = 0.74L(y_{t-1}) + 0.25L(IE_t) - 0.11L(IE_{t-1}) + 0.05L(IE_{t-2}) - 0.22 \quad (7)$$

where y_t denotes the container throughput of Qingdao Port. The import and export value (IE_t) is chosen as the explanatory variable, and L refers to the natural logarithmic form. This equation has passed the required verification tests for econometric models, such as the Breusch–Godfrey serial correlation LM test and the bound test. The results also show a good correlation between the actual historical container throughput and the estimated values. Thus, this equation is used to project the long-term trend of container throughput according to the local government's economic planning for imports and exports (IE_t). On this basis, container volumes transported by feeder vessels are determined according to the mode share of feeder vessels (approximately 12%) among various port-hinterland transport modes. The results show that the freight demand of feeder vessels increases continuously, from approximately 3 million TEU in 2025 to approximately 9 million TEU until 2050.

4.1.2. Parameter Setting

Parameters used in the system dynamics model and their values regarding the case are summarized in Table **1**. To be specific, the initial number of various vessels is estimated according to the container volume in the initial year and the average utilization rate and operating days of vessels, as specified in Eq. (4). Price of conventional and alternative-fuel vessels refers to the data from Shanghai Shipping Exchange. Interest rates of regular credit and green credit refer to Center for green finance research of Tsinghua NIFR (2022) [7]. The average utilization rate and operating days of vessel fleet are obtained based on on-site survey. Since it commonly takes two days for a round trip from feeder ports to Qingdao Port, the average utilization rate is set as 0.5. The average transport mileage for feeder vessels is estimated using a weighted average method according to container volume and mileage of different feeder ports. GHG emission factors of conventional and alternative fuels refer to both the IMO's guideline and the study of China's fuel production and supplies [28, 29]. Note that the values of these factors are related to lifecycle emissions, rather than direct emissions from combustion. Moreover, except for methanol, for which the dynamic evolution from gray methanol to green methanol is taken into account, the emission factors of conventional fuel and natural gas are set as fixed values during the simulation period.

4.1.3. Model Validation

After the parameters are set, the model is implemented via the Vensim DSS® software package. The model is validated through a series of validation tests, such as direct structure tests, structure-oriented behavior tests, and behavior pattern tests [30]. Direct structure tests, also known as the theoretical structure tests, compare the model equations with generalized knowledge in the literature. The proposed model is developed based on the classic four-step transport framework [31], which converts freight demand into freight traffic flow and calculates associated GHG emissions, thus has concrete theoretical basis. Structure-oriented behavior tests include the behavior sensitivity test and the extreme-condition test. The behavior sensitivity test is conducted on freight demand. Three economic scenarios are constructed, among which the medium scenario corresponds to the economic setting in Eq. (7). On this basis, a low scenario and a high scenario are constructed to reflect the pessimistic and optimistic economic prospects. Container volumes for feeder vessels under these three scenarios are shown in Figure **2a**. GHG emissions from the vessel fleet under different economic scenarios are estimated and compared. The results show that the change in GHG emissions is

Table 1: Parameter Values for the Feeder Vessel Fleet of Qingdao Port

Parameter	Value	Unit
Initial value of number of C-, N-, M-, and O-vessels ($S_{i,0}$)	10,0,0,0	vessel
Price of C-, N-, M-, and O-vessels (P_i)	40,65,80,130	million CNY/vessel
Interest rate of regular credit (k_R)	0.0475	dmnl
Interest rate of regular credit (k_G)	0.032	dmnl
Average utilization rate of vessels (U)	0.5	dmnl
Operating days of a year (O)	250	day
Average transport mileage of vessel fleet (M)	230	km
Starting year of N-, M-, and O-vessel penetration	2015,2025,2025	year
Starting year of green finance implementation	2020	year
GHG emission factor for C-vessels ($E_{C,t}$)	5.1	ton/ton
GHG emission factor for N-vessels ($E_{N,t}$)	4.1	ton/ton
GHG emission factor for M-vessels ($E_{M,t}$) (gray methanol)	3.8	ton/ton
GHG emission factor for M-vessels ($E_{M,t}$) (green methanol)	0.5	ton/ton
GHG emission factor for O-vessels ($E_{O,t}$)	0.76	ton/hour
Price of carbon trading (h)	75	CNY/ton

Note: CNY denotes Chinese yuan. Dmnl denotes dimensionless. C-, N-, M-, and O-vessels refer to conventional, natural gas, methanol, and other vessels, respectively.

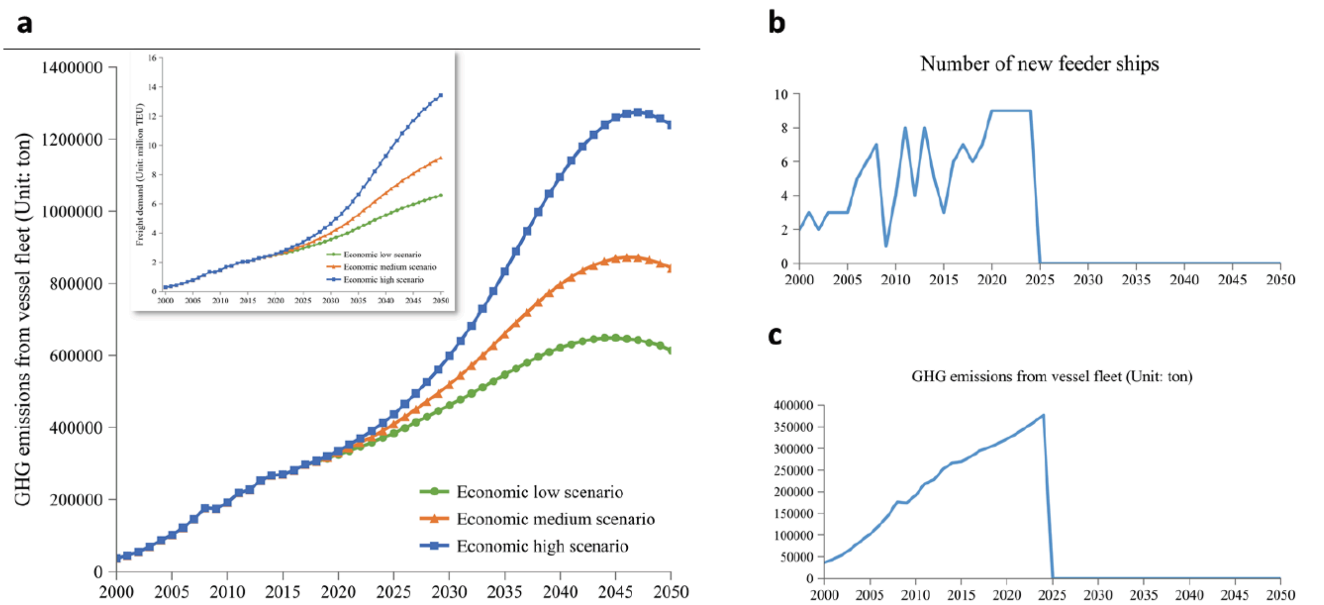

Figure 2: Results of model validation. (**a**) The sensitivity of GHG emissions to the change of freight demand. (**b**) Extreme-condition test on the number of new vessels. (**c**) Extreme-condition test on GHG emissions from the vessel fleet.

sensitive to the variation of freight demand. This simulated behavior is consistent with that in the real system. The extreme-condition test involves assigning extreme values to selected parameters and comparing the model-generated behavior to the observed or anticipated behavior of the real system under the same extreme condition. An extreme condition we can easily anticipate the behavior of the real system is that there is no freight demand after 2025. Under this extreme condition, the model estimates that there would be no new vessels (Figure **2b**), and since maritime transport stops, there would be no GHG emissions (Figure **2c**). These simulated behaviors are consistent with those in the real system. The behavior pattern test is conducted on the penetration rate of natural gas-vessels. The simulated values are well correlated with the historical values in their trends, which grow from zero in 2015 to approximately 8% in 2025.

4.2. Effect of Green Finance on the Greening of Vessel Fleets

The proposed model provides a long-term projection of the effect of green finance on the evolution of the feeder vessel fleet for Qingdao Port. The simulation period extends from 2000 to 2050, with the end year consistent with the IMO's vision of a net-zero GHG emission target in the shipping industry. To compare the effects of the implementation of green finance, three scenarios are defined: the baseline scenario, in which green finance is not considered, and two green finance scenarios, which correspond to the implementation of green credit and carbon trading. The effect of green finance on the renewal of vessel fleets is illustrated in Figure **3**.

Figure **3a** and **b** show the differences in the greening of vessel fleets without and with the support of green finance, respectively. Notable results are twofold. First, as illustrated as the stacked chart in Figure **3b**, the results show a significant effect of green credit on the penetration of alternative-fuel vessels, and this effect increases over time. Specifically, in this feeder vessel fleet case in China, the penetration of natural gas and methanol vessels began in approximately 2015 and 2025, respectively, and the implementation of green finance commenced in approximately 2020. Until 2050, the share of alternative-fuel vessels increases to 75% under the support of green credit, significantly exceeding the 42% under the baseline scenario. The effects of green credit on facilitating the penetration of natural gas vessels and methanol vessels are similar because the prices of these two types of vessels are similar. Notably, this study does not consider potential restrictive policies on natural gas vessels, given that natural gas is regarded as a transition fuel. Thus, the share of methanol vessels would increase if these restrictive policies were implemented. On the other hand, other vessels (primarily hydrogen-powered vessels and potential electric vessels) account for only a very small proportion. This is primarily due to their high price. If long-term technological improvements were considered, the price of these emerging vessels would decline; this may lead to a higher penetration rate of these types of vessels. Second, as illustrated as the line chart in Figure **3b**, the effect of carbon trading on accelerating the penetration of alternative-fuel vessels is weaker than that of green credit. This is primarily due to the relatively low carbon trading price in China, which currently stands at 75 CNY per ton, far below the European price ranging from 70 to 80 euros per ton.

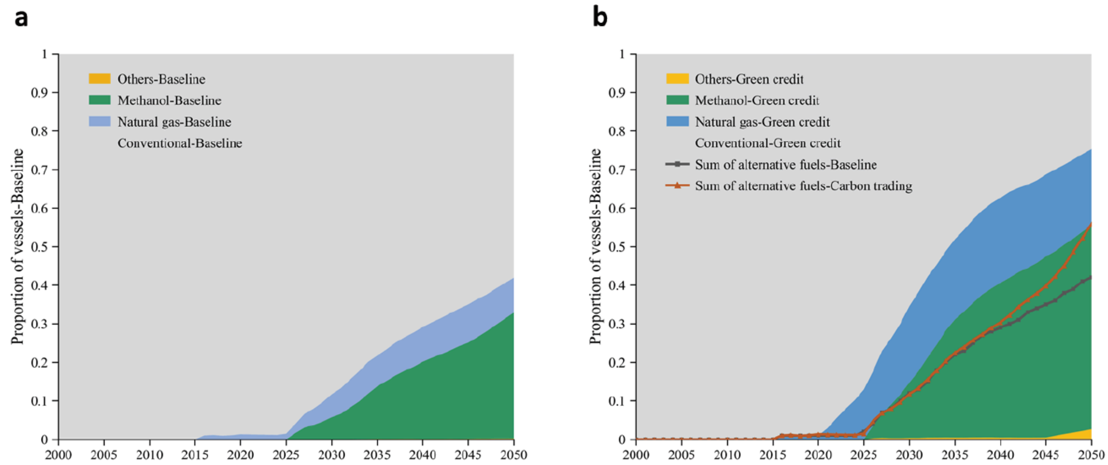

Figure 3: Proportion of vessels (**a**) without and (**b**) with the support of green finance.

4.3. Effect of Green Finance on GHG Emissions of Vessel Fleet

The effect of green financing on reducing GHG emissions from the vessel fleet is demonstrated by comparing the GHG emissions without and with the support of green finance, as illustrated in Figure **4a** and **b**, respectively. The stacked chart in Figure **4b** shows GHG emissions from the vessel fleet under the support of green credit. For comparison, the aggregate GHG emissions under the baseline and carbon trading scenarios are added in line chart. Notable results are twofold. First, given a continuously increasing freight demand (see the medium scenario in Figure **2a**), GHG emissions from the vessel fleet under both baseline and green finance scenarios will peak and subsequently reduce. This is primarily due to the increasing share of methanol vessels among the vessel fleet and the greening of methanol supplies. Second, the implementation of green finance promotes the penetration of alternative-fuel vessels. GHG emissions from alternative-fuel vessels increase noticeably, but those from conventional-fuel vessels decrease to a greater magnitude. Consequently, the green finance scenarios (both the green credit scenario and the carbon trading scenario) achieve an earlier peak time and a lower amount of GHG emissions. Until 2050, green credit reduces GHG emissions by 29.9% compared to baseline. Carbon trading reduces GHG emissions by 16.5%, which is lower than the percentage achieved by green credit. This is also primarily due to its low price.

4.4. Sensitivity Analysis

The long-term trend of GHG emissions from the vessel fleet is subject to the changes in future fuel prices, technological advancements, and policies. Thus, sensitivity analyses are conducted on a series of model parameters that reflect these future changes.

Future technological advancements may reduce the price of alternative-fuel vessels. Figure **5a** shows the change in the GHG emissions of the vessel fleet when the price of alternative-fuel vessels decreases from 0 to 50%. The results show that lower prices yield a significant and continuous effect on mitigating GHG

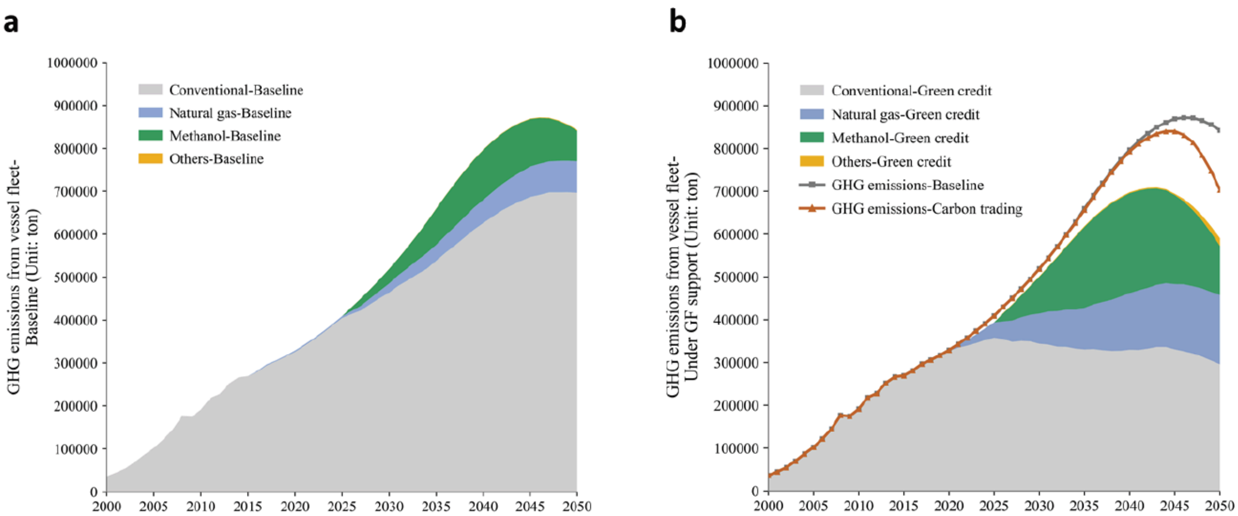

Figure 4: GHG emissions from the vessel fleet (**a**) without and (**b**) with the support of green finance.

emissions because of the increase in the proportion of alternative-fuel vessels.

Figure **5b** shows the change in GHG emissions from the vessel fleet when the greening of methanol supplies accelerates from 0% to 50%. Specifically, the proposed model assumes a linear greening process of methanol, from gray methanol in 2025 to 100% green methanol until 2050. When this greening process is accelerated by 50%, complete green methanol supplies are achieved by approximately 2037. The results indicate that green methanol plays a significant role in mitigating GHG emissions from the vessel fleet. Nonetheless, owing to the continuous growth in freight demand, GHG emissions still follow an upward trend in the long term even despite the use of 100% green methanol.

In the future, the price of conventional fuels may fluctuate with changes in crude oil production, consumption, and geopolitical conditions. Figure **5c** shows the change in GHG emissions from the vessel fleet when the price of conventional fuels increases from 0 to 50%. Since the fuel price directly affects vessels' operational costs, the results show a significant reduction in GHG emissions when the increase in conventional fuel price facilitates the adoption of more environmentally friendly alternative-fuel vessels.

Future technological advancements may accelerate the R&D and implementation of fuel-related carbon mitigation technologies, such as the carbon capture and storage (CCS) technology, which can be reflected in the decrease of carbon emission factors. Figure **5d** shows the change in GHG emissions from the vessel fleet when the carbon emission factors of both conventional fuels and alternative fuels decrease from 0 to 50%. The results reveal an instant and remarkable effect of such fuel-related carbon mitigation technologies on mitigating GHG emissions. This implies that a broader range of green financial instruments, which target on not only the demand and supply of shipping fuels but also fuel-related GHG emission reduction technologies, would be conducive to the decarbonization of maritime transport.

The penetration of alternative-fuel vessels and GHG emissions from the vessel fleet are also affected by the intensities of green financial instruments, which in this study refer to the interest rate of green credit and the price of carbon trading. This study sets the credit interest rate for vessel purchasing loans as 0.032. This is actually an average value of the interest rate between green credit (0.0175) and regular credit (0.06) since most of the financial agencies may not approve the full amount of green credit requested by shipping companies. Figure **5e** shows the change in GHG emissions from the vessel fleet when the interest rate varies between green credit rate and regular credit rate. The results reveal that lower credit rates can significantly reduce GHG emissions from the vessel fleet. Nonetheless, the actual impact of changing green credit rate maybe more complicated and uncertain because a lower credit rate may erode financial agencies' profits, thereby constraining the availability of credit. Figure **5f** shows the change in GHG emissions

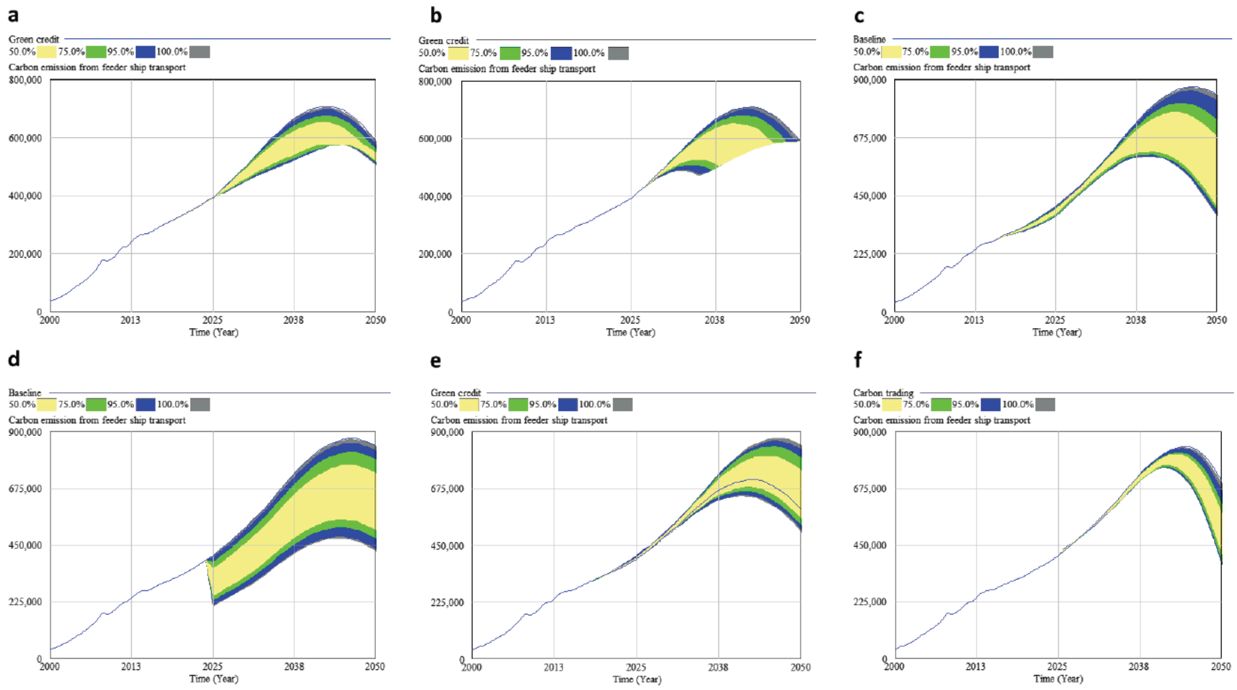

Figure 5: Sensitivity of (**a**) vessel price, (**b**) green methanol, (**c**) conventional fuel price, (**d**) carbon emission factors of fuels, (**e**) interest rate of green credit, and (**f**) carbon trading price to GHG emissions from the vessel fleet.

when the price of carbon trading fluctuates between the levels observed in China (75 CNY/ton) and Europe (75 EUR/ton). The results also demonstrate the sensitivity of GHG emissions to the change in the price of carbon trading.

5. IMPLICATIONS FOR MORE TARGETED FINANCING MECHANISMS

The above analysis explains the results of the model application to a local feeder vessel fleet for a seaport in China and reveals the trend of both the renewal of the vessel fleet and the associated GHG emissions under the support of green finance. The proposed method and new results extend the existing studies that either qualitatively investigate the suitability of green finance in maritime transport sectors or quantitatively examine the relationships between general financial indicators and shipping-related indicators. Through a comparison between scenarios with and without green finance support and a sensitivity analysis of key model parameters, implications for more targeted policies and financing mechanisms to facilitate the decarbonization of maritime transport are drawn.

This study reveals that GHG emissions from maritime transport are influenced by multiple economic, technological and policy factors. Freight demand is one of the most important factors that affect economic and environmental performances of maritime transport. Growing freight demand imposes greater challenges for the decarbonization of maritime transport. The greening of vessel fleet is conducive to mitigating maritime transport GHG emissions via replacing the consumption of conventional fuels with that of alternative fuels. However, the vision of net-zero GHG emission target must be achieved by a concurrent greening of alternative fuels. This lays emphasis on the adoption of those alternative fuels with net-zero emission potentials, such as methanol, battery, and hydrogen, but these green-fuel vessels typically face major barriers of high price. These intertwined influencing factors necessitate the implementation of green finance in accelerating the adoption of alternative-fuel vessels and the greening of alternative fuels.

The results of this study imply that a combination of multiple green financial instruments can facilitate the decarbonization of maritime transport.. The sensitivity analysis reveals the significant impact of the greening of alternative fuels on GHG emissions from the vessel fleet. Therefore, financial agencies are suggested to design more diverse green financial instruments and extend green financial support to more stakeholders within the alternative fuel supply chains. Such measures may include green credit on the energy demand side, tailored to shipping companies for their renewal of alternative-fuel vessels, and green bonds on the energy supply side, tailored to ports who invest and construct green-fuel facilities. Such combinations of multiple green financial instruments, implemented on both the energy demand side and the supply side, will accelerate the pace of the decarbonization of maritime transport.

Moreover, a broader portfolio of green financial instruments tailored to the maritime industry should be developed. This study considers mainly the green financial instruments targeted to alternative-fuel vessels. In fact, with the support of targeted financing instruments, conventional fleets can also contribute to GHG mitigation. For example, governments are advised to allocate green funds to support the R&D of carbon capture technologies for conventional-fuel engines [32]. Financial agencies are suggested to develop targeted green credit products to support the installation of carbon capture equipment, paired with green insurance schemes that guarantee the performance of carbon capture technologies and equipment [33]. Specially for China's shipping industry, it is recommended that governments could consider to include broader maritime transport sectors into the unified domestic carbon trading market to incentivize shipping companies to scale up the uptake of alternative fuels.

6. CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

Green finance provides a targeted and effective solution for alleviating the pressure of decarbonization in the field of maritime transport. However, the application of green finance in this specific field remains in its infancy, with limited time series data and scattered application records. This limits the use of established empirical methods in the field of finance. This study contributes to the literature by proposing an alternative system dynamics model to evaluate the effect of green finance on the renewal of vessel fleets and associated GHG emissions. The proposed model is developed based on classic freight transport theories and simulates the interactions among freight transport processes, such as freight demand, traffic flow, fleet evolution, and GHG emissions. The support of green finance is incorporated into the model via the fleet evolution subsystem. Thus, the proposed model framework and results clearly demonstrate how the application of green finance influences the penetration of alternative-fuel vessels and how structural changes in vessel fleets influence maritime transport GHG emissions. The proposed model is applied to a feeder vessel fleet serving a major seaport in China. The results show that green credit has a significant effect on accelerating the penetration of alternative-fuel vessels and reduces GHG emissions from the vessel fleet. In contrast, carbon trading shows a weaker effect on mitigating GHG emissions than green credit primarily due to its low price. The sensitivity analysis reveals that GHG emissions from the vessel fleet are also influenced by other multiple factors, such as vessel price, the pace of the greening of methanol, price of conventional fuels, and carbon emission factors of fuels. These results indicate that a combination of multiple green financial instruments, implemented on both the fuel demand side and the supply side, can facilitate the decarbonization of maritime transport.

This study has several limitations. First, the estimated ARDL model uses the import and export value as the single exogenous explanatory variable. In future work, additional economic variables could be introduced. These tested variables can be utilized to represent more diverse economic scenarios. Second, the vessel fleet evolution model assumes a fixed vessel service life at 15 years. In reality, vessel retirement decisions may be influenced by fuel prices, regulations, and technological obsolescence. Third, when projecting the long-term impact of green finance, the proposed model assumes the continuous implementation of green financial instruments. However, the continuity and intensity of green financial instruments in the future remain uncertain and subject to policy changes; this may lead to an overestimation of the effect of green finance.

The proposed system dynamics model can be extended in the following directions. First, the vessel fleet in the case study primarily includes conventional, natural gas-fueled vessels and methanol-fueled vessels. The proposed model can be extended to include other alternative fuels, such as biofuel and ammonia (including E-ammonia). The vessel fleet evolution subsystem can incorporate these additional vessel types and simulate the coevolutionary dynamics of the stocks of multiple alternative-fuel vessels. Second, the proposed model includes green credit and carbon trading and does not consider other green financial instruments. In future work, additional subsystems can be developed and incorporated into the proposed model. For example, a green bond support subsystem could be developed to examine how the capital raised via green bonds affects the upgrading of alternative fuel facilities. This impact is reflected in both the reduction in expenditures for fuel (FuelEX) and the decrease in the carbon intensity of alternative fuels. Finally, this study investigates the impact of green finance on the long-term evolution of vessel fleets on the basis of its effect on reducing ships' CAPEX. It does not consider the impact of the availability of alternative fuels on the renewal of vessel fleets. In future work, this issue could be addressed by incorporating fuel availability-related costs into the TCO of containerships. In this way, shortages in the supply of a certain alternative fuel would increase the TCO of vessels using this type of fuel, thereby curbing the growth of the penetration of these vessels.

ACKNOWLEDGEMENTS

This work is supported by the National Social Science Foundation of China (Grant No. 24BJY020).

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTION

Pei Liu: Conceptualization, Methodology, Data curation, Formal analysis, Writing-Original draft preparation.

Dong-ping Song: Conceptualization, Writing-Reviewing and Editing.

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