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CO_2 emission projection for Arctic shipping: A system dynamics approach

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ABSTRACT

As the Arctic route has shown its potential for Europe-North Asia trade, the number of ships across Arctic route is surging. However, CO_2 emissions generated by ships would harm the regional environment. Thus, how to quantify the CO_2 emissions brought by ships for the present stage and future is critical for Arctic environment governance. As shipping emissions are determined by economic, political, environmental and operational factors, little research has been done to estimate CO_2 emission from a systematical way. This paper proposed a System Dynamics (SD) model that incorporates those comprehensive factors simultaneously for Arctic shipping CO_2 emission projection. The Northern Sea Route (NSR) and the ships sail across NSR are selected for estimation. 12 scenarios with different fuel usage conditions and ship speeds have been set to investigate the trend of CO_2 emissions. Results show that when under the BAU scenario, the overall shipping CO_2 emission on the NSR by 2050 will be 5506149 tons, which is 1.76 times of the emission level in 2020. Switching to cleaner fuels (such as LNG) and slow steaming are effective ways of emission reduction based on the simulation results. The conclusions can facilitate policy makers in making emission reduction decision.

1. Introduction

The Arctic sea ice has kept melting in recent decades due to the continuous global warming. The retreating Arctic glaciers and ice have made it possible for shipping. Three potential sea routes have emerged: Northeast Passage (NEP) along Russian coasts (the most critical navigation section is Northern Sea Route, short for NSR[1]), Northwest Passage (NWP) along Canadian coasts and the Trans-Polar Passage (TPP) (Ding et al., 2020). Among which, as NSR connects Asia and Europe with an up to 40% reduction in sailing distance compared to the traditional Asia-Europe Suez Canal Route (Furuichi and Otsuka, 2013), NSR has attracted certain attention from the international shipping industry (Østreng, 2013). The trade volume along NSR is anticipated to exceed 80 million ton by 2024 (Vorotnikov, 2019).

However, the booming shipping activities along NSR would bring significant pollution to the Arctic region, such as oil spill, Greenhouse Gas (GHG) emission, sewage discharge, etc. (Ding et al., 2020). According to Cariou and Faury (2015), some shipping activities have already raised certain environmental concerns upon Arctic shipping. Especially for shipping caused GHG emissions, they would aggravate the warming in the Arctic region, warming aggravates the melting of Arctic sea ice. This might form a reinforcement feedback that a continuous melting Arctic would attract more ships with a better navigability that might generate more shipping-caused GHG emissions. This reinforcement feedback system would harm the Arctic regional ecosystem severely. A clear GHG emission projection might be helpful for future Arctic environmental management and Arctic shipping governance. A bunch of research has explored the environmental assessment of NSR, which is mainly focused on shipping-caused CO_2 emissions or other relevant GHG emissions (Theocharis et al., 2018). But the past research on environmental (emission) assessment is mainly from the perspective of a single voyage for one or several selected sample vessels (e.g. Ding et al., 2020). A systematic projection of GHG emissions within the whole Arctic region considering future voyages of different kinds of ships and ice condition in Arctic is needed.

Ship-generated emissions in Arctic is not endogenous. From the macro level, trade volume, emission reduction policies all could affect the total emissions of ships. From the micro level, Arctic ice condition, ship's operational conditions and fuel types also affect the emissions together (Dai, 2018). All these findings remind us that estimating shipping emissions in the Arctic region should be conducted from a systematic perspective. Economic factors, political factors, environmental concerns, ice conditions, energy selections all should be included

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[1] The term NSR is used hereinafter to denote either the NSR or NEP for both transit and destination voyages in this research.

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Nomenclature

NEP	Northeastern Passage
NSR	Northern Sea Route
NWP	Northwest Passage
GHG	Greenhouse Gas
CO_2	Carbon dioxide
SD	System Dynamics
AIS	Automatic Identification System
PMx	Fine Particulate Matter
IMO	International Maritime Organization
MEs	Main Engines
AEs	Auxiliary Engines
HFO	Heavy Fuel Oil
MDO	Marine Diesel Oil
LNG	Liquefied Natural Gas
SSE	Shore Side Electricity
BAU	Business as Usual

in the projection process. Considering this, the aim of this research is to establish a System Dynamics (SD) model which takes all those aforementioned factors into account and try to forecast the future NSR shipping CO_2 emissions comprehensively.

The rest of this paper is organized as follows: the related literature on Arctic shipping, ship emission accounting and SD modeling in shipping emission projection is reviewed in Section 2. An Arctic shipping emission projection model based on SD is proposed in Section 3. Section 4 presented the scenario and parameter settings, policy simulations and discussions. Finally, conclusions and policy suggestions are addressed in Section 5.

2. Literature review

In this section, the literature is reviewed in 2 parts: the first part includes a brief review of sustainable Arctic shipping and shipping emission accounting methodologies; the second part introduces related research on shipping, social, economic, environmental, and technical systems modeling.

2.1. Sustainable Arctic shipping and emission accounting

The majority of past literature on Arctic shipping is focused on the feasibility of Arctic shipping, especially for the economic feasibility of NSR against conventional Suez Canal Route (SCR) (such as Liu and Kronbak, 2010; Lasserre, 2014; Cariou and Faury, 2015; Faury and Cariou, 2016; Zhao et al., 2016; Raza and Schøyen, 2014; Pruyn, 2016; Milaković et al., 2018; Faury et al., 2020). The major finding of the past literature shows that NSR is economically competitive against SCR for single/round voyages (Theocharis et al., 2018).

While in recent years, more attention has been paid on assessing the environmental impacts of Arctic shipping and trying to reduce ship emissions in Arctic region. Some researchers have estimated CO_2 emissions of different types of ships (e.g. containership, LNG carrier, oil tanker) with selected vessel cases (e.g. Faury and Cariou, 2016 for tanker; Ding et al., 2020 for containership, Shibasaki et al., 2018 for LNG carrier). Their methodologies are mainly based on the bottom-up method through which the emissions are estimated by ships' activity-based data, such as engine workload, vessel speed, location, duration, etc. (Ng et al., 2012; Berechman and Tseng 2012; Song 2014; Chen et al., 2020). However, among the research, CO_2 emissions are estimated for one or a few case vessels within single or round-trip voyage, there is a lack of the overall picture of Arctic shipping CO_2 emission inventories.

Moreover, some researchers have investigated the impacts of environmental and alternative energy policies on Arctic shipping and further exploring the emission reduction potentials of different policy mix. Corbett et al. (2010) found that the small black carbon (BC) particles generated by vessel's engine would severely affect the ice, snow and cloud in Arctic. Furuichi and Otsuka (2013) claimed that reduced distance would emit less emissions per trip via NSR, while some argued that the negative effects of GHG and atmospheric pollutant emissions in the Arctic would outweigh the advantage of shorter distance, even if cleaner fuels are used (Lindstad et al., 2015). Østreng (2015) found that Arctic shipping activities would harm the regional ecosystem. Researchers from Danish Centre of Environment and Energy (2018) predicted the CO_2 emissions from Arctic shipping activities under different fuel type choices, and found that cleaner fuel types (e.g. LNG) could help reduce CO_2 emissions significantly than conventional fuel types (e.g. HFO). Zhu et al. (2018a, b) incorporated the GHG emission in the economic model, quantified the cost of global warming (CGW) and test how the environmental coast affects NSR's economic viability. Stevenson et al. (2019) also found that switching conventional fuel types to cleaner fuel types could reduce emissions effectively. Ding et al. (2020) proposed two types of carbon tax schemes to investigate the CO_2 emission reduction potential under different carbon tax schemes and different fuel type choices.

Researchers have realized the importance of CO_2 emission accounting and emission reduction in Arctic. Although some existing Arctic shipping CO_2 emission inventories have been established based on past data (e.g. Danish Centre of Environment and Energy, 2018), a rigorous projection of long-term CO_2 emission for future shipping activities concerning a set of economic factors, technical factors, energy and environmental policies is still needed for Arctic environment governance.

2.2. Shipping and social-economic-environmental systems modeling

As mentioned before, shipping closely connects with trade, environment, energy, governments, etc. All these connections help to make a complex shipping system. To tackle with this, many researchers have applied System Dynamics models on shipping research and policy research.

SD is used to consider the system as fully as possible. To make the model structure clear, it is necessary to divide the whole system into several subsystems. SD is especially applicable to these problems with nonlinear and feedback features that arise from the intercorrelations of multiple factors in complex social-economic-environmental systems (Hjorth and Bagheri, 2006). SD was initially developed by Professor Forrester in the 1950s (Forrester, 1959), and it was first applied to the transportation system modeling in the 1990s (Abbas and Bell, 1994) and then get widely used in complex social system and emission projection modeling. For example, Liu et al. (2019) established a SD model for port hinterland truck emission projection. Within their hinterland emission projection system, main factors such as transport time, freight volume, truck fleet, etc. are considered. Chen et al. (2012) built a SD model for analyzing the shipping capacity of global dry bulk shipping market, and conducted strategies simulation for dealing with excess capacity. Zhao et al. used the SD model to establish an overall shipping and trade research system and then simulate the international dry bulk market operations and predict the cost of dry bulk shipping and supply-demand structure. Wen et al. (2017) established a SD model for mitigation of regional vessel exhausts emissions. The port of Tianjin's annual CO_2 emission and economic benefits were predicted by the SD model considering the main factors of policy, economic and technical issues. Bahadir and Akdag (2019) applied SD on hub and spoke container network's capacity and transportation planning. With policy simulation, they get the optimized policies which would help to maximize the long-term earnings. For emissions reduction policy research and emission prediction, SD models have been applied in many other areas. Jia et al. (2019) used a SD model to analyze the effect of air pollution charge fee policy on the fine particulate matter (PMx) generation in China. Environmental and economic factors and effects were taken into consideration within the system. The literature has shown the advantage of SD models on analyzing complex social-economic-technical systems.

In summary, SD is capable for emission projection of a complex transportation system such as the Arctic route usually with political, environmental, technical and social considerations. In this way, based on the previous findings and the specific characteristics of the Arctic, a novel SD model of Arctic shipping will be established for long-term shipping CO_2 emission.

In shipping emission related research, 5 kinds of segments or subsystems are usually taken into consideration: shipping, energy, economic, environmental and policy factors (as summarized in Table 1). Thus, a SD model which includes 5 subsystems is established in this article to explore the future CO_2 emission potentials in the Arctic route.

3. Methodology

3.1. Model hypothesis

This study aims to develop a SD model to evaluate the potential long-term effects of energy and environmental policies on Arctic shipping emissions and predict the future Arctic shipping CO2 emission. For this research objective, the following hypotheses are assumed.

(1) This research concentrates on the ship emission on the NSR. Other emission related with Arctic shipping are not taken into consideration.
(2) 2 parts of ship emissions are considered in this research: emissions during sailing at sea and emissions during hoteling at berth.
(3) There is no sudden event that can influence the normal development of Arctic shipping greatly during the study period.

3.2. Model framework

The SD model is developed in a modular manner, which indicates that the whole research system consists of several subsystems to reflect the interactions between each subsystem (Liu et al., 2019).

In the Arctic region, shipping is not an isolated business, that it correlates with other factors: international trade and economic profits drive the activities of shipping, while shipping related emissions and waste disposals may harm the regional environment, issued environmental and energy policies such as IMO 2020 Sulphur limit (IMO, 2017) and other potential policies might restrain the fuel oil usage and emissions in Arctic. So, from a systematic perspective, it is necessary to classify the Arctic shipping system into some subsystems and then figure out the detailed factors and form the feedback loops within the system. To determine related subsystems and factors, we referred to some previous researches, and combed the subsystems they investigated. As Table 1 shows, most scholars concentrated on shipping, energy and economic subsystems, and some involved policy and environmental subsystems. Therefore, based on the previous research, in this paper, the whole Arctic shipping system consists of 5 subsystems: economic subsystem, environmental subsystem, shipping subsystem, energy subsystem and policy subsystem.

Table 1
Related subsystems proposed in previous research.

Reference	Subsystems in related research
Wen et al. (2017), Milaković et al. (2018)	Shipping, economic, energy, environmental, policy
Zhu et al. (2018b), Ammar (2019), Wan et al. (2019)	Shipping, economic, energy, environmental
Zhang et al. (2016), Raj et al. (2016)	Shipping, economic, energy
Winther et al. (2014)	Shipping, energy, environmental

The detailed description of subsystems and impact factors are listed in Table 2. The primary logic of the SD model is that the CO_2 emissions from the Arctic shipping system are generated by the consumption of fuel oil by ships' main engines (MEs) and auxiliary engines (AEs). As the fuel consumptions depends on the number of ships, each ship's size, ship's sailing speed, ship's sailing time and berthing time in ports, etc. All these factors interact with others and thus form the feedback loops. The detailed description of the factors and feedback loops given in the next section.

3.3. Model development

3.3.1. Causal loop

The causal loop shows the feedback effects among variables. The relationship of relative factors of NSR CO2 emissions are shown in Fig. 1.

The 8 key loops within the system are listed in Table 3. The details are described as below.

Take Loop 1 for instance, when the total revenue/benefits of whole system increase, government can introduce more air pollution control policies and shipping companies are more likely to invest on emission reduction measures and technologies. One of the pollution control measure is to change the fuel structure, that is to reduce the proportion of HFO usage and increase the usage of MDO, LNG and other cleaner fuel. While changing the fuel structure to higher usage of cleaner fuel would cause an increase in total fuel costs of the shipping subsystem, which would in turn affects the total revenue. Loop 2 shows the change of total revenues affected by overall trade volume across NSR. More revenue would promote the development of Arctic shipping, which could in turn stimulate larger trade volume. Larger trade volume needs more voyages to transport goods, and thus the overall shipping income also increases. Loop 3 and 4 are similar with loop 2, but they consider the effect of the number of voyages from another perspective. More voyages consume more energy and produce more CO_2 emissions. The increase of CO_2 emission would lead to stricter emission reduction policies, then the fuel structure will change and more SSE will be used. Loop 5 and 6 indicate that air pollution control policy adjusts the fuel structure, and then influences the CO_2 emission. Loop 7 shows how the ice concentration can affect the total emission. When other conditions remain the same, vessels need extra power to sail through ice-covered water, so icy Arctic condition costs additional fuel consumption compared to conventional shipping in blue water. More fuel leads to more emission, while more CO_2 emission would strengthen the warming effects in Arctic region, which would accelerate the sea-ice melting and would help to improve the navigability in the long run. Loop 8 is similar to Loop 7, but it shows another way that ice concentration can affect the total emission. Besides affecting the operational power directly, ice concentration can also influence the operational power by affecting the vessel's speed, and finally affect the total emission.

Table 2
Classification of factors.

Subsystem	Factor
Economic system	total revenues, environmental benefits, shipping income, trade volume, shore side electricity cost, fuel costs
Environmental system	total CO_2 emission, emission from HFO, emission from MDO, emission from LNG, environmental benefits, ice thickness, freezing time, ice concentration
Shipping system	shipping revenue, shipping cost, voyages number on the NSR, port candling capacity, operational power, speed, sailing time, sailing distance, total energy consumption
Energy system	usage rate of HFO, usage rate of MDO, usage rate of LNG, total energy consumption, shore side electricity usage
Policy system	air pollution control policy (energy usage policy, energy restriction policy)

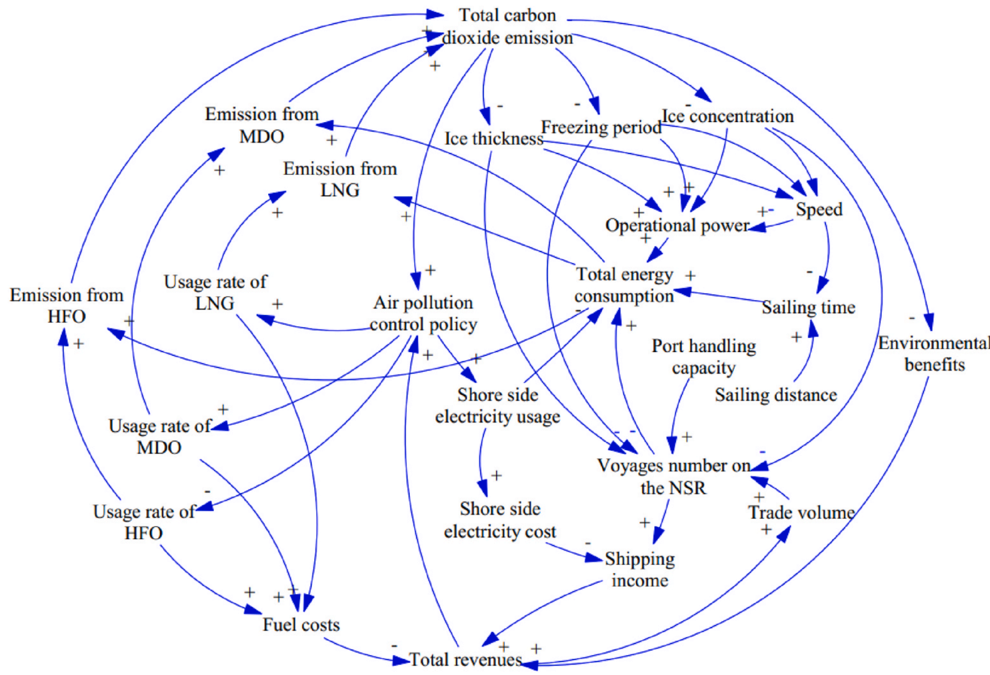

Fig. 1. Causal loop of the proposed Arctic shipping model.

Table 3
Details of key loops.

No.	Detail
1	Total revenues$\xrightarrow{+}$Air pollution control policy→Usage of fuel$\xrightarrow{+}$Fuel costs→Total revenues
2	Total revenues$\xrightarrow{+}$Trade volume$\xrightarrow{+}$Voyages number on the NSR$\xrightarrow{+}$Shipping income$\xrightarrow{+}$Total revenues
3	Total revenues$\xrightarrow{+}$Trade volume$\xrightarrow{+}$Voyages number on the NSR$\xrightarrow{+}$Total energy consumption$\xrightarrow{+}$Emission from fuel$\xrightarrow{+}$Total carbon dioxide emission$\xrightarrow{+}$Air pollution control policy→Usage of fuel$\xrightarrow{+}$Total revenues
4	Total revenues$\xrightarrow{+}$Trade volume$\xrightarrow{+}$Voyages number on the NSR$\xrightarrow{+}$Total energy consumption$\xrightarrow{+}$Emission from fuel$\xrightarrow{+}$Total carbon dioxide emission$\xrightarrow{+}$Air pollution control policy$\xrightarrow{+}$Shore side electricity usage$\xrightarrow{+}$Shore side electricity cost→Shipping income$\xrightarrow{+}$Total revenues
5	Air pollution control policy→Usage of fuel$\xrightarrow{+}$Emission from fuel$\xrightarrow{+}$Total carbon dioxide emission$\xrightarrow{+}$Air pollution control policy
6	Air pollution control policy$\xrightarrow{+}$Shore side electricity usage→Total energy consumption$\xrightarrow{+}$Emission from fuel$\xrightarrow{+}$Total carbon dioxide emission$\xrightarrow{+}$Air pollution control policy
7	Ice concentration$\xrightarrow{+}$Operational power$\xrightarrow{+}$Total energy consumption$\xrightarrow{+}$Emission from fuel$\xrightarrow{+}$Total carbon dioxide emission→Ice concentration
8	Ice concentration$\xrightarrow{+}$Speed$\xrightarrow{+}$Operational power$\xrightarrow{+}$Total energy consumption$\xrightarrow{+}$Emission from fuel$\xrightarrow{+}$Total carbon dioxide emission→Ice concentration

3.3.2. *Stock-flow model*

The 3 types of variables: level, rate and auxiliary variable of the system are shown in Fig. 2. As the main research objective is to evaluate the effects of potential energy and environmental policies on Arctic shipping emissions, the values of some economic factors and their direct impacts are referenced from the literature (Danish Centre of Environment and Energy, 2018).

The detailed descriptions of some variables and the quantification methodologies are clarified as below.

(1) Total CO_2 emissions

Total CO_2 emissions is the integral for annual CO_2 emission, and could be modeled as:

$$\varepsilon_T = \int \varepsilon_A \mathrm{d}t \tag{1}$$

where:

ε_T: total CO_2 emissions in ton
ε_A: annual CO_2 emission in ton

(2) Annual CO_2 emission

Annual CO_2 emission is the sum of emissions from different kinds of fuel. The annual CO_2 emission could be modeled as:

$$\varepsilon_A = \Sigma \varepsilon_j \tag{2}$$

where:

ε_j: CO_2 emission from fuel j in ton

(3) Emission from every kind of fuel

Emissions from each kind of fuel could be modeled as below:

$$\varepsilon_j = FC_j \cdot \varepsilon_j / 10^6 \tag{3}$$

where:

ε_j: CO_2 emission factor of fuel j in g/g
FC_j: consumption of fuel j in g

(4) Fuel consumption

With the global decarbonization trend and the development of shipping technology, some kinds of less-sulphur-composed alternative fuel, like MDO and LNG have been applied in shipping industry. Since different kinds of fuel have different emission factors, the consumption of different kinds of fuel and related CO_2 emission are calculated separately in the later section. In this article, a coefficient λ_j has been

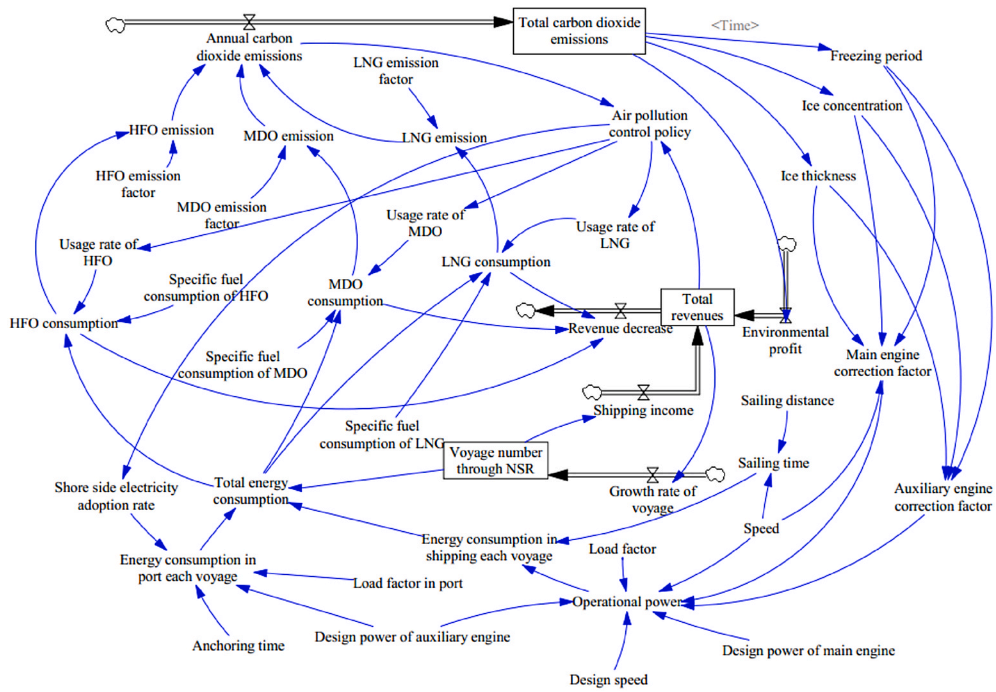

Fig. 2. Stock-flow diagram of the proposed model.

introduced to represent the usage rate of different kinds of fuel. The consumption of each kind of fuel could be modeled as:

$$FC_j = E_T \cdot \lambda_j \cdot sfc_j / 100 \tag{4}$$

where:

E_{T_i}: total energy consumption in year i in kWh
λ_j: usage rate of fuel j in percentage
sfc_j: specific fuel consumption of fuel j in g/kWh
(5) Total energy consumption

In this article, vessel status is classified into two categories: sailing at sea and anchoring in port. Then energy consumption of ships is calculated based on each status. So, the total energy consumption of all vessels can be modeled as:

$$E_{T_i} = n_{V_i} \cdot (E_S + E_P) \tag{5}$$

where:

n_{V_i}: number of shipping voyages in year i
E_s: Energy consumption in shipping each voyage in kWh
E_P: Energy consumption in port each voyage in kWh
(6) Number of shipping voyages through NSR

Generally, the number of voyages through NSR has the same growth trend with the trade volume, as more trade volume across NSR happens each year, the number of voyages is anticipated to increase. The value of n_{V_i} is denoted as the integral of number of voyages in past years. GR_V in Equation (6) represents the average annual growth rate of voyages across NSR. It is assumed that the average vessel carrying capacity remains stable in this research, so the value of GR_V is assumed to be equal to the average maritime trade volume growth rate across the Arctic region. Then, the voyage number could be modeled as:

$$n_{V_i} = n_{V_0} + \int_0^i n_{V_i} \cdot GR_V \, \mathrm{d}t \tag{6}$$

where:

n_{V_0}: number of voyages in year 0
GR_V: average annual growth rate of ship voyages
(7) Energy consumption in shipping each voyage

When the vessel is sailing at sea, the average energy consumption could be modeled as:

$$E_s = P_O \cdot T_s \tag{7}$$

where:

P_o: average operational power of the vessel in kW
T_S: sailing time in hours
(8) Energy consumption in port each voyage

During the anchoring time in ports, ships will switch off MEs, while AEs are still working for onboard energy supply. Thus, the energy consumption of AEs and related CO_2 emissions need to be taken into consideration in this research. According to Dai et al. (2019), Shore Side Electricity (SSE) has been installed in many countries as a clean power resource for vessels to reduce in-port emissions. SSE also has great potential of usage in Arctic ports in the future as the usage of SSE is usually assumed to be zero CO_2 emission in port. So, the usage of SSE in future will help to reduce in-port CO_2 emissions and the in-port CO_2 emissions accounting should be based on the future SSE adoption rate and the amount of used SSE. Then the average energy consumption of a vessel in port on each voyage could be modeled as:

$$E_P = (1 - \beta) \cdot T_a \cdot P_{AP} \tag{8}$$

where:

β: average shore side electricity adoption rate in Arctic ports
T_a: average anchoring time in Arctic ports in hours
LF_P: average load factor of auxiliary engine in port
P_{AP}: average power of auxiliary engine in port in kW
(9) Operational power on the voyage

There are 2 parts of engines working during the voyage: ME and AE. Then the total operational power could be modeled as:

$$P_O = P_M + P_A \tag{9}$$

P_M: average operational power of ME on the voyage in kW
P_A: average operational power of AE on the voyage in kW

(10) Sailing time

For a single voyage, the sailing distance can be defined as the distance from the origin port to the destination port. There are many types of voyages, like intra-navigation, destination and transit via NSR, and each type of voyage has different sailing distance. As it is hard to anticipate the proportion of each voyage type across NSR in each year, a coefficient named distance adjustment factor (α) is introduced to average the sailing distance for the types of voyages of each kind of vessel type for model's mathematical tractability.

For example, for containership, general cargo ship and bulk carrier, the distance adjustment factors for these 3 vessel types are set with a value close to 1. For tankers, they sailed the waters between Sabetta and Murmansk mostly, so factor for tankers is set equal to the ratio of this segment's length to total length of NSR. For support ship, the most active sailing area is near Kara Sea and Ob Bay. For passenger ship and fishing ship, their active areas are smaller, so are the value of their distance adjustment factors. The detailed assumption of the values of distance adjustment factors are given in Section 4.

$$T_S = D \cdot \alpha_i / V \tag{10}$$

where:

D: distance of the NSR in nm
α_i: distance adjustment factor for vessel type i

(11) Power of auxiliary engine in port

According to Mou et al. (2019), the operational power of AE is related to the ship load and the design power of AE. Thus, it could be modeled as:

$$P_{AP} = P_{DA} \cdot LF_P \tag{11}$$

where:

P_{DA}: design power of auxiliary engines in kW
LF_P: load factor of auxiliary engine in port

(12) Operational power of main engine on the voyage

The operational power of ME follows the so-called cubic law of design speed and operational speed for ships sailing in conventional blue water. While when ships sail in the ice-covered sea, such as in the Arctic region, due to the resistance of sea ice, ME and AE would consume additional fuel oil for propelling, thus the traditional parameters of cubic law cannot be directly applied. Considering the sea ice resistance in calculating actual operational power, an adjustment factor or so-called ice condition correction factor (f_{IM}) has been introduced to calibrate the equation of operational power (Corbett et al., 2009; Mou et al., 2019). Obviously, the value of f_{IM} depends on the ice condition of each sea route, for example, during August to October, NSR is assumed to be blue water route (University of Bremen,), thus the value equals to 1, while during winter and spring, the route is significantly covered with ice, the value will be larger than 1. For model tractability, an average value of f_{IM} will be given in next section. The operational power of the ship could be modeled as:

$$P_M = P_{DM} \cdot \left(\frac{V}{V_D}\right)^3 \cdot f_{IM} \tag{12}$$

where:

P_{DM}: design power of main engine in kW
V: operational speed in knot (kn)
V_D: the design speed in knot (kn)
f_{IM}: the ice condition correction factor of MEs

(13) Operational power of auxiliary engine on the voyage

Similar to the explanation of calculating operational power of ME, the ice condition should also be taken into consideration. So, the factor f_{IA} is introduced for AE operational power calculation. The operational power of AE on the voyage could be modeled as:

$$P_A = P_{DA} \cdot LF_V \cdot f_{IA} \tag{13}$$

where:

LF_V: load factor of auxiliary engine on the voyage
f_{IA}: the ice condition correction factor of AEs

3.4. Scenario design

3.4.1. Fuel structure mode design

Based on IMO's latest regulations on shipping emission reduction and the trend of using alternative fuels, 3 different fuel structure modes (HFO, MDO and LNG) were set in this research to forecast the future shipping CO_2 emissions. Besides, the adoption of SSE has also been considered when estimating future energy consumption in port.

The neutral mode is regarded as the mode which can reflect the most likely fuel structure situation in the future. As currently there is no ban of HFO usage in the Arctic, so it is assumed that HFO could still be used in Arctic shipping till 2020. According to IMO's sulphur control regulations, HFO will be prohibited in Arctic shipping in 2024 by Canada, and Russian government will ban HFO in 2029. Because this research focuses on the NSR, the scenario design is subject to Russia policy. Therefore, HFO will be banned thoroughly in 2030 in the neutral mode. The aggressive mode accounts more LNG and MDO usage in the compound fuel structure. Considering the higher equipment upgrading cost and lower market share, we think LNG is a more advanced alternative fuel than MDO. In the conservative mode, less LNG is used compared to the neutral mode.

It is also assumed that every adjustment of energy and environmental policies can last for 10 years. The general trend for fuel usage in shipping industry is increasing the usage of MDO and LNG, especially for LNG, and decreasing the usage of HFO.

3.4.2. Ship's average speed mode design

As ship speed is also a crucial direct factor that affects the final emissions, some scholars pointed out that slow steaming is another effective way for emission reduction (e.g. Chen et al., 2019). Therefore, different modes of ship speed have been proposed to investigate the speed effect on emissions. 4 speed modes are set as: conventional speed, 10% decrease, 20% decrease and 10% increase.

Therefore, 12 scenarios with different fuel structures and speeds were set in this article. The scenarios are set based on the conventional fuel structure and ship's average speed on NSR. All 12 scenarios were listed in Table 4. Scenario 1 is set as the most likely scenario that would be applied in the future in this article. So, Scenario 1 is set as the business as usual (BAU) scenario. And it will be the basic scenario contrasting with other scenarios in following parts.

Table 4
Parameter settings of different scenarios.

Scenarios	Indicators	2016–2019	2020–2029	2030–2039	2040–2050
Scenario 1 (BAU scenario)	Usage rate of HFO (%)	85	73	0	0
	Usage rate of MDO (%)	15	25	90	70
	Usage rate of LNG (%)	0	2	10	30
	Speed	Conventional speed			
Scenario 2	Usage rate of HFO (%)	85	60	0	0
	Usage rate of MDO (%)	15	30	65	45
	Usage rate of LNG (%)	0	10	35	55
	Speed	Same as BAU			
Scenario 3	Usage rate of HFO (%)	85	73	0	0
	Usage rate of MDO (%)	15	25	95	90
	Usage rate of LNG (%)	0	2	5	10
	Speed	Same as BAU			
Scenario 4	Usage rate of fuel	Same as BAU			
	Speed	−10%			
Scenario 5	Usage rate of fuel	Same as Scenario 2			
	Speed	Same as Scenario 4			
Scenario 6	Usage rate of fuel	Same as Scenario 3			
	Speed	Same as Scenario 4			
Scenario 7	Usage rate of fuel	Same as BAU			
	Speed	−20%			
Scenario 8	Usage rate of fuel	Same as Scenario 2			
	Speed	Same as Scenario 7			
Scenario 9	Usage rate of fuel	Same as Scenario 3			
	Speed	Same as Scenario 7			
Scenario 10	Usage rate of fuel	Same as BAU			
	Speed	+10%			
Scenario 11	Usage rate of fuel	Same as Scenario 2			
	Speed	Same as Scenario 10			
Scenario 12	Usage rate of fuel	Same as Scenario 3			
	Speed	Same as Scenario 10			

Source: Third IMO GHG Study

4. Numerical results and discussion

4.1. Numerical results

4.1.1. Sample route and vessel selection

The area studied in this research is shown in Fig. 3, as is from Cape Zhelaniya to Cape Dezhnev, the total distance (*D*) is about 3500 nm, which is considered as the length of NSR. As vessels sail on NSR are in different types and with different sizes, it is hard to estimate the total CO_2 emissions from single vessel perspective. For model mathematical tractability, all the vessels sail across NSR are divided into 9 categories, such as crude oil tanker, oil products tanker, and containership (see Table 5). One typical vessel for each category which is actually put into use on NSR is selected as the sample vessel for model calculation. Considering the geographical features of NSR, only vessels that have navigational record on the NSR or with ice class 1A-1C were selected.

The detailed data of the samples is shown in Table 5.

4.1.2. Parameter setting

Ships' operational data is shown in Table 6.

The emission parameters are listed in Table 7.

According to the current infrastructure situation of ports in the Arctic region, the values of SSE adoption rate are set as listed in Table 8. It is assumed that SSE would not be adopted widely by ports on NSR in the next 40 years as the deployment of SSE facilities depends on the upgradation of port infrastructure and government financial incentives (Dai et al., 2019; Dai et al., 2020).

Ice concentration is the ratio of the area covered by sea ice to total

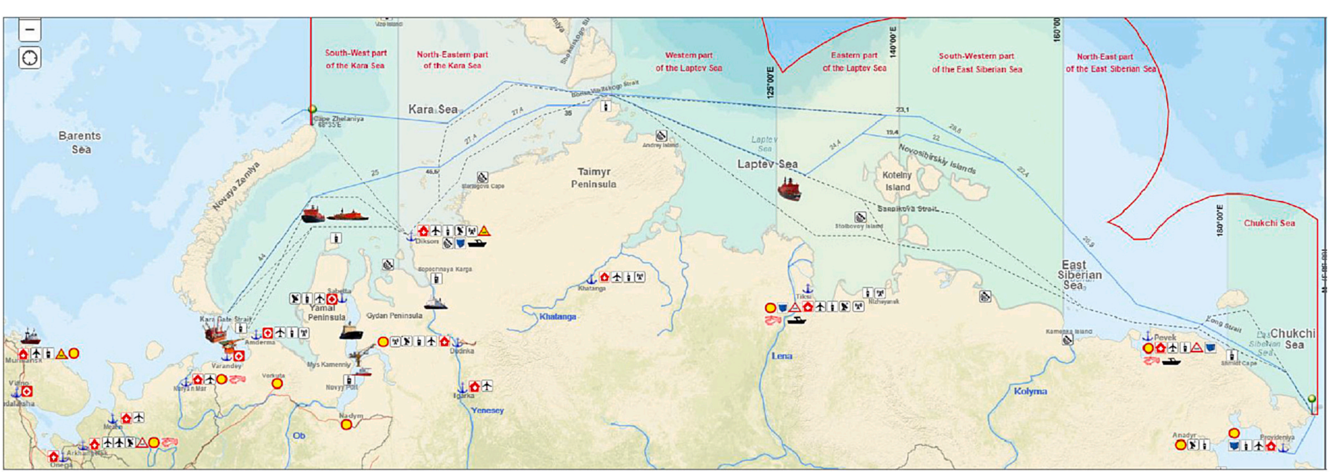

Fig. 3. NSR track chart.
Source: Center for High North Logistics (http://www.tschudiarctic.com/page/548/Centre_for_High_North_Logistics).

Table 5
Basic ship parameters of all sample vessels.

Vessel category	Crude oil tanker	Oil products tanker	Gas tanker	Container ship	General cargo ship	Bulk carrier	Passenger ship	Support ship	Fishing ship
Vessel name	Bodil Knutsen	Kronviken	Chris-tophe de Marge-rie	Polar Brasil	Lian Hua Song	Koun-douros	Basto V	Polarstern	Kapitan Kayzer
Dead Weight DW(ton)	150000	114523	96779	52023	27412	175247	1350	11820	5408
Length L(m)	285	250	299	230	179	292	143	118	105
Breadth B(m)	50	44	50	37	27	45	21	26	20
P_{DM} (kW)	21770	14313	21770	19620	8250	16860	4560	14116	4200
P_{DA} (kW)	13200	1100	16900	4520	2100	2700	514	2580	488
V (knot)	10.3	10.8	13.5	11.5	11.7	9.4	10.5	8.4	7.5
V_D (knot)	19.5	18.1	22.5	22	18.3	16	18.3	16	12.8
α	0.3664	0.3664	0.3664	0.9	0.9	0.9	0.2	0.2857	0.2
n_{V_0}	560	397	13	103	591	110	15	162	37

Note: vessel data is from https://www.fleetmon.com. For some sample vessels which lacks data of P_{ae}, we calculated their P_{ae} according to ratio of P_{ae} to P from Qian et al. (2016). For number of vessels, because the study period for this article is from 2016 to 2050, the voyage number in 2016 is selected as n_{V_0}. The original data is from Center for High North Logistics.

Table 6
Navigational parameters.

Parameter	Unit	Value
T_a	hour	72
GR_V	%	3.6
LF	0.2	
LF_P	0.22	

Note: Value of GR_V is from the official report (Danish Centre of Environment and Energy, 2018) based on the projection of future trade growth along NSR. Value of LF and LF_P is from Starcrest Consulting Group LLC (www.starcrestllc.com/).

Table 7
Emission parameters.

Parameter	Unit	HFO	MDO	LNG
sfc	g/kWh	179	170	150
ε	g/g	3.144	3.206	2.75

Note: Values are from Gilbert et al. (2018).

Table 8
SSE adoption rate assumption.

Unit	2016–2019	2020–2029	2030–2039	2040–2050
%	0	0	0	10

sea area. Because the ice correction factor is affected by ice concentration condition, it is necessary to set the values of ice concentration. And the values of ice concentration rate assumptions are listed in Table 9.

Based on the assumption listed in Table 9, f_{IM} and f_{IM} under different ice concentration are listed in Table 10. The correction factor of MEs is related with breadth, speed and other basic ship parameters, so the f_{IM} of each sample vessel is calculated separately. And for the correction factor of AEs, the factor can be considered as a constant approximately

Table 9
Ice concentration assumption.

Unit	2016–2030	2031–2050
%	50	40

Note: Assumptions are made based on data from University of Bremen http://www.iup.uni-bremen.de/iuppage/psa/2001/amsrop.html.

(Winther et al., 2014). In addition, the effect of sea ice can be ignored from August to October during the summer time (Mou et al., 2019). Therefore, all these factors are estimated with weighted averages and are listed below.

4.1.3. Model validation and numerical analysis results

To examine the reasonability of the model structure and parameter setting, model validation is necessary. In this article, the annual CO_2 emission ε_A is selected to compare with the reference value from Danish Centre of Environment and Energy (2018).

Table 11 shows parts of simulated data under BAU scenario. The ratio of simulated value to the referenced value is about 20% in 2016 and increased in following years. The reference value is calculated based on all the shipping activities within the greater Arctic area, and areas counted from Pole southward to southern Norway and include the Canadian Arctic region. That means the reference value covers the magnitude of all 3 Arctic routes (NSR, Northwester Route and Polar Route). While the number of voyages considered in this research just includes shipping activities along NSR and only within the Arctic circle. Therefore, based on all these differences mentioned above, order of magnitude of the predicted CO_2 emissions is assumed to be acceptable, and these results have a relatively high credibility.

Fig. 4 shows the trend of annual CO_2 emission on NSR during 2016–2050 under BAU scenario. Because of the increase of voyage numbers, the emission shows an upward tendency generally. And there are 3 fluctuations in 2020, 2030, and 2040. These fluctuations in 2020 and 2040 are caused by the fuel structure adjustment, because turning to cleaner fuels like LNG can decrease CO_2 emission compared to HFO. For the dramatic fluctuation in 2030, though there is a fuel adjustment in 2030, it is mainly caused by the ice concentration ratio change. This reveals that better navigability could significantly reduce energy consumption then could help to reduce CO_2 emissions significantly, as the ice concentration is assumed to decline from 50% to 40%.

Fig. 5 shows the detailed contributions from each kind of vessel. As the figure shows, crude oil tankers and general cargo ships make the largest contributions to overall CO_2 emission, which make up nearly 70% of total emission. Oil products tankers and bulk carriers also contribute significantly. So, these types of vessels will be the key vessel types to be considered for emission reduction.

4.2. Sensitivity analysis and discussion

4.2.1. Fuel structure sensitivity

Scenario 1, 2 and 3 are selected as fuel structure sensitivity analysis samples to keep ships' average speed as invariant. From Fig. 6a, it could

Table 10
Ice condition correction factors of all sample vessels.

Vessel category	Crude oil tanker	Oil products tanker	Gas tanker	Container ship	General cargo ship	Bulk carrier	Passenger ship	Support ship	Fishing ship
Vessel name	Bodil Knutsen	Kronviken	Chris-tophe de Marge-rie	Polar Brasil	Lian Hua Song	Koun-douros	Basto V	Polarstern	Kapitan Kayzer
f_{IM}(ice concen-tration = 50%)	5.774	5.0401	4.8176	4.2254	3.3204	5.6344	2.9737	3.93860	3.4825
f_{IM}(ice concen-tration = 40%)	3.7864	3.3578	3.228	2.8824	2.3542	3.7047	2.1518	2.7150	2.4488
f_{IA}	1.1875								

Table 11
Annual CO_2 emission.

	2016	2030	2050
Reference value (ton)	17,890,000	16,883,000	17,757,000
Simulated value (ton)	2,750,573	3,075,708	5,910,313
Ratio (%)	15.4	18.2	33.3

Note: reference value is from Danish Centre of Environment and Energy (2018).

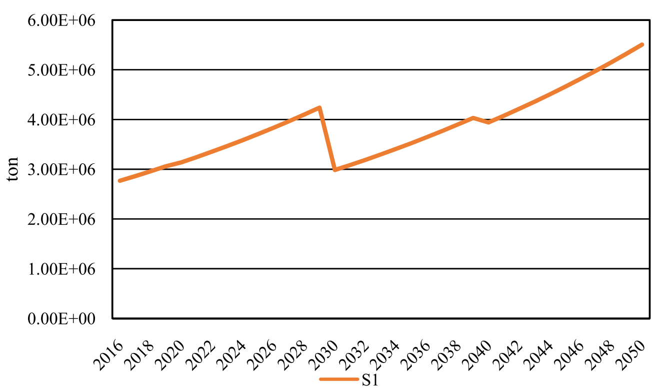

Fig. 4. Annual CO_2 emission under BAU scenario.

be found that with the less usage of HFO and more usage of LNG, the total CO_2 emissions of Scenario 2 is the least in the long run. While for the emissions of Scenario 3, due to the largest usage proportion of HFO by 2030, the emission is the largest among other scenarios. And after the complete ban of HFO in 2030, Scenario 3 still keeps the largest emission, because of the largest MDO usage.

From the aspect of emissions of different types of fuel, Fig. 6b shows the total emissions of HFO usage. As is shown in Table 3, due to the long-term trend of decarbonization in Arctic shipping, the usage of HFO is gradually decreasing, thus the HFO generated CO_2 emission reduction turning points emerge at the timing of fuel structure adjustments on 2020 and 2030. However, due to the increase of shipping activities, the emissions of HFO usage still increases in a fixed fuel structure stage. For emissions of MDO and LNG usage, as the usage shares of these two alternative fuels are increasing, the long-term trend of emissions are increasing accordingly as shown in Fig. 6c and d. The growing shipping activities also reinforce the trend of CO_2 emission increase.

From the perspective of total CO_2 emission, as Fig. 6a shows, all 3 scenarios have the same emission in the first 4 years. The first difference appears in 2020. As Fig. 6c shows, because the same fuel structure was used in Scenario 1 and 3, while more MDO and LNG were used in Scenario 2, this led to less emission in Scenario 2. However, the emission gap is relatively limited, and the difference between Scenario 2 and 3 is 72,909 tons.

The second fuel structure adjustment is set in 2030. The differences of fuel structure among these 3 types of scenarios enlarge gradually. While HFO is banned, the difference is from the usage of MDO and LNG.

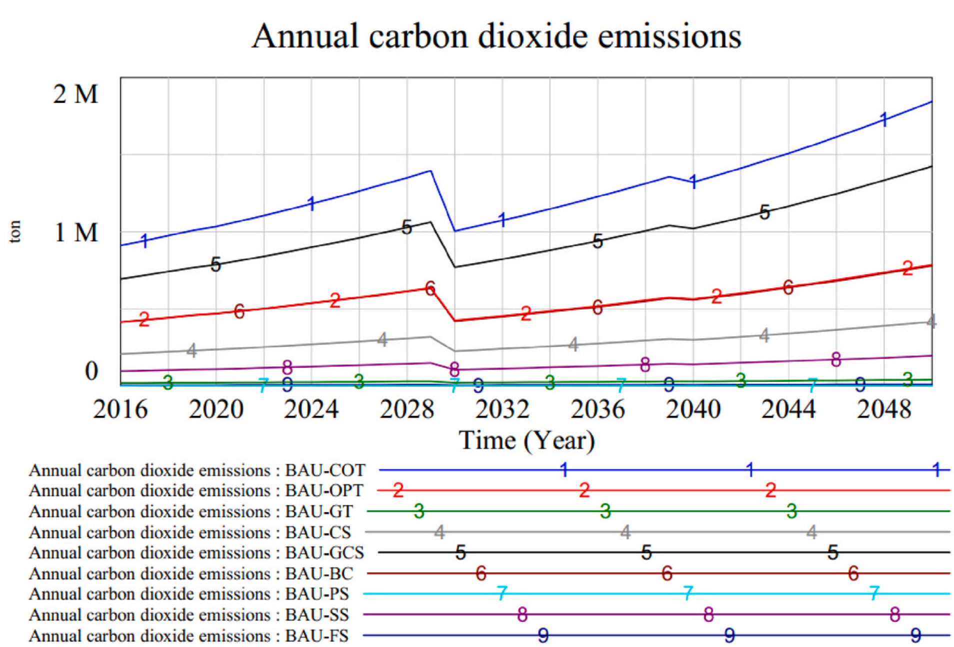

Fig. 5. Annual CO_2 emission segmentation of each kind of vessel under BAU scenario.

Fig. 6a. Total CO_2 emissions under scenario 1-3.

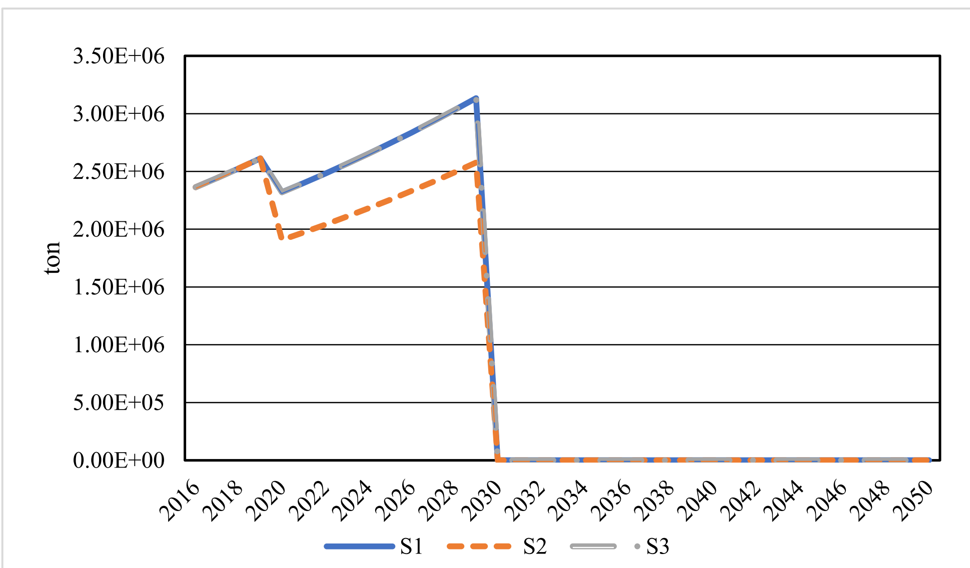

Fig. 6b. Total CO_2 emissions of HFO usage under scenario 1-3.

Emission gap between Scenario 1 and 2 is 185865 tons and the gap between Scenario 1 and 3 is 37180 tons. An interesting phenomenon is that these gaps in 2030 is not much larger than gaps in 2020, though the fuel structure differences enlarge and shipping activities increase. That's because the change on ice concentration reduced the total energy consumption, and emission gaps changed accordingly.

The third adjustment happens in 2040. The emission gap between scenario 1 and 2 is 258437 tons, and the emission gap is 203464 tons between Scenario 1 and 3. The difference between the emission gaps are expanding as the gap of usage rate of cleaner fuels between the scenarios is increasing and the increase of voyages contributed to total energy consumption. And based on the simulation results, it's obvious that the emission gap between Scenario 1 and 2 is always bigger than it between Scenario 1 and 3. The fuel structure differences between Scenario 1 and 2 happened on the usage rate of HFO and LNG mostly, and usage rate of HFO and MDO are obvious under Scenario 1 and 3. This demonstrates that CO2 emission reductions are mainly caused by replacing HFO with LNG, and the use of MDO didn't contribute much. This is because HFO and MDO have very similar specific fuel consumption and emission factors, while the specific fuel consumption and emission factor of LNG are much less than those of HFO.

4.2.2. *Ship's average speed sensitivity*

The effect of fuel structure change has been discussed in the previous section. Apart from the fuel structure, ship's average speed is another important parameter which affects overall CO_2 emission. As the operational power of the main engine follows the so-called cubic law of design speed and operational speed, the impact of ship speed on emission is significant. We set 4 different speed modes, and annual emissions are selected to reflect the sensitivity. The total 12 scenarios are classified into 3 segments, each segment with 4 scenarios. The emission results of the 3 segments are shown in Fig. 7a, b and 7c, each represents the neutral speed mode, aggressive speed mode and conservative speed mode respectively.

Although the operational power of the main engine follows the cubic law of ratio of design speed and operational speed, the annual CO_2 emission follows a nearly quadratic law based on the experimental data. For example, as seen from Fig. 7a, the ratio of annual emission under

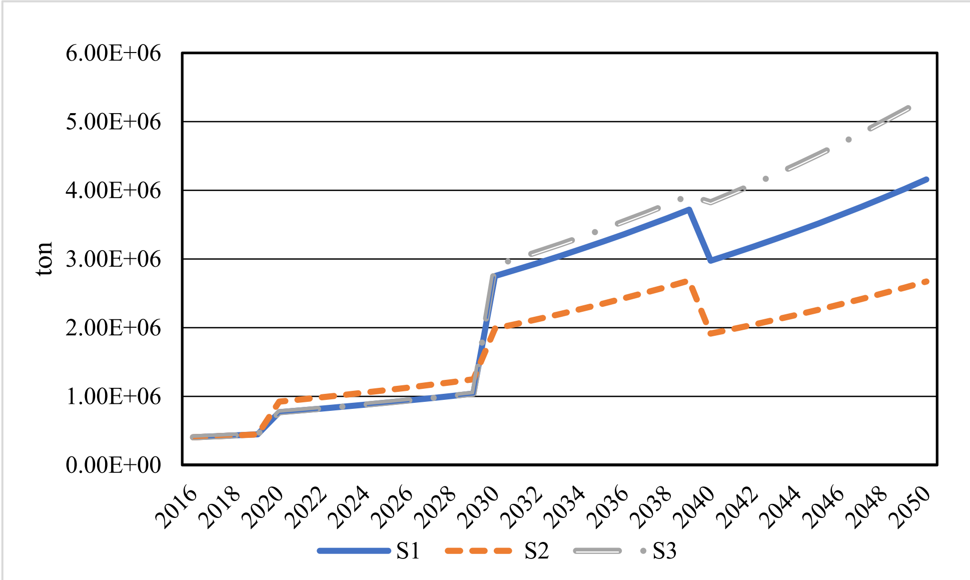

Fig. 6c. Total CO_2 emissions of MDO usage under scenario 1-3.

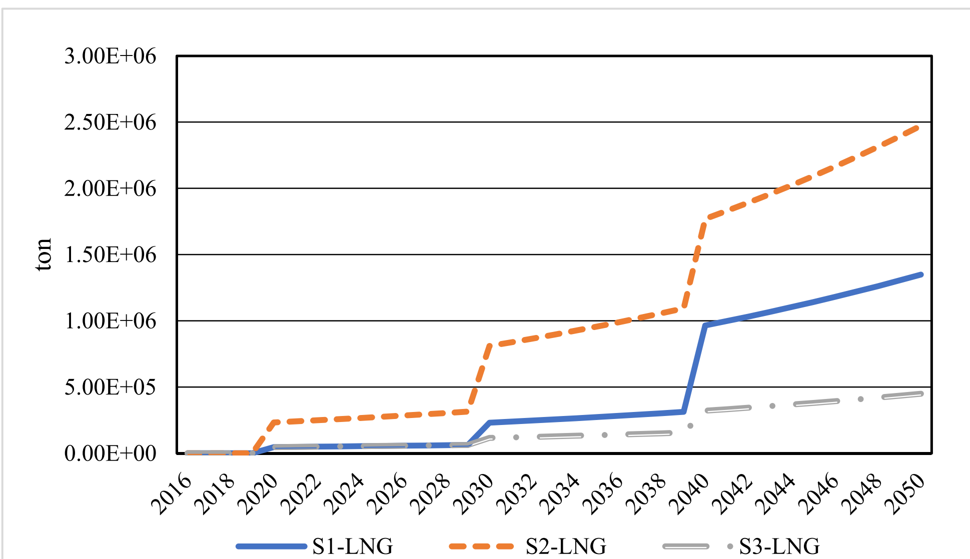

Fig. 6d. Total CO_2 emissions of LNG usage under scenario 1-3.

scenario 10 to scenario 1 is 1.17 while the speed in scenario 10 was 1.1 times of the speed in scenario 1. This result is mainly caused by the sailing time, which is inversely proportional to ship speed, as faster speed in scenario 10 leads to shorter sailing time across NSR. Power of AE has a limited effect on the emission gap.

According to Fig. 7a–c, it could be found that under scenarios where fuel structure is more traditional (more HFO was applied), emission reduction effect is more significant. Take BAU as an example, if all the voyages on the NSR reduce speed by 10% as set in scenario 4, it could reduce 15.3% CO_2 emission (in volume of 20586739 tons) by 2050 compared to the total emissions of BAU. If the average speed can be reduced to 80% as set in scenario 7, the total CO_2 emission reduction can achieve 28.6% (in volume of 38,488,087 tons). In scenario 2, if speeds reduce to 90%, total emission reduction was 15.3% (in volume of 19,624,847 tons). If scenario 3 is considered as basic scenario, total CO_2 emission reduction is 15.3% (in volume of 21,054,977 tons) when speed reduces to 90%.

The ratios of total emissions under different scenarios are listed in Table 12. We set the emission under Scenario BAU as denominator every year, and data in other columns are the ratios of other scenarios to BAU. This table summarizes and compares the emission reduction performance of every scenario. According to the data listed in Table 10, as time goes by, scenario 8 has the best performance of CO2 emission in the long run, while scenario has the worst performance with an increase in total emission.

Fig. 8 shows the emission reduction percentage of each scenario compared to BAU in 2050. It's evident that scenario 8 has the most emission reduction effect (32%) compared to BAU. There are 2 reasons contributing to this achievement: the aggressive alternative fuel usage mode and the most significant speed reduction policy (by 20%). In contrast, influencing by the traditional fuel mode and 10% acceleration, Scenario 12 produces nearly 20% more CO_2 emission than BAU. This result indicates that the fuel and speed reduction policies can be applied together, and achieved a better performance.

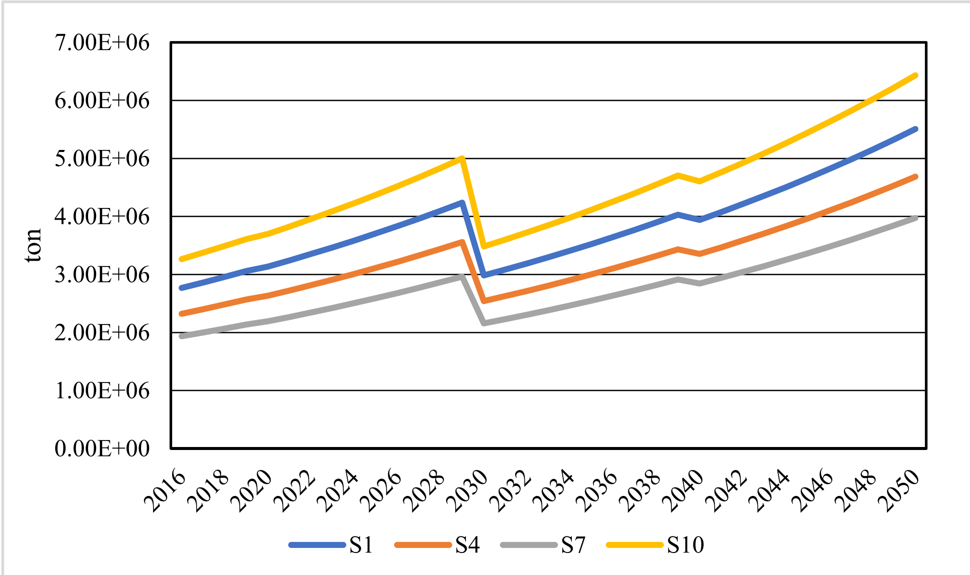

Fig. 7a. Total CO2 emissions under neutral speed mode.

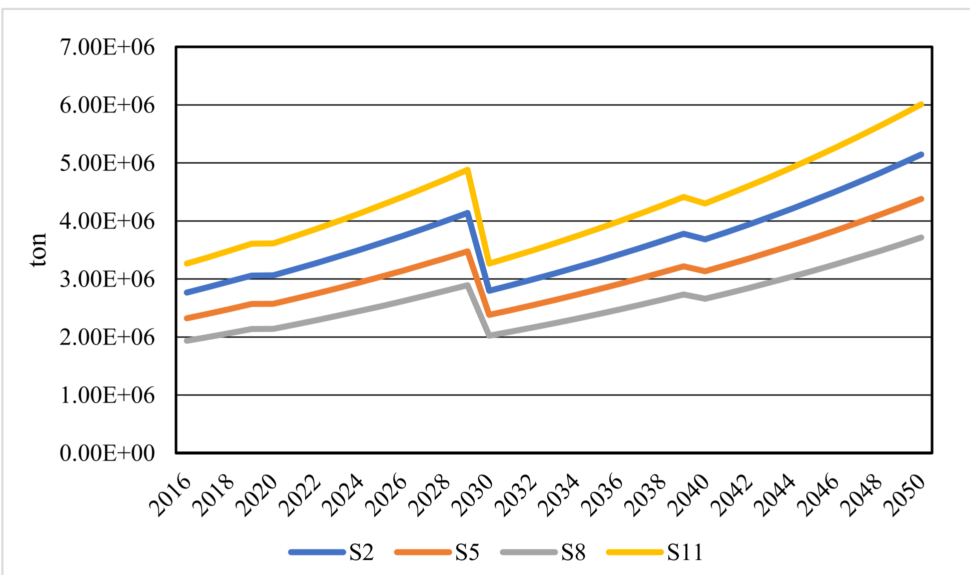

Fig. 7b. Total CO2 emissions under aggressive speed mode.

5. Conclusion and policy implications

5.1. Conclusion

To systematically investigate the projection of total shipping CO_2 emissions along NSR, this article sets up an SD model and applied it for NSR CO_2 emission study. Different scenarios on fuel structure change and ship speed change have been set to capture the CO_2 emission trend. Main conclusions are drawn as bellow:

- As the shipping emission load is affected by various factors, this paper firstly proposed an SD model incorporating the political issues (such as energy use regulation), economic issues (such as trade volume, shipping revenue), technical issues (such as impacts of ice concentration on ME, AE power), operational issues (such as fuel oil usage) together for better forecasting the overall CO_2 emissions. The reliability of the proposed SD model has been verified by the comparison of simulation data and reference data.
- 12 scenarios with different conditions of fuel usage and ship speed have been set to investigate the evolution trend of CO_2 emissions. Under the BAU scenarios, it is anticipated that by 2050 CO_2 emission on the NSR will be 134, 640, 873 tons. Among which, concerning the selected 9 ship types considered in this research, crude oil tankers accounts for most of the emissions, follows by general cargo ships.
- For the 3 specific fuel structures set in this article, the simulation results reveal that proper fuel structure adjustment policy can ease the growth of emissions. The results also indicate that LNG would be an effective fuel in Arctic shipping in CO_2 emission reduction than MDO.
- For the 4 specific ship speed scenario segments, the simulation results show that slow steaming also performs well in overall CO_2 emission reduction. But due to the dynamic link between sailing time within NSR and ship speed, the CO_2 emission follows a nearly

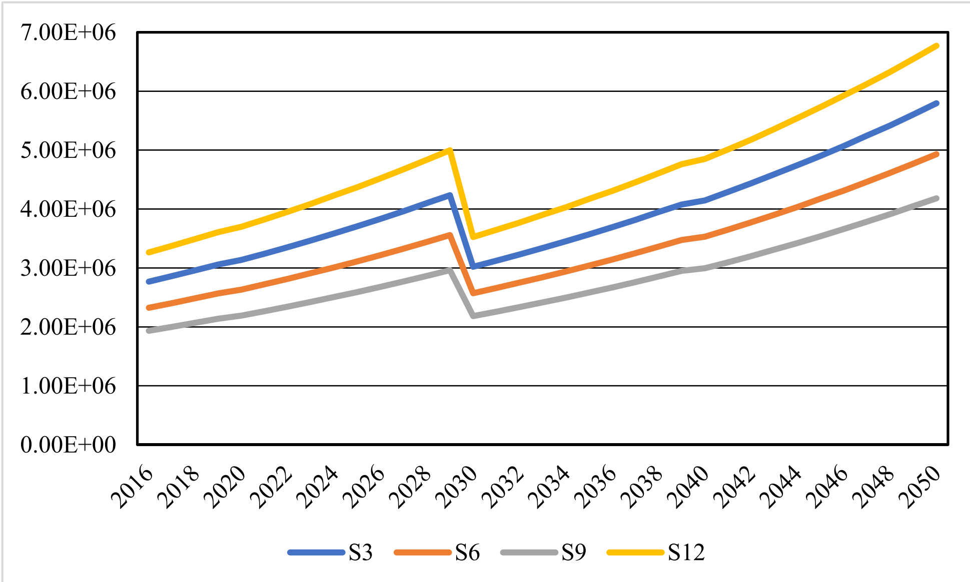

Fig. 7c. Total CO2 emissions under conservative speed mode.

Table 12
The ratio of emission under different scenarios to emission under BAU.

Scenario		1	2	3	4	5	6
Year	2016	1	1	1	0.839641	0.839641	0.839641
	2020	1	0.976755	1	0.839642	0.820123	0.839642
	2030	1	0.937699	1.012462	0.851688	0.798627	0.862301
	2040	1	0.934429	1.051623	0.850983	0.795183	0.895622
	2050	1	0.934433	1.052565	0.850984	0.795185	0.895679
Scenario		**7**	**8**	**9**	**10**	**11**	**12**
Year	**2016**	0.699209	0.699209	0.699209	1.179702	1.179702	1.179702
	2020	0.69921	0.682956	0.69921	1.179704	1.152277	1.179704
	2030	0.723274	0.678213	0.732287	1.167388	1.094657	1.181935
	2040	0.721957	0.67462	0.759828	1.168185	1.091586	1.230492
	2050	0.721959	0.674621	0.759757	1.168185	1.091589	1.229727

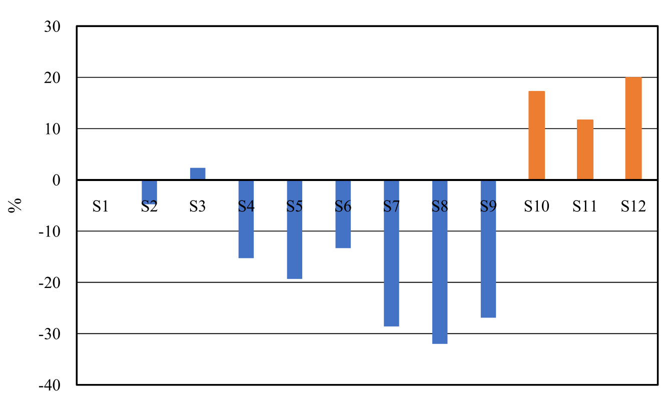

Fig. 8. The emission reduction ratios under different scenarios compared to BAU in 2050.

quadratic law based on the experimental data, compared to the conventional conclusion of cubic law.

- The simulation results also show that the ice concentration is a critical factor that can affect the overall emission. The decrease of ice concentration can reduce the emission significantly.

5.2. Policy implications

As illustrated by the simulation results, the shift of fuel usage types from conventional HFO to cleaner fuels is efficient in CO_2 emission reduction in the Arctic region. Especially for LNG, it has shown prominent performance in emission reduction than other fuels, such as MDO. But emission reduction in Arctic needs joint efforts from the parties of IMO, related governments, shipping industry, energy sector, etc. From the perspective of regulative administrations, we suggest that aggressive regulations on fuel usage should be issued to stimulate the shift the fuel usage of HFO to LNG to achieve better emission reduction effects. Besides, as demonstrated by the results, slow steaming would also be an effective way of emission reduction, so it is suggested that the governments would issue slow steaming regulations to reduce emission. While from the industry perspective, the shipowners are encouraged to keep a relatively low speed when sailing across the Arctic. Moreover, as the results indicate that crude oil tankers and general cargo ships are the two main CO_2 emitters in Arctic shipping, specific regulations on these two ship types may be considered. And the change of ice condition should be taken into consideration. Since it has a negative feedback loop with shipping emission, regulations should take advantage of this balance.

For future research, a more comprehensive SD model covering the financial performance of ship operators could be formed to simulate the emission reduction effects. As in this research the emission reduction effect is estimated on a static level, while ship operators' dynamic decisions are neglected which may lead to unanticipated shipping activities and may cause uncertain emissions. Future research could focus on those dynamic reactions and estimate the potential emission reduction systematically.

Declaration of competing interest

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.

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References

Abbas, K.A., Bell, M.G.H., 1994. System dynamics applicability to transportation modeling. Transport. Res. Part A 28, 373e390. https://doi.org/10.1016/09658564(94)90022-1.
Ammar, N.R., 2019. An environmental and economic analysis of methanol fuel for a cellular container ship. Transport. Res. Transport Environ. 69, 66–76.
Bahadir, M.C., Akdag, H.C., 2019. The system dynamics modelling for container capacity & transportation planning policies. Asian J. Shipping Logistics 35 (4), 200–212.
Berechman, J., Tseng, H., 2012. Estimating the environmental costs of port related emissions: the case of Kaohsiung. Transport. Res. Part D 17 (1), 35–38.
Cariou, P., Faury, O., 2015. Relevance of the Northern Sea route (NSR) for bulk shipping. Transport. Res. Pol. Pract. 78, 337–346.
Chen, J., Zheng, T., Garg, A., Xu, L., Li, S., Fei, Y., 2019. Alternative Maritime Power application as a green port strategy: barriers in China. J. Clean. Prod. 213, 825–837.
Chen, J., Fei, Y., Wan, Z., Yang, Z., Li, H., Choi, K.S., Xie, X., 2020. Allometric relationship and development potential comparison of ports in a regional cluster: a case study of ports in the Pearl River Delta in China. Transport Pol. 85, 80–90.
Chen, Y., et al., 2012. Study on the shipping power of dry bulkshipping market based on system dynamics. J. Wuhan Univ. Technol. (Transp. Sci. Eng.) 36, 799–803.
Corbett, J., 2009. The effectiveness and costs of speed reductions on emissions from international shipping. Transport. Res. Transport Environ. 14 (8), 593–598.
Corbett, J., et al., 2010. Arctic shipping emissions inventories and future scenarios. Atmos. Chem. Phys. Discuss. 10 (4), 10271–10311.
Dai, L., et al., 2019. An environmental and techno-economic analysis of shore side electricity. Transport. Res. Transport Environ. 75, 223–235.
Dai, L., et al., 2020. Is Shore Side Electricity greener? An environmental analysis and policy implications. Energy Pol. 137, 111144.
Dai, W.L., et al., 2018. Emission charge and liner shipping network configuration – an economic investigation of the Asia-Europe route. Transport. Res. Pol. Pract. 110, 291–305.
Danish Centre of Environment and Energy, 2018. Emissions from Shipping in the Arctic from 2012-2016 and Emission Predictions for 2020, 2030 and 2050.
Ding, W.Y., Wang, Y.B., Dai, L., Hu, H., 2020. Does a carbon tax affect the feasibility of Arctic shipping? Transport. Res. Part D 80, 102257.
Faury, O., Cariou, P., 2016. The Northern Sea Route competitiveness for oil tankers. Transport. Res. Pol. Pract. 94, 461–469.
Faury, O., Cheaitou, A., Givry, P., 2020. Best maritime transportation option for the Arctic crude oil: a profit decision model. Transport. Res. E Logist. Transport. Rev. 136, 101865.
Forrester, J.W., 1959. Advertising: a problem in industrial dynamics. Harv. Bus. Rev. 37 (2), 100–110.
Furuichi, M., Otsuka, N., 2013. Cost Analysis of the Northern Sea Route (NSR) and the Conventional Route Shipping. International Association of Maritime Economists (IAME), 2013.
Gilbert, P., et al., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. J. Clean. Prod. 172, 855–866.
Hjorth, P., Bagheri, A., 2006. Navigating towards sustainable development: a system dynamics approach. Futures 38, 74e92. https://doi.org/10.1016/j.futures.2005.04.005.
International Maritime Organization, 2017. Adopt. International code for ships operating in polar waters (polar code) (accessed January 2020). http://www.imo.org/en/mediacentre/hottopics/polar/pages/default.aspx.
Jia, S., et al., 2019. Effect of APCF policy on the haze pollution in China: a system dynamics approach. Energy Pol. 125, 33–44.
Lasserre, F., 2014. Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector. Transport. Res. Pol. Pract. 66, 144–161.
Lindstad, H., Bright, R.M., Stromman, A.H., 2015. Economic savings linked to future arctic shipping trade are at odds with climate change mitigation. Transport Pol. 45 (JAN.), 24–30.
Liu, M., Kronbak, J., 2010. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. J. Transport Geogr. 18 (3), 434–444.
Liu, et al., 2019. A system dynamics model for emissions projection of hinterland transportation. J. Clean. Prod. 218, 591–600.
Milaković, A.-S., et al., 2018. Current status and future operational models for transit shipping along the Northern Sea Route. Mar. Pol. 94, 53–60.
Mou, J., et al., 2019. Emission inventory of ship based on navigation data in the Arctic region. J. Traffic Transport. Eng. 19 (5), 116–124.
Ng, S.K.W., et al., 2012. Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. Atmos. Environ. 76, 102–112.
Østreng, W., Eger, K.M., Brit, Fløistad, Arnfinn, Jørgensen-Dahl, Lothe, L., Mejlænder-Larsen, Morten, et al., 2013. Shipping in Arctic Waters. Springer Berlin Heidelberg.
Østreng, W., 2015. Science, geopolitics and culture in the polar region: norden beyond borders. Scandia 81 (1), 135–137.
Pruyn, J.F.J., 2016. Will the northern sea route ever be a viable alternative? Marit. Pol. Manag. 43 (6), 661–675.
Qian, F., 2016. Influence vessel enlargement on emission of atmosphere pollutants. Logistics Technol. 35, 104–107.
Raj, R., et al., 2016. A techno-economic study of shipping LNG to the Asia-Pacific from Western Canada by LNG carrier. J. Nat. Gas Sci. Eng. 34, 979–992.
Raza, Z., Schøyen, H., 2014. A comparative study of the Northern Sea Route (NSR) in commercial and environmental perspective with focus on LNG shipping. In: 6th International Conference on Maritime Transport 2014.
Shibasaki, R., et al., 2018. How do the new shipping routes affect Asian liquefied natural gas markets and economy? Case of the Northern Sea Route and Panama Canal expansion. Marit. Pol. Manag. 45 (4), 543–566.
Stevenson, T., et al., 2019. An examination of trans-Arctic vessel routing in the Central Arctic Ocean. Mar. Pol. 100, 83–89.
Song, S., 2014. Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. Atmos. Environ. 82, 288–297.
Theocharis, D., et al., 2018. Arctic shipping: a systematic literature review of comparative studies The port of New York and New Jersey emission inventory for container terminal cargo handling equipment, automarine terminal vehicles, and associated locomotives. J. Transport Geogr. 69, 112–128. Available at: http://www.starcrestllc.com/projectnews.html.
University of Bremen. http://www.iup.uni-bremen.de/iuppage/psa/2001/amsrop.html accessed on October, 2020.
Vorotnikov, V., 2019. Russia invests billions into arctic dredging projects. Dredg. Port Constr. (DPC) 53 (607), 6-6.
Wan, C., et al., 2019. Analysis of risk factors influencing the safety of maritime container supply chains. Int. J. Shipping Transport Logs 11 (6), 476–507.
Wen, Y., et al., 2017. Research on System dynamics modeling for mitigation of regional vessel exhausts emissions. Environ. Sci. Technol. 40, 193–199.
Winther, M., et al., 2014. Emission inventories for ships in the arctic based on satellite sampled AIS data. Atmos. Environ. 91, 1–14.
Zhang, Y., et al., 2016. Shipping efficiency comparison between Northern Sea route and the conventional asia-europe shipping route via Suez canal. J. Transport Geogr. 57, 241–249.
Zhao, H., et al., 2016. Study on China-EU container shipping network in the context of Northern Sea Route. J. Transport Geogr. 53, 50–60.
Zhu, M., et al., 2018a. Impact of maritime emissions trading system on fleet deployment and mitigation of CO2 emission. Transport. Res. Transport Environ. 62, 474–488.
Zhu, S., et al., 2018b. The environmental costs and economic implications of container shipping on the Northern Sea Route. Marit. Pol. Manag. 45 (4), 456–477.