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Economic viability of arctic shipping under IMO environmental regulations: a well-to-wake assessment of different carbon tax scenarios

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The accelerated melting of Arctic sea ice has established the Northern Sea Route (NSR) as an emerging alternative for international shipping. However, increased maritime activities pose significant environmental risks to this sensitive region. This study evaluates the economic implications of the International Maritime Organization (IMO) environmental regulations on Arctic shipping through a well-to-wake assessment framework. Using a multi-scenario economic analysis model, we compare transportation costs between the NSR and the traditional Suez Canal Route (SCR) under various IMO environmental policy scenarios. Our findings reveal: (1) Without carbon taxation, the NSR generally offers lower unit transportation costs than the SCR. However, the IMO's prohibition of heavy fuel oil (HFO) in Arctic waters creates a 12-15% cost advantage for vessels using HFO on the SCR compared to those using clean fuels on the NSR. (2) However, the IMO's prohibition of heavy fuel oil (HFO) in Arctic waters creates a 12-15% cost advantage for vessels using HFO on the SCR compared to those using clean fuels on the NSR. (3) In unilateral carbon tax scenarios, the NSR consistently remains less economically viable than the SCR using HFO, primarily due to mandatory clean fuel requirements in Arctic waters. (4) The environmental benefits of LNG propulsion demonstrate considerable technological sensitivity, with life-cycle emission reduction efficiency heavily dependent on engine selection and methane slip mitigation. Our analysis indicates that current Arctic environmental regulations lack policy coordination. To simultaneously achieve ecological protection and economic viability, we recommend implementing a dynamic carbon tax threshold mechanism linked to clean fuel technology standards.

KEYWORDS

Northern Sea Route, IMO environmental regulations, economic viability, carbon tax, well-to-wake

1 Introduction

The accelerated melting of Arctic sea ice due to global warming has significantly enhanced the navigational potential of Arctic shipping routes, positioning them as emerging strategic corridors in international maritime transport (Quinn et al., 2008; Lindstad et al., 2016; Gunnarsson, 2021). However, this expansion of shipping activities intensifies environmental vulnerabilities in this ecologically sensitive region, with vessel emissions of black carbon, petroleum residues, and nitrogen oxides presenting significant ecological concerns (Dalsøren et al., 2007; Corbett et al., 2010; Lack and Corbett, 2012; Lindstad et al., 2016; Zhu et al., 2018; Raut et al., 2022). While black carbon emissions from Arctic shipping remain a concern, recent studies suggest that its direct climatic impact may be limited during summer months due to deposition in open waters (Li et al., 2021). In response to these environmental challenges, market-based policy instruments have gained prominence in global maritime governance (Harrison, 2010; World Bank, 2021). The International Maritime Organization's (IMO) proposed carbon tax schemes ($18.75/$100/$150 per ton of CO_2 equivalent emitted on a life cycle basis) (ISWG-GHG 17, 2024) represent a significant policy intervention whose cost transmission mechanisms are fundamentally reshaping the economic evaluation framework for Arctic routes (Zhang and Baranzini, 2004; Cheaitou et al. 2022). A systematic assessment of Arctic route feasibility under varying carbon tax scenarios not only informs operational decisions for shipping enterprises but also provides essential parametric support for developing sustainable Arctic shipping policy frameworks.

Current literature predominantly focuses on developing and validating economic viability assessment frameworks for Northern Sea Route (NSR) (Zhang and Baranzini, 2004; Pruyn, 2016; Zhang et al., 2016a; Zhang et al., 2016b; Milaković et al., 2018; Sui et al., 2021; Zhao et al., 2016). Container liner shipping has emerged as a primary research subject due to its pivotal role in global trade networks (Xu et al., 2011; Furuichi and Otsuka, 2013), followed by economic analyses of dry bulk carriers and tanker operations (Pruyn, 2016; Theocharis et al., 2018). Scholars typically employ evaluation metrics encompassing transit time, voyage distance, and comprehensive cost structures, with substantial evidence confirming the Arctic routes' significant cost advantages over the traditional Suez Canal Route (SCR) (Otsuka et al., 2013; Xu and Yin, 2021; Li et al., 2023). However, several studies indicate potential operational cost increases or uncertainties attributable to icebreaker escort fees and insurance premiums (Verny and Grigentin, 2009; Liu and Kronbak, 2010; Lasserre, 2014; Zhang et al., 2016a). Notably, extended navigable windows are revealing the economic potential of combined NSR-SCR routing models, potentially reconfiguring traditional economies of scale dynamics in global shipping (Furuichi and Otsuka, 2015). Methodologically, mainstream studies employ three-tier cost decomposition models (operational/voyage/capital costs) to quantify environmental variables' impacts (Theocharis et al., 2018), yet existing literature largely neglects internalization mechanisms for environmental externalities, particularly the economic effects of market-based instruments like carbon taxation.

Current Arctic shipping governance demonstrates marked asymmetry between academic consensus and regulatory implementation. While scholarly research has established clear consensus on environmental risks from shipping pollution (Liu and Kronbak, 2010; Pagano et al., 2012; Østreng et al., 2013; Furuichi and Otsuka, 2013; Lindstad et al., 2016; Yumashev et al., 2017; Zhu et al., 2018; Zhu et al., 2018; Makarova et al., 2021; Qi et al., 2024), policy responses lag behind operational realities. Although the Polar Code partially addresses environmental concerns through vessel technical standards (Liu, 2016), regulatory gaps persist – particularly the delayed implementation of Heavy Fuel Oil (HFO) restrictions until 2024 (IMO International Code for Ships Operating in Polar Waters (Polar Code), 2025) and absence of black carbon controls – revealing systemic limitations in current governance frameworks. This regulatory context elevates the strategic importance of carbon taxation as a Market-based measurement (MBM) instrument. Global carbon pricing practices demonstrate that carbon tax mechanisms in 35 countries already encompass 21.5% of global emissions, with maritime transport emerging as a new frontier – evidenced by EU's inclusion of shipping in carbon markets and IMO's legislative progress on global maritime carbon taxation (Harrison, 2010; Carl and Fedor, 2016). However, existing research inadequately addresses the coupling mechanisms between carbon taxation and Arctic route economics, particularly lacking systematic frameworks to analyze differential impacts of carbon pricing schemes on Arctic shipping cost structures. This knowledge gap hinders policymakers' ability to anticipate carbon taxation's constraining or optimizing effects on Arctic shipping development.

The impact of maritime carbon taxation on Arctic route economics demonstrates significant regulatory elasticity. As an environmental consumption tax levied on vessel operational emissions (Tiwari et al., 2021; Gao et al., 2022; Song et al., 2024), carbon pricing reshapes route selection decision models through cost transmission effects (Zhu et al., 2018; Joseph et al., 2021; Kavirathna et al., 2023). Studies indicate that uniform carbon taxation enables NSR to maintain economic advantages over SCR through voyage-shortening emission reductions that offset tax costs. Notably, current research predominantly focuses on micro-level operational analyses, lacking systematic modeling of carbon taxation's macro-level impacts - including strategic Arctic adjustments by maritime powers and carbon market interactions (Xiang et al., 2025). Particularly, the evolutionary mechanisms governing shipping behaviors under carbon constraints for key Arctic stakeholders remain underexplored, constituting a critical theoretical gap.

Existing evaluations of NSR economic viability reveal three critical limitations in well-to-wake (WtW) based assessments of environmental policy impacts: First, excessive focus on explicit operational costs (fuel consumption/canal fees) neglects implicit factors like fuel production/transport emissions and engine technological disparities, resulting in distorted carbon intensity calculations for alternative fuel systems like Liquified Natural Gas (LNG). Second, insufficient dynamic analysis of policy combination effects, particularly unresolved synergistic/

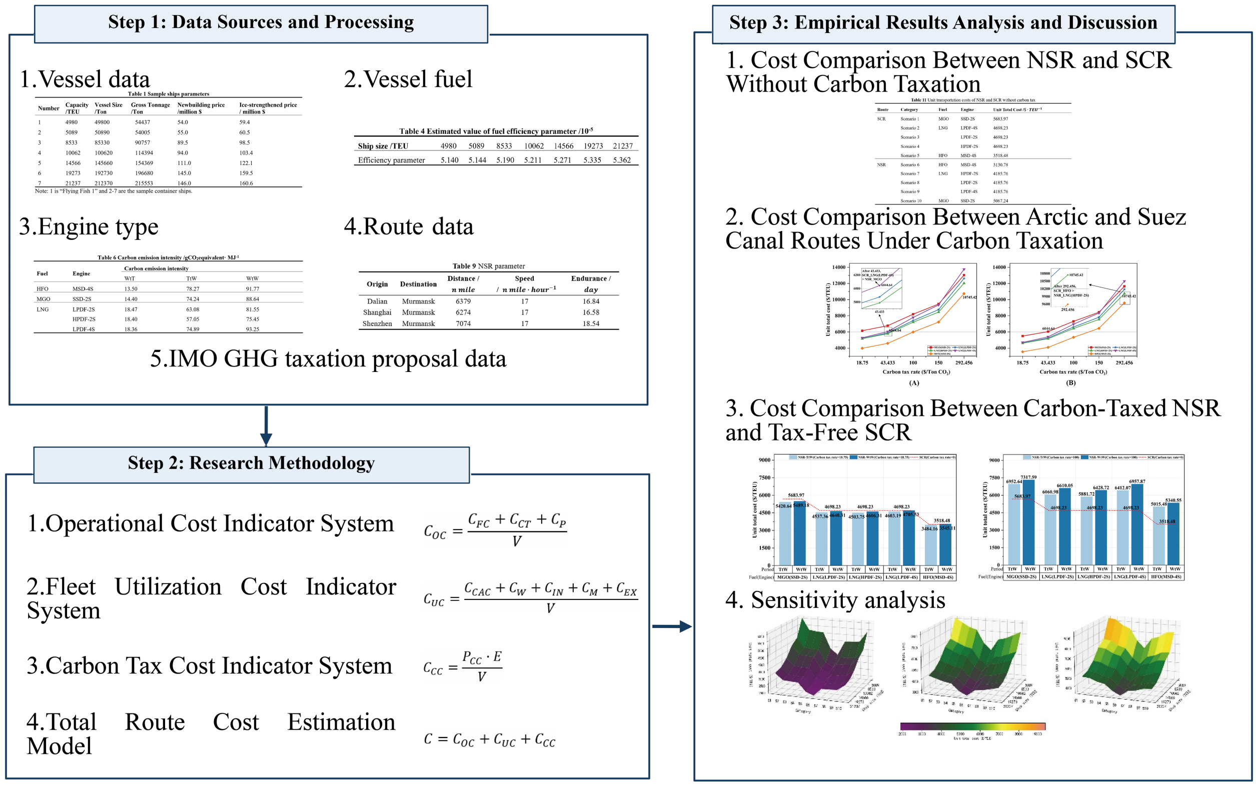


FIGURE 1
The framework of the study.

counteractive interactions between IMO's carbon tax proposals and Arctic HFO bans. Third, neglect of differential impacts of vessel infrastructure and logistics efficiency along the route on emissions from different fuel types. This study addresses these limitations through a WtW analytical framework that systematically reveals environmental policies' transmission mechanisms on NSR feasibility, with methodological innovations manifested in three dimensions:

1. Development of WtW Emission Assessment Framework: Overcomes the systemic boundary limitations of traditional Tank-to-Wake (TtW) analysis by integrating full-chain fuel production and transportation emissions data with engine technical parameters, establishing a precision measurement model for environmental benefits of alternative fuels in Arctic shipping.
2. Design of Policy Coupling Analysis Model: Employs multi-scenario simulations to reveal interactive effects between IMO's carbon tax schemes and Arctic HFO bans, quantifying impact pathways of environmental policy combinations on route economics.
3. Geospatial Differentiated Empirical Research: Case validation across China's three major hubs (Shanghai/Dalian/Shenzhen) demonstrates Shanghai Port's cost optimization through route operational maturity under carbon taxation, while Shenzhen Port maintains competitiveness via SCR advantages, uncovering synergistic mechanisms between geographical features and environmental policies.

This study establishes a comparative economic analysis framework between NSR and SCR using China's Dalian, Shanghai, Shenzhen ports and Russia's Murmansk Port as origin-destination pairs, implemented through three phases (see Figure 1): (1) Data Standardization Phase: Integrates vessel technical parameters (deadweight tonnage, speed), fuel data (price, efficiency), engine efficiency metrics (carbon emission intensity, coefficients), and route parameters (distance, toll fees) into a unified dataset. (2) Cost Modeling Phase: Develops a three-tier cost accounting system – operational costs (fuel, canal fees and port charges), fleet costs (capital, labor, maintenance), and carbon tax costs (TtW and WtW cycles) – ultimately calculating unit transportation costs ($/TEU). (3) Comparative Analysis Phase: Implements four scenarios – carbon tax-free baseline, differentiated carbon tax policies, NSR-specific taxation, and sensitivity testing (port and vessel size variations) – systematically revealing carbon taxation's impact mechanisms on route economics.

The remainder of this article is organized as follows: Section 2 outlines the economic assessment framework for Arctic shipping, focusing on core parameters and methodologies for evaluating capital costs, operational costs, and environmental externalities. Section 3 employs a cost-benefit model to quantitatively compare the lifecycle economic performance of vessels powered by HFO, LNG, and Marine Gas Oil (MGO) on the NSR versus SCR,

TABLE 1 Sample ships parameters.

Number	Capacity /Ton	Vessel Size /Ton	Gross Tonnage /Ton	Newbuilding price /million $	Ice-strengthened price / million $
1	4980	49800	54437	54.0	59.4
2	5089	50890	54005	55.0	60.5
3	8533	85330	90757	89.5	98.5
4	10062	100620	114394	94.0	103.4
5	14566	145660	154369	111.0	122.1
6	19273	192730	196680	145.0	159.5
7	21237	212370	215553	146.0	160.6

1 is "Flying Fish 1" and 2–7 are the sample container ships.

elucidating the mechanisms through which policy interventions shape route competitiveness. Section 4 conducts scenario-based sensitivity analyses to assess the marginal effects of dynamic factors, including ice-class upgrades, energy price volatility, and carbon trading mechanisms, on investment decisions. Finally, Section 5 synthesizes the findings, proposes tailored recommendations for stakeholders, and identifies future research directions for low-carbon transitions in Arctic shipping. For ease of understanding, Appendices A and B have been added in this article to facilitate the reference of the meanings of symbols and abbreviations.

2 Data sources and research methodology

2.1 Data sources and processing

This study draws on comprehensive data from academic databases, industry reports, and public datasets, focusing on vessel operational parameters for the NSR and SCR from 2011 to 2024. The dataset encompasses critical operational metrics including voyage distance, sailing speed, fuel consumption, and carbon emissions, with a particular focus on container ships of varying capacities. Data processing follows a standardized three-stage workflow: (1) harmonizing vessel capacity units across different ship types to ensure cross-class comparability, (2) imputing missing values through validated statistical models based on historical data patterns, and (3) developing a unified unit transportation cost calculation framework that enables systematic economic comparisons between routes under varying environmental policy scenarios.

2.1.1 Vessel data

Container ships were selected as the analytical focus due to their optimal operational flexibility and efficiency for long-haul routes. Given the significant impact of vessel capacity on economic performance, the sample capacity range was established at 5,000–24,000 TEU—the lower bound aligns with minimum transoceanic transport requirements, while the upper limit corresponds to the Suez Canal's maximum recorded vessel transit capacity. The sample includes six COSCO Shipping mainstream vessel types spanning this capacity range, complemented by the Arctic-experienced "Flying Fish 1" vessel. Arctic navigation necessitates ice-class vessels, whose construction standards significantly influence economic viability. This study assumes NSR operations employ Arc4 ice-class vessels (approximately 10% costlier than conventional ships (Erikstad and Ehlers, 2012)), while SCR utilizes standard vessel types (Table 1). Arc4-certified vessels are engineered to navigate through ice with a maximum thickness of 0.6 meters during winter/spring and 0.8 meters during summer/autumn, requiring reinforced hulls, enhanced propulsion systems, and specialized equipment to ensure safe navigation in seasonal ice conditions (Gong, 2017). This classification balances ice navigability and construction costs: Arc4-class ships satisfy basic Arctic transit requirements while demonstrating superior per-voyage cost-saving advantages through route shortening (Pruyn and Van Hassel, 2022). Crew allocation complies with China's Minimum Safe Manning Regulations for Ships, requiring a minimum of 19 personnel for oceangoing vessels (7 deck officers, 10 engine department staff, 2 service crew). Per-voyage labor costs are calculated based on total monthly crew salaries, with position-specific wages benchmarked against the Shanghai Shipping Exchange's International Seafarer Salary Index (Table 2).

2.1.2 Vessel fuel

The study examines three primary marine fuel types: HFO, MGO, and LNG. Industry data indicates LNG dual-fuel vessels account for 70% of newbuild orders in 2024, reflecting the maritime industry's accelerating decarbonization trends (Park et al., 2024). The analysis assumes all sample vessels possess multi-fuel compatibility (HFO/MGO/LNG), with retrofit costs excluded to maintain model consistency. Fuel price parameters follow standardized calculation methods (see Table 3): LNG and HFO costs utilize Ding et al.'s (Ding et al., 2020) model validated against International Energy Agency policy scenarios, while MGO pricing references the 2025 week 3 Marine Bunker Exchange index. Fuel efficiency parameters demonstrate significant capacity-dependent characteristics, a correlation substantiated by Notteboom et al (Notteboom and Vernimmen, 2009), with specific values detailed in Table 4.

TABLE 2 Seamen's monthly salary.

Number	Job	Salary /$	Count
1	Captain	10384	1
2	First mate	8551	1
3	Second mate	5572	1
4	Third mate	5266	1
5	Chief engineer	9910	1
6	First engineer	8534	1
7	Second engineer	5561	1
8	Third engineer	5228	1
9	Electrical engineer	5496	1
10	Boatswain	2858	2
11	Crew chief	2864	1
12	Sailor	2519	1
13	Machinist	2519	2
14	Electrician	3611	2
15	Chef	2679	1
16	Steward	1396	1

2.1.3 Engine types

Engine technologies significantly influence carbon emission profiles through variations in combustion characteristics. LNG-fueled vessels equipped with low-pressure dual-fuel engines (LPDF-4S/LPDF-2S) exhibit higher methane slip compared to high-pressure dual-fuel engines (HPDF-2S), yet existing research frequently overlooks this technological disparity, leading to systematically biased assessments of LNG's environmental benefits. Concurrently, medium-speed four-stroke engines (MSD-4S) using HFO generate higher CO_2 concentrations and exhaust temperatures than slow-speed two-stroke engines (SSD-2S) utilizing MGO. This thermodynamic variation directly impacts carbon emission intensity calculations through Oh's (Oh et al., 2024) fuel consumption-emission correlation model (Tables 5-7). The research reveals that neglecting engine-specific technological features introduces systematic biases in carbon emission cost evaluations. Methane slip—the phenomenon where unburned methane (CH_4) is directly emitted during LNG engine operation—occurs particularly in low-pressure dual-fuel four-stroke engines due to incomplete combustion or system leakage (Oh et al., 2024), significantly undermining LNG's greenhouse gas reduction potential.

2.1.4 Route data

This study establishes a comparative framework for NSR and SCR between Asia and Europe using Dalian, Shanghai, and Shenzhen ports in China alongside Murmansk Port in Russia. The selection rationale is as follows: Murmansk serves as the NSR core hub with year-round navigability and 10-million-ton throughput capacity; Shanghai Port, an international shipping nexus, handles over 50 million TEUs annually; Dalian Port manages 97% of Northeast China's foreign trade container volume, functioning as a regional economic gateway; Shenzhen Port demonstrates southern China's maritime vitality through 265 international routes and 13% foreign trade growth. The geographical and functional diversity of these four ports provides a multidimensional basis for route economic comparisons. Port cost calculations adopt a dual framework of handling and pilotage fees: Chinese ports follow the Ministry of Transport Port Charging Rules (Foreign Trade Section) (handling fee: $ 61/TEU; pilotage fee: $ 0.075 per freight ton), while Murmansk's fees are set at $ 100/TEU for handling (Furuichi and Otsuka, 2013) and $ 0.065 per freight ton for pilotage based on existing studies.

Route comparisons reveal SCR's ice-free advantage ensures operational efficiency, whereas NSR's ice-covered segments necessitate speed reduction, potentially increasing fuel consumption and operational costs despite shorter distances (voyage distance differences detailed in Table 8). Speed parameters are set using industry benchmarks: SCR speeds reference Clarksons' 2024 annual average for container ships, while NSR speeds are calibrated to ice navigation characteristics at 17 knots (typical range: 13–25 knots). Complete technical parameter configurations for both routes are detailed in Table 9. SCR transit fees employ a progressive surcharge system based on net tonnage, with differentiated rates by vessel type and gross tonnage. Following Furuichi et al.'s methodology (Furuichi and Otsuka, 2013), this study substitutes gross tonnage for net tonnage in calculations, reflecting the fee structure's inherent characteristic: unit rates decrease with increasing gross tonnage for same-type vessels. Specific fee standards are derived from official Suez Canal Authority data (see Table 10).

TABLE 3 Different fuel unit prices /$ Ton^{-1}.

Classification	Price	Classification	Price	Classification	Price
MGO	802.83	HFO	477.13	LNG	654.57

TABLE 4 Estimated value of fuel efficiency parameter /10^{-5}.

Ship size /TEU	4980	5089	8533	10062	14566	19273	21237
Efficiency parameter	5.140	5.144	5.190	5.211	5.271	5.335	5.362

TABLE 5 Lower calorific values for fossil fuels /MJ g^{-1}.

Fuel	Lower calorific values	Fuel	Lower calorific values	Fuel	Lower calorific values
MGO	0.0427	LNG	0.0500	HFO	0.0405

2.1.5 IMO GHG taxation proposal data

The IMO has proposed a three-tier carbon tax framework: \$18.75 per ton CO_2e (International Chamber of Shipping proposal), \$100 per ton CO_2e (EU-Japan coalition proposal), and \$150 per ton CO_2e (Small Island States proposal). This proposal introduces a Well-to-Wake (WtW) lifecycle accounting methodology, dividing emissions into fuel production and transportation (Well-to-Tank, WtT) and vessel utilization (Tank-to-Wake, TtW) phases. The framework mandates taxation coverage for full lifecycle emissions of CO_2, CH_4, and N_2O, representing a significant advancement beyond current research predominantly limited to TtW analyses.

2.2 Operational cost indicator system construction

Operational costs encompass all expenses incurred during vessel navigation, primarily including fuel cost C_{FC}, canal transit fee C_{CT}, and port usage fee C_P. Accounting for variations across vessel types and routes, this study models the unit TEU operational cost C_{OC} through Equation 1:

$$C_{OC} = \frac{C_{FC} + C_{CT} + C_P}{V} \tag{1}$$

The specific calculation methodologies for each cost component are developed as follows.

2.2.1 Fuel cost estimation methodology

The unit TEU fuel cost C_{FC} for both routes is modeled as Equation 2:

$$C_{FC} = \frac{P \cdot Q}{V} \tag{2}$$

where P denotes fuel price, Q represents total fuel consumption for the entire voyage, and V indicates vessel container capacity (TEU). Total fuel consumption Q is modeled as Equation 3:

$$Q = \alpha \cdot \delta \cdot \sqrt{U} \cdot S^3 \cdot T \tag{3}$$

where α is the adjustable fuel consumption coefficient for the route ($\alpha_{SCR} = 1$, $\alpha_{NSR} = 1.3$ accounting for ice-class vessels' 30% higher daily fuel consumption), δ represents the fuel efficiency parameter, U denotes vessel size, S is average sailing speed, T signifies total voyage time. The relationship between fuel consumption and speed is derived from Ding's modeling assumption (Ding et al., 2020).

2.2.2 Canal transit fee estimation methodology

Canal transit fee C_{CT} varies by route selection: NSR incurs icebreaking service fees, while SCR involves canal transit charges. The SCR per-voyage canal fee C_T is modeled as Equation 4:

$$C_T = scnf \cdot GT \tag{4}$$

where $scnf$ denotes the progressive surcharge rate, and GT represents the vessel's gross tonnage transiting the Suez Canal. Thus, SCR's unit TEU canal transit fee C_{CT} is expressed as Equation 5:

$$C_{CT} = \frac{C_T}{V} \tag{5}$$

According to the Northern Sea Route Administration (NSRA) access rules, NSR-transiting vessels require icebreaking services with associated fees. Given NSR's high summer utilization, this study adopts Ding's assumption of a summer icebreaking fee rate of \$5/ton (Ding et al., 2020). NSR's unit TEU canal transit fee C_{CT} is formulated as Equation 6:

$$C_{CT} = \frac{C_{PB}}{V} \tag{6}$$

where C_{PB} denotes the per-voyage icebreaking service fee for NSR.

2.2.3 Port fee estimation methodology

All ports calculate cargo handling and pilotage fees using fixed rates. The unit TEU port fee C_P is modeled as Equation 7:

TABLE 6 Carbon emission intensity /gCO_2 equivalent MJ^{-1}.

Fuel	Engine	Carbon emission intensity		
		WtT	TtW	WtW
HFO	MSD-4S	13.50	78.27	91.77
MGO	SSD-2S	14.40	74.24	88.64
LNG	LPDF-2S	18.47	63.08	81.55
	HPDF-2S	18.40	57.05	75.45
	LPDF-4S	18.36	74.89	93.25

TABLE 7 Carbon emission parameter /gCO_2 equivalent $gfuel^{-1}$.

Fuel	Engine	Carbon emission parameter		
		WtT	TtW	WtW
HFO	MSD-4S	0.54675	3.169935	3.716685
MGO	SSD-2S	0.61488	3.170048	3.784928
LNG	LPDF-2S	0.9235	3.154	4.0775
	HPDF-2S	0.92	2.8525	3.7725
	LPDF-4S	0.918	3.7445	4.6625

TABLE 8 Distance from China port to Murmansk Port NSR and SCR nautical miles /n mile.

Origin	Destination	Route		Nautical miles difference
		SCR	NSR	
Dalian	Murmansk	12429	6379	6050
Shanghai	Murmansk	11985	6274	5711
Shenzhen	Murmansk	11332	7074	4258

SCR nautical miles come from China Maritime Service Network, NSR nautical miles is obtained through Google map distance measurement.

$$C_P = C_{TF} + C_L \tag{7}$$

where C_{TF} denotes the unit TEU pilotage fee and C_L represents the unit TEU cargo handling fee.

2.3 Fleet utilization cost indicator system construction

Fleet utilization costs encompass all expenses for maintaining daily operations, primarily including capital cost C_{CAC}, crew wages C_W, vessel insurance C_{IN}, maintenance C_M, and other expenses C_{EX}. This study models the unit TEU fleet utilization cost C_{UC} as Equation 8:

$$C_{UC} = \frac{C_{CAC} + C_W + C_{IN} + C_M + C_{EX}}{V} \tag{8}$$

The specific calculation methodologies for each cost component are modeled as follow.

2.3.1 Capital cost estimation methodology

Capital costs originate from vessel depreciation. According to the Baltic and International Maritime Council (BIMCO) latest market report, nearly 70% of container ships have been in service for over a decade. With China's shipping fleet ranking third among global top-ten ship-owning nations by gross tonnage and maintaining an average vessel age of 10.2 years, this study assumes a 10-year average vessel lifespan. Annual capital cost per vessel C_{CCY} is estimated as one-tenth of newbuild prices C_{NB}, see Equation 9:

$$C_{CCY} = \frac{C_{NB}}{10} \tag{9}$$

This 10-year vessel lifespan assumption aligns with industry trends reported by BIMCO and simplifies depreciation calculations for consistent comparison with prior studies (Furuichi and Otsuka, 2013). However, this approach may not fully capture operational variability such as maintenance practices and market-driven retirements or regulatory shifts affecting lifespan constraints. Annual voyage frequency is derived from voyage time T, enabling the allocation of C_{CCY} to individual voyages and subsequent averaging per TEU, yielding the capital cost per TEU per voyage C_{CAC}, see Equation 10:

$$C_{CAC} = \frac{C_{CCY}}{V \cdot \frac{365}{T}} = \frac{T \cdot C_{NB}}{10 \cdot 365 \cdot V} \tag{10}$$

2.3.2 Crew cost estimation methodology

Crew wages encompass base salaries, allowances, bonuses, and social benefits. Referencing the Shanghai Shipping Exchange's International Seafarer Salary Index, the unit TEU crew cost C_W is modeled as Equation 11:

$$C_W = \frac{\sum_{i=1} crew_{salaries-i} \cdot crew_{counts-i}}{V} \tag{11}$$

where $crew_{salaries-i}$ denotes the monthly salary for the i-th position, and $crew_{counts-i}$ represents the number of crew members in the i-th position.

2.3.3 Insurance cost estimation methodology

Maritime navigation faces various risks including severe weather, piracy, and collisions. Annual insurance costs are assumed to equal 1% of the newbuild price C_{NB} (Furuichi and Otsuka, 2013). This cost is allocated across the vessel's operational lifespan and averaged per TEU, as shown in Equation 12:

$$C_{IN} = \frac{C_{NB} \cdot 1\% \cdot T}{10 \cdot 365 \cdot V} \tag{12}$$

2.3.4 Vessel maintenance cost estimation methodology

Regular inspections (annual, biennial, and quinquennial) are critical for maritime safety. Maintenance costs are estimated at 3% of C_{NB} (Wang, 2019), annually allocated and averaged per TEU, as shown in Equation 13:

TABLE 9 SCR parameter and NSR parameter.

Route	Origin	Destination	Distance /n mile	Speed /n mile ·hour^{-1}	Endurance /day
SCR	Dalian	Murmansk	12429	15.24	33.98
	Shanghai	Murmansk	11985	15.24	32.77
	Shenzhen	Murmansk	11332	15.24	30.98
NSR	Dalian	Murmansk	6379	17	16.84
	Shanghai	Murmansk	6274	17	16.58
	Shenzhen	Murmansk	7074	17	18.54

TABLE 10 Suez Canal tolls /$ GT^{-1}.

Gross tonnage/Ton	First 5000	Second 5000	Third 10000	Forth 20000	Fifth 30000	Sixth 50000	The rest
Suez Canal toll rates	11.04	7.58	5.89	4.13	3.82	3.01	2.88

$$C_M = \frac{C_{NB} \cdot 3\,\% \cdot T}{10 \cdot 365 \cdot V} \tag{13}$$

2.3.5 Other utilization cost estimation methodology

Vessel operations incur additional expenses including corporate administration and management costs. These costs are estimated at 2% of the newbuild price C_{NB} (Wang, 2019), as shown in Equation 14:

$$C_{EX} = \frac{C_{NB} \cdot 2\,\% \cdot T}{10 \cdot 365 \cdot V} \tag{14}$$

2.4 Carbon tax cost indicator system construction

Carbon taxation levies fees on vessel emissions proportional to transportation-related carbon output. The unit TEU carbon tax C_{CC} is modeled as Equation 15:

$$C_{CC} = \frac{P_{CC} \cdot E}{V} \tag{15}$$

where P_{CC} denotes the carbon tax rate, and E represents total carbon emissions, expressed as Equation 16:

$$E = GHG \cdot \varepsilon \cdot Q \tag{16}$$

where GHG signifies carbon emission intensity, and ε denotes fuel calorific value.

2.4.1 TtW carbon emission estimation methodology

Existing research predominantly focuses on carbon emissions from fuel combustion during transportation (TtW phase). Following Oh's study (Oh et al., 2024), the TtW carbon emission intensity GHG_{TtW} varies by fuel type, the calculation method is shown as Equations 17, 18:

$$GHG_{TtW}[HFO, LFO] = \frac{\sum_i^n \sum_j^m (Q_{i,j} \cdot (C_{fCH_4,i} \cdot GWP_{CH_4} + C_{fN_2O,i} \cdot GWP_{N_2O}) + CO_{2,generated,j})}{\sum_i^n (Q_i \cdot LCV_i)} \tag{17}$$

$$GHG_{TtW}[LNG] = \frac{\sum_i^n \sum_j^m (Q_{i,j} \cdot (C_{fCH_4,i} \cdot GWP_{CH_4} + C_{fN_2O,i} \cdot GWP_{N_2O}) + CO_{2,generated,j}) + CH_{4,slip}}{\sum_i^n (Q_i \cdot LCV_i)} \tag{18}$$

where Q_i denotes the fuel consumption of fuel i, $Q_{i,j}$ represents the fuel consumption of fuel i in energy converter j, LCV_i is the lower calorific value of fuel i, C_f refers to the TtW greenhouse gas emission factor for methane emissions associated with petroleum fuels, GWP stands for global warming potential, and $CO_{2,generated,j}$ indicates the CO_2 emissions generated by energy converter j.

2.4.2 WtW carbon tax cost estimation methodology

Unlike TtW calculations, WtW accounting encompasses full fuel lifecycle emissions. The full lifecycle carbon emission intensity GHG_{WtW} is derived as the sum of WtT and TtW emissions, the calculation method is shown as Equations 19, 20:

$$GHG_{WtW} = GHG_{WtT} + GHG_{TtW} \tag{19}$$

$$GHG_{WtT} = \frac{\sum_i^n (Q_i \cdot CO_{2eq\ WtT,i} \cdot LCV_i)}{\sum_i^n (Q_i \cdot LCV_i)} \tag{20}$$

where GHG_{WtT} represents the WtT carbon emission intensity, and $CO_{2eq\ WtT,i}$ denotes the WtT greenhouse gas emission factor for fuel i, expressed in CO_2 equivalent terms.

2.5 Total route cost estimation model construction

Integrating operational and utilization costs, the unit transportation cost C without carbon taxation is expressed as Equation 21:

$$C = C_{OC} + C_{UC} \tag{21}$$

Under carbon taxation, the unit transportation cost C becomes (as shown in Equation 22):

$$C = C_{OC} + C_{UC} + C_{CC} \tag{22}$$

3 Empirical results analysis and discussion

3.1 Cost comparison between NSR and SCR without carbon taxation

Under carbon tax-free conditions, NSR and SCR exhibit significant fuel-specific economic disparities (Table 11). The cost hierarchy follows HFO< LNG< MGO, driven by fuel market price gradients: HFO maintains cost advantages through its lower market price, though its high carbon intensity would become an economic liability under environmental cost internalization. MGO incurs the highest operational costs due to refining expenses, though its low-carbon advantages emerge progressively under carbon taxation. LNG

TABLE 11 Unit total cost of NSR and SCR without carbon taxation.

Route	Category	Fuel	Engine	Unit Total Cost /$ ·TEU^{-1}	Unit Total Cost (without capital costs) /$ ·TEU^{-1}
SCR	Scenario 1 (S1)	MGO	SSD-2S	5683.97	5583.02
	Scenario 2 (S2)	LNG	LPDF-4S	4698.23	4597.28
	Scenario 3 (S3)		LPDF-2S	4698.23	4597.28
	Scenario 4 (S4)		HPDF-2S	4698.23	4597.28
	Scenario 5 (S5)	HFO	MSD-4S	3518.48	3417.53
NSR	Scenario 6 (S6)	HFO	MSD-4S	3130.78	3075.75
	Scenario 7 (S7)	LNG	HPDF-2S	4185.76	4130.73
	Scenario 8 (S8)		LPDF-2S	4185.76	4130.73
	Scenario 9 (S9)		LPDF-4S	4185.76	4130.73
	Scenario 10 (S10)	MGO	SSD-2S	5067.24	5012.21

occupies an intermediate position, balancing environmental benefits with moderate operational costs, though upstream emissions and methane slip require careful consideration in lifecycle assessments.

With identical fuel configurations, NSR demonstrates superior unit transportation costs through voyage-shortening advantages: reduced sailing durations enhance fleet turnover efficiency while decreasing fuel consumption and emissions. However, the IMO's 2024 Arctic HFO ban compels NSR vessels to adopt cleaner fuels, substantially increasing operational costs. In contrast, SCR retains cost competitiveness through continued HFO utilization in tax-free conditions. Carbon taxation implementation fundamentally alters this dynamic—by internalizing environmental externalities, SCR's HFO advantages gradually diminish, while NSR's clean fuel transition evolves into a long-term competitive advantage, demonstrating synergistic effects between environmental regulation and market mechanisms.

The last column in Table 11 reveals unit transportation costs excluding capital costs for both routes. The data demonstrates that capital costs represent a fixed expense with notable differences in unit allocation between routes: SCR's capital cost is $100.95/TEU while NSR's is significantly lower at $55.03/TEU. This disparity primarily stems from voyage duration differences: SCR's longer transit times and fewer annual voyages result in weaker cost distribution capacity and higher unit capital costs, leading to more substantial cost reductions when capital expenses are excluded. In contrast, NSR's shorter voyages and higher annual frequency enable more efficient cost distribution, resulting in lower unit capital costs and consequently smaller impact when these costs are removed. Nevertheless, even after excluding capital costs, NSR maintains considerable economic advantages over SCR, confirming that its competitiveness extends beyond capital cost efficiencies.

3.2 Cost comparison between NSR and SCR under carbon taxation

3.2.1 Carbon tax calculation based on TtW

TtW cycle cost analysis under varying carbon tax levels ($18.75/$100/$150 per ton of CO_2 equivalent) reveals that SCR consistently incurs higher unit transportation costs than NSR with identical fuel configurations, primarily due to SCR's extended voyage distances increasing fuel consumption (Figure 2). When tax rates fall below $61.01 per ton of CO_2 equivalent, HFO maintains optimal economic viability through price advantages. However, constrained by the Arctic HFO ban, SCR using HFO emerges as the de facto lowest-cost option, remaining cheaper than NSR's LNG/MGO alternatives. As rates rise to $61.01 per ton of CO_2 equivalent, SCR's high-emission LNG engine costs surpass NSR's MGO usage, indicating NSR's environmental advantages from cleaner fuels gradually translate into economic competitiveness. At rates exceeding $162.105 per ton of CO_2 equivalent, SCR's HFO costs are overtaken by NSR's low-emission LNG engines, though MGO and high-emission LNG options still lack cost advantages, demonstrating a threshold effect in carbon taxation's suppression of high-carbon fuels. Notably, even at $287.155 per ton of CO_2 equivalent, NSR's MGO and high-emission LNG solutions remain costlier than SCR's HFO, underscoring the necessity to balance environmental objectives with maritime economic realities in policy design.

3.2.2 Carbon tax calculation based on WtW

Under the WtW lifecycle perspective, varying carbon tax levels ($18.75/$100/$150 per ton of CO_2 equivalent) exert distinct impacts on route economics (as shown in Figure 3). With identical fuel configurations, SCR's unit transportation costs persistently exceed NSR's, consistent with TtW cycle conclusions, but fuel-specific economic rankings undergo structural shifts. LNG's WtW tax costs rise significantly due to high upstream production and transport emissions (24.5–32.25% higher than TtW phase), eroding its economic advantages. In contrast, HFO and MGO exhibit smaller WtW emission increments (17.25% and 19.4%), maintaining more stable cost profiles.

When tax rates remain below $43.433 per ton of CO_2 equivalent, HFO retains optimal economic viability, yet SCR using HFO becomes the practical low-cost option under Arctic HFO ban constraints. As rates reach $43.433 per ton of CO_2 equivalent, SCR's high-emission LNG solutions are surpassed by

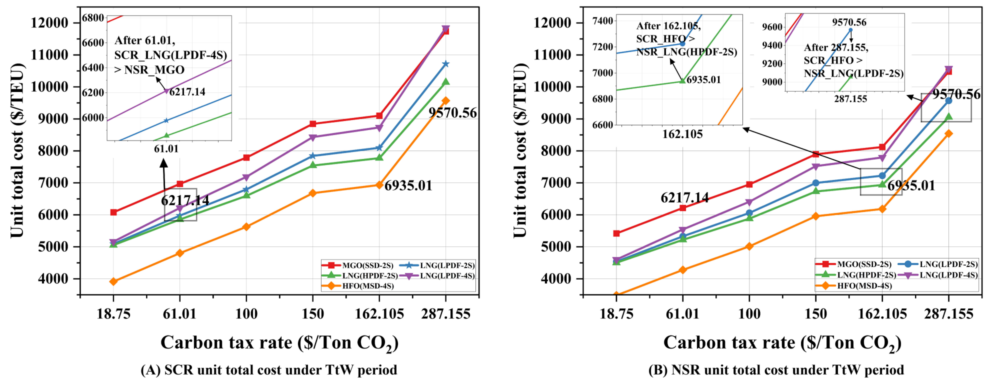


FIGURE 2
(A, B) Unit total cost under TtW period.

NSR's MGO applications, marking the transition of environmental advantages into economic competitiveness. Notably, under IMO's maximum tax rate ($150 per ton of CO_2 equivalent), NSR still fails to outperform SCR's HFO-based economics. Only when rates escalate to $292.456 per ton of CO_2 equivalent does NSR's low-emission LNG strategy demonstrate cost superiority, exposing the limited incentivizing effect of current carbon tax schemes on Arctic route adoption.

3.2.3 Impact of carbon emissions from fuel production based on WtW carbon tax calculations

The previous section presented detailed calculations of full lifecycle fuel emissions, including the production phase. However, since carbon taxation policies may not always encompass fuel production stages, analyzing emissions excluding this phase becomes necessary. This section compares the economic viability of SCR and NSR based on adjusted emission data. According to Pavlenko et al (Pavlenko and Bryan, 2020), the LNG liquefaction process contributes 30-60% of emissions in the WtT phase, with the remaining emissions primarily originating from production activities. Based on these findings, this study adopts 50% as the proportion of LNG production-related emissions within the WtT phase. For MGO and HFO fuels, which do not require liquefaction processing, production activities constitute a larger share of WtT emissions, estimated at 80% in this research. Table 12 presents the carbon emission coefficients for various fuels after excluding the production phase.

Experimental results in Table 13 demonstrate that removing the fuel production phase reduces unit transportation costs across all scenarios, with cost differentials for identical fuel types widening as carbon tax rates increase. Carbon tax costs are influenced by the combined effects of fuel consumption, fuel price, and carbon emission coefficients (derived from emission volumes). Different fuel types exhibit distinct characteristics: though HFO has a high proportion of production emissions removed (80%), its inherently low WtT emissions result in limited changes to carbon tax costs; MGO, despite relatively low WtT emissions, shows the largest carbon tax cost variations due to its high price; LNG, with moderate pricing but substantial WtT emissions, exhibits significant emission reductions when production emissions are excluded, yielding considerable carbon tax cost decreases. Comparing SCR and NSR routes, the impact of removing production emissions on costs is relatively similar proportionally.

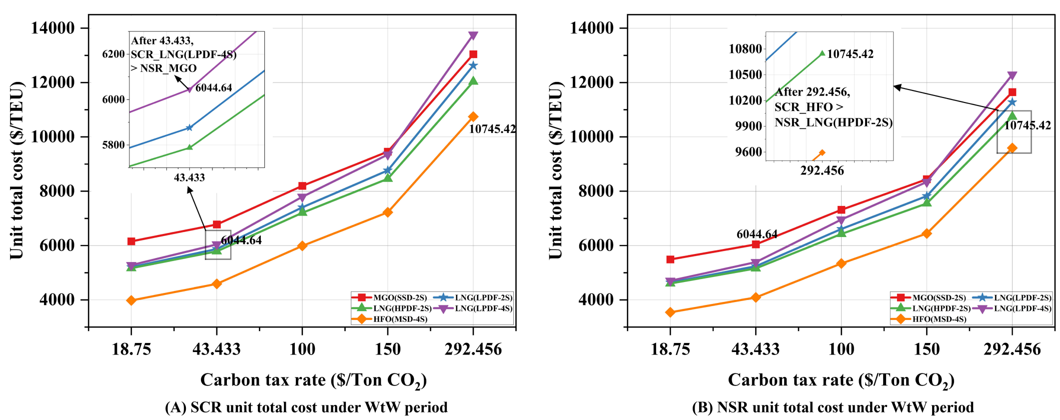


FIGURE 3
(A, B) Unit total cost under WtW period.

TABLE 12 Carbon emission parameter without production stage /gCO2 equivalent gfuel^{-1}.

Fuel	Engine	Carbon emission parameter		
		WtT	TtW	WtW
HFO	MSD-4S	0.32805	3.169935	3.497985
MGO	SSD-2S	0.36893	3.170048	3.538978
LNG	LPDF-2S	0.5541	3.154	3.7081
	HPDF-2S	0.552	2.8525	3.4045
	LPDF-4S	0.5508	3.7445	4.2953

Consequently, NSR maintains significant cost advantages that remain robust across various scenarios, demonstrating the consistency of its economic benefits regardless of emission accounting methodologies.

3.3 Cost comparison between carbon-taxed NSR and tax-free SCR

3.3.1 Carbon tax calculation based on TtW

Unilateral carbon taxation on NSR creates significant economic disparities compared to the tax-exempt SCR (Figure 4 and Table 14). At low tax rates, NSR maintains competitiveness through its shorter voyage distance advantage. However, this advantage systematically erodes as carbon tax rates increase, with a clear progression of economic tipping points for different fuel types. The economic viability thresholds reveal a distinct hierarchy of fuel sensitivity to carbon taxation. HFO loses its economic advantage first at just \$20.57 per ton of CO_2 equivalent, demonstrating its high vulnerability to carbon taxation due to elevated emission intensity. LNG follows with engine-specific thresholds: high-emission engines (\$23.02), medium-emission engines (\$27.33), and low-emission engines (\$30.22) per ton of CO_2 equivalent. MGO demonstrates the greatest resilience, maintaining economic viability until reaching \$32.73 per ton of CO_2 equivalent.

This sequenced transition highlights the varying policy sensitivity across marine fuel technologies, with HFO exhibiting the greatest economic fragility under carbon taxation, while MGO offers superior policy resilience despite higher initial costs. Despite these thresholds, the IMO Arctic HFO ban creates a regulatory paradox: NSR vessels must use cleaner fuels (MGO/LNG), but even at the IMO's maximum proposed carbon tax rate (\$150 per ton of CO_2 equivalent), these environmentally preferable options cannot economically compete with SCR's untaxed HFO operations. This regulatory asymmetry undermines the intended decarbonization incentives of both policies.

3.3.2 Carbon tax calculation based on WtW

Expanding the analysis to include full lifecycle emissions (WtW) reveals two significant shifts in the economic dynamics between NSR and SCR under asymmetric carbon taxation (as shown in Table 15): First, the economic viability thresholds universally decrease by 23-28% compared to TtW calculations. HFO's critical point drops to \$17.55 per ton of CO_2 equivalent. LNG engines show graduated reductions: high-emission (\$18.49), medium-emission (\$21.14), and low-emission (\$22.85) per ton of CO_2 equivalent. MGO's threshold decreases to \$27.41 per ton of CO_2 equivalent. This systematic reduction in viability thresholds demonstrates that WtW accounting accelerates the economic impact of carbon taxation by internalizing previously excluded upstream emissions.

Second, LNG's economic profile deteriorates significantly under WtW accounting. Most notably, at \$506.75 per ton of CO_2 equivalent, medium-emission LNG engine costs exceed MGO solutions—a crossover that does not occur in TtW calculations. This reveals LNG's particular vulnerability to comprehensive emissions accounting due to its substantial upstream emissions during production and transportation phases, whereas MGO maintains relatively greater policy resilience with more modest full-cycle emission increments (19.4% above TtW).

While WtW analysis generally reinforces TtW trends, it exposes a fundamental contradiction in current environmental policy design: carbon taxation alone creates insufficient alignment between environmental and economic incentives for LNG adoption. The analysis demonstrates that effective environmental policy for Arctic shipping requires a coordinated approach combining carbon taxation with targeted technological standards to address specific challenges like methane slip in LNG engines.

3.4 Cost comparison with navigation condition changing based on WtW

Given the trend of decreasing summer sea ice coverage in Arctic waters, several assumptions in previous calculations warrant reassessment (see Table 16). These include the necessity of ice-class vessels, icebreaker assistance requirements, elevated fuel consumption factors, and speed restrictions. More critically, with continued global warming, these assumptions may become obsolete by 2030, 2035, or beyond. This section reconstructs the calculation model by eliminating all these restrictive assumptions to provide a more comprehensive and objective assessment of NSR's long-term economic viability compared to SCR.

As greenhouse effects continue to accelerate Arctic sea ice retreat, multiple studies indicate that NSR's navigational conditions will gradually approach those of SCR, potentially eliminating the need for ice-class vessels and icebreaker support (Pastusiak, 2020; Li et al., 2021). Based on this premise, this section evaluates the impact on NSR transportation costs (see Table 16). Analysis shows that removing the ice-class vessel requirement reduces NSR unit transportation costs by a fixed \$5.3/TEU, enhancing its economic advantage. However, this impact remains relatively limited, primarily because the additional costs of ice-class vessels are effectively distributed through NSR's higher annual voyage frequency, contributing minimally to unit costs. More

TABLE 13 Impact of carbon emissions from fuel production based on WtW carbon tax calculations.

Carbon tax rate /$ ·(Ton CO_2)$^{-1}$	Route	Fuel	Engine	Unit Total Cost (without production stage) /$ ·TEU^{-1}	Unit Total Cost /$ · TEU^{-1}
18.75	SCR	MGO	SSD-2S	6120.04	6155.81
		LNG	LPDF-2S	5160.49	5206.55
			HPDF-2S	5122.65	5168.52
			LPDF-4S	5233.70	5279.47
		HFO	MSD-4S	3959.66	3981.82
	NSR	MGO	SSD-2S	5457.20	5489.18
		LNG	LPDF-2S	4599.13	4640.31
			HPDF-2S	4565.29	4606.31
			LPDF-4S	4664.59	4705.53
		HFO	MSD-4S	3525.30	3545.11
100	SCR	MGO	SSD-2S	8009.68	8200.46
		LNG	LPDF-2S	7163.64	7409.25
			HPDF-2S	6961.79	7206.46
			LPDF-4S	7554.05	7798.20
		HFO	MSD-4S	5871.45	5989.60
	NSR	MGO	SSD-2S	7146.99	7317.59
		LNG	LPDF-2S	6390.43	6610.05
			HPDF-2S	6209.92	6428.72
			LPDF-4S	6739.55	6957.87
		HFO	MSD-4S	5234.90	5340.55
150	SCR	MGO	SSD-2S	9172.54	9458.71
		LNG	LPDF-2S	8396.35	8764.75
			HPDF-2S	8093.56	8460.57
			LPDF-4S	8981.97	9348.18
		HFO	MSD-4S	7047.93	7225.16
	NSR	MGO	SSD-2S	8186.86	8442.76
		LNG	LPDF-2S	7492.76	7822.20
			HPDF-2S	7222.00	7550.19
			LPDF-4S	8016.44	8343.92
		HFO	MSD-4S	6286.95	6445.44

significantly, eliminating icebreaker fees reduces NSR route unit transportation costs by a fixed $54.65/TEU. As a key fixed cost component of the NSR route, removing this fee substantially improves NSR's economic competitiveness relative to SCR.

Continual improvement in NSR navigational conditions will significantly narrow the fuel efficiency gap with SCR and enable more optimal sailing speeds. This section analyzes the impact on unit transportation costs after reducing fuel efficiency coefficient disparities and eliminating speed restrictions, reassessing NSR's economic performance compared to SCR (see Table 16). Referencing existing research (Cheaitou et al. 2022), this analysis sets NSR's optimal sailing speed at 19 n mile·hour^{-1} under ideal navigational conditions, while also comparing cost variations when NSR matches SCR's speed of 15.24 n mile·hour^{-1}. Results demonstrate significant cost differences across three scenarios: NSR maintaining its original speed of 17 n mile·hour^{-1} with high fuel factors yields the highest costs; increasing speed to 19 n mile·hour^{-1}, despite non-linear growth in fuel consumption and carbon emissions, shows sufficient fuel efficiency improvements to offset these negative impacts; reducing speed to 15.24 n mile·hour^{-1} combines lower fuel factors with reduced speed to

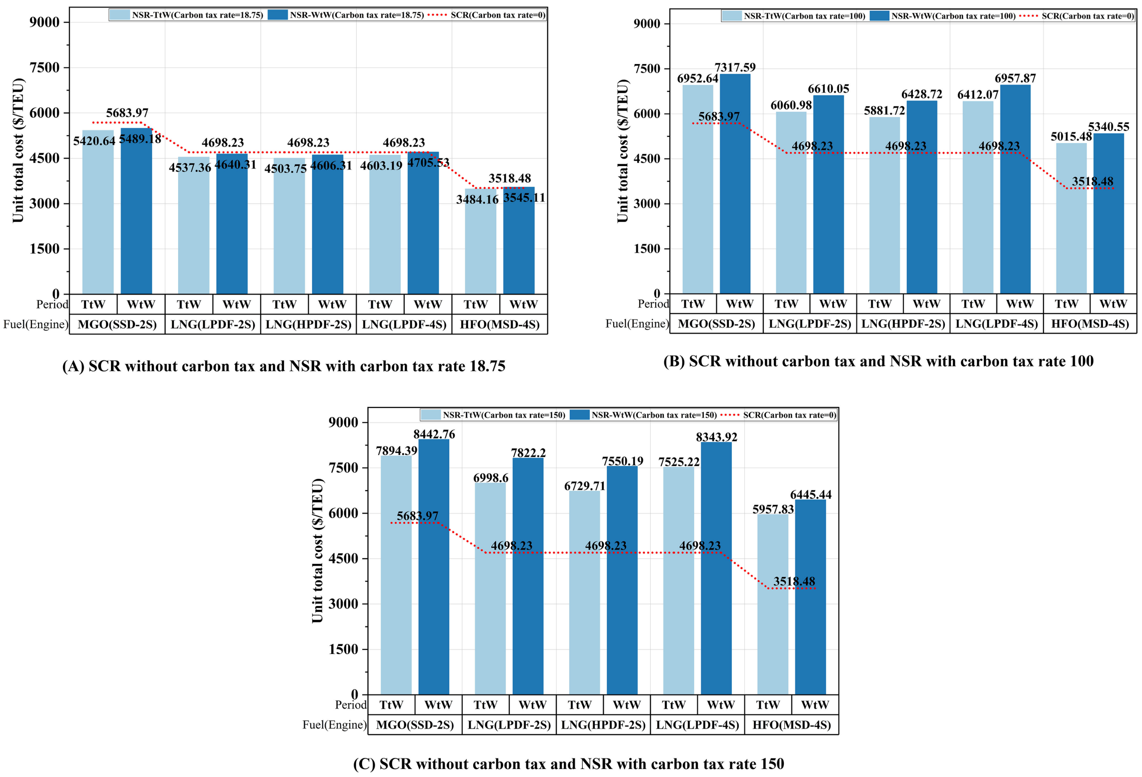


FIGURE 4
Unit total cost of SCR without carbon tax and NSR with carbon tax.

significantly decrease fuel and carbon tax costs, emerging as the most cost-effective option. The research indicates that with improved fuel efficiency, NSR speed can be optimally adjusted to maintain competitive advantages in both cost and transit time simultaneously.

3.5 Sensitivity analysis

3.5.1 Impact of vessel types based on WtW carbon tax calculations

Vessel size analysis (Figure 5) reveals a nonlinear attenuation in economies of scale: unit transportation cost reductions decelerate significantly for vessels exceeding 10,000 TEU. This stems from dual constraints: Larger vessels dilute unit construction costs through capacity expansion, but physical hull dimension limits restrict further cost reductions. Ultra-large vessels reduce per-TEU canal fee allocations but incur escalating absolute toll charges with increasing tonnage. Under IMO's three-tier carbon tax scheme, vessel cost rankings remain stable, yet heightened tax intensity diminishes marginal returns from scale effects, particularly pronounced in large vessel categories.

3.5.2 Impact of ports based on WtW carbon tax calculations

Empirical analysis of the "Flying Fish 1" (Figure 6) reveals significant spatial differentiation in NSR-SCR economic

TABLE 14 Unit total cost of SCR without carbon tax and NSR with other carbon tax under TtW period.

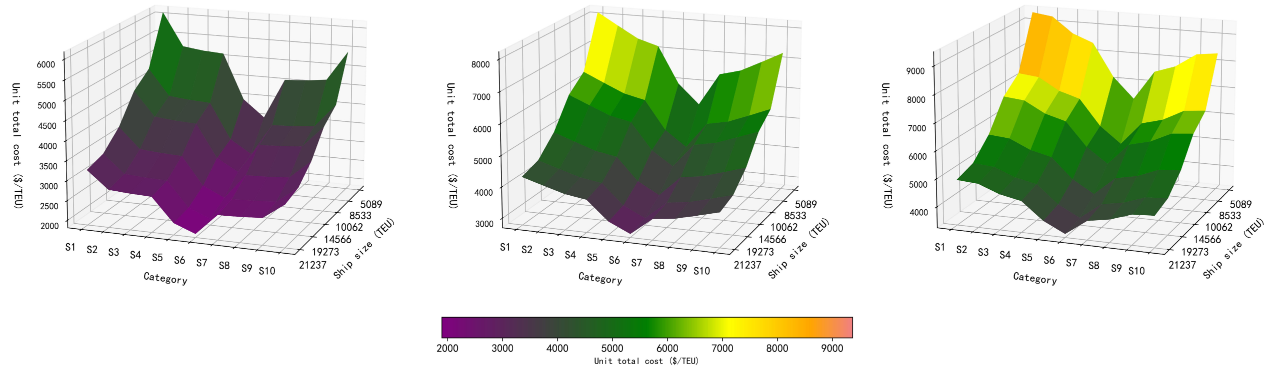
Route	Carbon tax rate /$ · (Ton CO_2)$^{-1}$	Fuel (Engine)				
		MGO (SSD-2S)	LNG (HPDF-4S)	LNG (LPDF-2S)	LNG (LPDF-4S)	HFO (MSD-4S)
SCR	0	5683.97	4698.23	4698.23	4698.23	3518.48
NSR	20.57	5454.96	5434.63	4571.51	4643.73	3518.48
	23.02	5501.10	4576.15	4617.42	4698.23	3564.62
	27.33	5582.32	4649.24	4698.23	4794.17	3654.84
	30.22	5636.76	4698.23	4752.39	4858.48	3700.28
	32.73	5683.97	4740.70	4799.36	4914.24	3747.48
	258.09	9931.64	8562.88	9025.53	9931.64	7995.00

TABLE 15 Unit total cost of SCR without carbon tax and NSR with other carbon tax under WtW period.

Route	Carbon tax rate /$ ·(Ton CO_2)$^{-1}$	Fuel (Engine)				
		MGO (SSD-2S)	LNG (HPDF-4S)	LNG (LPDF-2S)	LNG (LPDF-4S)	HFO (MSD-4S)
SCR	0	5683.97	4698.23	4698.23	4698.23	3518.48
NSR	17.55	5462.07	4579.28	4611.10	4672.12	3518.48
	18.49	5483.26	4600.41	4633.93	4698.23	3539.29
	21.14	5542.94	4659.90	4698.23	4771.75	3597.90
	22.85	5581.40	4698.23	4739.66	4819.13	3635.67
	27.41	5683.97	4800.46	4850.16	4945.48	3736.39
	168.94	8869.09	7975.12	8281.49	8869.10	6864.08
	506.75	16470.88	15551.95	16470.88	18233.43	14328.80

TABLE 16 Impact of Navigation condition on WtW carbon tax calculations.

Carbon tax rate /$·(Ton CO_2)$^{-1}$	Route	Fuel	Engine	Unit Total Cost /$ ·TEU^{-1}				
				Without C_{PB}	Without ice-class vessel	With speed 19	With speed 15.24	Contrast
18.75	SCR	MGO	SSD-2S	6155.81	6155.81	6155.81	6155.81	6155.81
		LNG	HPDF-2S	5168.52	5168.52	5168.52	5168.52	5168.52
			LPDF-2S	5206.55	5206.55	5206.55	5206.55	5206.55
			LPDF-4S	5279.47	5279.47	5279.47	5279.47	5279.47
	NSR	MGO	SSD-2S	5434.53	5483.88	5210.35	3476.67	5489.18
		LNG	HPDF-2S	4551.66	4601.01	4373.70	2936.83	4606.31
			LPDF-2S	4585.66	4635.01	4405.92	2957.62	4640.31
			LPDF-4S	4650.87	4700.23	4467.72	2997.49	4705.53
100	SCR	MGO	SSD-2S	8200.46	8200.46	8200.46	8200.46	8200.46
		LNG	HPDF-2S	7206.46	7206.46	7206.46	7206.46	7206.46
			LPDF-2S	7409.25	7409.25	7409.25	7409.25	7409.25
			LPDF-4S	7798.20	7798.20	7798.20	7798.20	7798.20
	NSR	MGO	SSD-2S	7262.94	7312.29	6943.04	4594.67	7317.59
		LNG	HPDF-2S	6374.06	6423.41	6100.70	4051.16	6428.72
			LPDF-2S	6555.40	6604.75	6272.54	4162.04	6610.05
			LPDF-4S	6903.21	6952.57	6602.15	4374.71	6957.87
150	SCR	MGO	SSD-2S	9458.71	9458.71	9458.71	9458.71	9458.71
		LNG	HPDF-2S	8460.57	8460.57	8460.57	8460.57	8460.57
			LPDF-2S	8764.75	8764.75	8764.75	8764.75	8764.75
			LPDF-4S	9348.18	9348.18	9348.18	9348.18	9348.18
	NSR	MGO	SSD-2S	8388.11	8437.46	8009.31	5282.67	8442.76
		LNG	HPDF-2S	7495.54	7544.89	7163.46	4736.90	7550.19
			LPDF-2S	7767.55	7816.90	7421.23	4903.22	7822.20
			LPDF-4S	8289.27	8338.62	7915.64	5222.23	8343.92



(A) Carbon tax rate=18.75 $/onT CO_2 (B) Carbon tax rate=100 $/Ton CO_2 (C) Carbon tax rate=150 $/Ton CO_2

FIGURE 5
The impact of different ship sizes on unit transportation costs under WtW period.

performance across China's three major ports. Under a $100/ton CO_2e carbon tax scenario: Shanghai Port's NSR achieves the lowest unit costs through mature route operations, outperforming its SCR counterpart by 10.5%. Dalian Port's NSR shows only a 12.7% cost reduction over SCR despite geographical advantages due to limited Arctic navigation experience. Shenzhen Port's SCR maintains a 5.96% cost advantage over NSR, leveraging proximity to traditional route hubs. This spatial pattern stems from dual drivers: northern ports overcome geographical constraints through NSR operational optimization, while southern ports sustain competitiveness via SCR's established advantages. Shanghai Port's case demonstrates that route operational maturity can supersede pure geographical advantages, offering critical insights for developing Arctic shipping capabilities.

3.5.3 Impact of delay cost

This section examines potential delay costs that shippers might incur due to extended voyage durations across different cargo value scenarios (as shown in Table 17). Research indicates these costs can range from 0.6% to 2.1% of containerized cargo value (Hummels and Schaur, 2013; Goldstein et al., 2022). Our analysis employs two delay cost calculation methodologies: fixed delay ratios and variable delay ratios. Under fixed delay ratios, higher-value cargo typically incurs proportionally higher delay costs, while variable delay ratios assign specific percentages to different cargo types based on their time sensitivity. The analysis focuses on three distinct cargo categories—consumer goods, automotive products, and capital goods—conducting sensitivity analysis on delay costs under asymmetric carbon taxation (NSR taxed, SCR untaxed).

Under fixed delay ratio scenarios with carbon taxation at $18.75 per ton of CO_2 equivalent, NSR's inherent economic advantages over SCR become more pronounced when delay costs are considered. When carbon tax increases to $100 per ton of CO_2 equivalent, even for consumer goods with the lowest delay cost ratio and cargo value, SCR's total costs exceed NSR's, indicating shippers' willingness to absorb higher carbon tax costs for NSR's expedited transit. At $150 per ton of CO_2 equivalent, consumer goods show comparable costs between routes, requiring comprehensive evaluation by shippers, while high-value cargo (automotive and capital goods) generates such substantial delay costs that shippers consistently prefer NSR to avoid these additional expenses.

Under variable delay ratio scenarios at $18.75 per ton of CO_2 equivalent, NSR maintains consistent economic advantages, with shippers preferring NSR despite carbon taxation. When carbon tax rises to $100 per ton of CO_2 equivalent with low delay ratios, shippers transporting consumer goods may evaluate both routes, while those shipping high-value cargo prefer NSR due to elevated delay costs; with medium-to-high delay ratios, shippers across all cargo categories favor NSR. At $150 per ton of CO_2 equivalent with low delay ratios, consumer goods shippers may select SCR while capital goods shippers prefer NSR; as delay ratios increase, shipper preference shifts decisively toward NSR to avoid substantial delay costs. Overall, NSR's economic advantages become most pronounced with high-value cargo and high delay sensitivity, offsetting carbon taxation's impact on route selection decisions.

4 Conclusions

The rapid retreat of Arctic sea ice has transformed the NSR into a potentially viable alternative to traditional shipping corridors, promising shorter transit times between Asia and Europe. However, this opportunity creates a fundamental tension between economic development and environmental protection in one of Earth's most fragile ecosystems. Our study examines this tension through the lens of carbon taxation, evaluating whether market-based instruments can effectively balance shipping economics with ecological imperatives. Our findings reveal a significant policy misalignment in current Arctic shipping governance. The IMO's dual approach—banning HFO in Arctic waters while proposing global carbon taxation—creates unintended consequences that undermine both economic and environmental objectives. Without

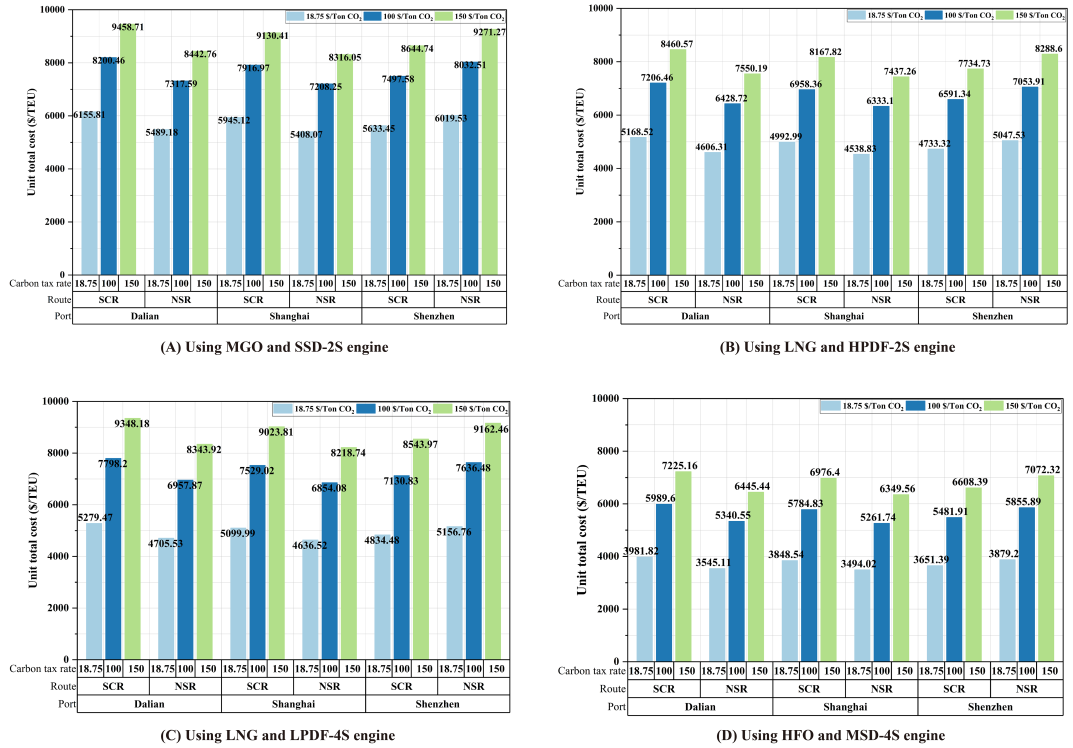


FIGURE 6
The impact of different ports on unit transport costs under WtW period.

carbon taxation, the HFO ban places NSR at a 12-17% cost disadvantage compared to the SCR, redirecting traffic to longer routes with potentially higher total emissions. Even with carbon taxation, our Well-to-Wake (WtW) analysis demonstrates that current proposed tax rates (up to \$150 per ton of CO_2 equivalent) remain insufficient to overcome this disadvantage and incentivize cleaner Arctic shipping.

The study exposes critical technological dependencies that policy must address. LNG, often promoted as a transitional clean fuel, demonstrates significant sensitivity to engine technology selection, with methane slip from certain engine configurations substantially eroding its environmental benefits. This technological variability creates a complex decision landscape for shipowners that carbon taxation alone cannot effectively navigate. Our spatial analysis reveals that port location and operational maturity significantly influence route economics under carbon taxation. Northern Chinese ports, particularly Shanghai, can leverage NSR advantages despite regulatory constraints, while southern ports maintain SCR competitiveness. This geographic differentiation suggests that carbon tax policies will have regionally varied impacts on shipping patterns and investment decisions.

These findings point to the need for an integrated policy approach beyond simple carbon taxation. Rather than uniform global mechanisms, effective Arctic shipping governance requires a coordinated policy framework that: (1) Aligns carbon taxation thresholds with clean fuel technology standards to create consistent economic signals for shipping operators; (2) Implements dynamic carbon taxation that accounts for technological advancement in engine efficiency and methane slip reduction; (3) Develops differentiated port infrastructure strategies that reflect regional variation in route economics under environmental regulation; (4) Creates targeted incentives for technological innovation that address specific environmental challenges like methane slip in LNG engines.

TABLE 17 Impact of delay cost.

Mode	Delay Ratio	Value of goods /\$ ·TEU^{-1}	Delay Cost /\$ ·TEU^{-1}
Fixed Delay Ratio	1.60%	10000	2742.4
	2.10%	22500	8098.65
	7.20%	50000	61704
Variable Delay Ratio	0.75%	10000	1285.5
		22500	2892.375
		50000	6427.5
	2.00%	10000	3428
		22500	7713
		50000	17140
	4.00%	10000	6856
		22500	15426
		50000	34280

Data availability statement

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

Author contributions

HM: Conceptualization, Data curation, Funding acquisition, Resources, Writing – original draft. XF: Conceptualization, Methodology, Supervision, Writing – original draft. XL: Methodology, Writing – review & editing.

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Conflict of interest

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Appendix A Table of abbreviations

Abbreviation	Full Name	Explanation
NSR	Northern Sea Route	Arctic shipping route along Russia's northern coast, connecting Europe and Asia.
SCR	Suez Canal Route	Conventional maritime route between Asia and Europe via the Suez Canal.
HFO	Heavy Fuel Oil	High-sulfur residual fuel oil traditionally used in marine engines.
MGO	Marine Gas Oil	Low-sulfur distillate fuel compliant with emission control regulations.
LNG	Liquefied Natural Gas	Low-carbon alternative fuel for ships, stored in cryogenic tanks.
WtW	Well-to-Wake	Comprehensive emissions accounting from fuel extraction to vessel propulsion.
WtT	Well-to-Tank	Emissions accounting from fuel production to onboard storage.
TtW	Tank-to-Wake	Emissions accounting from onboard fuel storage to vessel exhaust.
TEU	Twenty-foot Equivalent Unit	Standardized measure of container ship capacity (1 TEU = 20-foot container).
GT	Gross Tonnage	Volumetric measure of a ship's total enclosed space.
LCV	Lower Calorific Value	Net energy content of fuel excluding latent heat of vaporization.
GWP	Global Warming Potential	Metric comparing radiative forcing of greenhouse gases relative to CO_2.
MBM	Market-Based Measure	IMO's policy instruments to reduce shipping emissions.
LPDF	Low-Pressure Dual-Fuel Engine	LNG combustion technology prone to methane slip in low-pressure conditions.
HPDF	High-Pressure Dual-Fuel Engine	Advanced LNG engine with minimized methane slip through high-pressure injection.
MSD	Medium Speed Diesel Engine	Diesel engine operating at 250–1200 RPM, commonly used for HFO/MGO.

Appendix B Table of notation

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Symbol	Description	Symbol	Description
C_{FC}	Fuel cost	Q	Total fuel consumption for the voyage

(Continued)

Continued

Symbol	Description	Symbol	Description
C_{CT}	Canal transit fee	V	Vessel container capacity (TEU)
C_P	Port usage fee	U	Vessel size
C_{OC}	Unit TEU operational cost	S	Average sailing speed
C_{UC}	Unit TEU fleet utilization cost	T	Total voyage time
C_{CC}	Unit TEU carbon tax cost	E	Total carbon emissions
C_{NB}	Newbuild vessel price	GT	Gross tonnage
C_{CCY}	Annual capital cost per vessel	GHG	Carbon emission intensity
C_{PB}	Per-voyage icebreaking service fee for NSR	ε	Fuel calorific value
C_{TF}	Unit TEU pilotage fee	α	Adjustable fuel consumption coefficient for route
C_L	Unit TEU cargo handling fee	δ	Fuel efficiency parameter
C_W	Crew wages cost	GHG_{TtW}	Tank-to-Wake carbon emission intensity
C_{IN}	Vessel insurance cost	GHG_{WtW}	Well-to-Wake carbon emission intensity
C_M	Vessel maintenance cost	GHG_{WtT}	Well-to-Tank carbon emission intensity
C_{EX}	Other utilization costs (administration, management, etc.)	GWP	Global Warming Potential
P_{CC}	Carbon tax rate	$scnf$	Progressive surcharge rate for Suez Canal transit fee
P	Fuel price	LCV	Lower calorific value of fuel