

THE ECONOMIC IMPACTS OF RESTRICTING BLACK CARBON EMISSIONS  
ON CARGO SHIPPING IN THE POLAR CODE AREA

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## **Abstract**

Since black carbon (BC) has become one of the most harmful pollutants and partly accelerated the melting of the Arctic sea ice, internationally mandatory policy to limit black carbon emissions in the whole Polar Code Area is on the agenda. To cope with this policy, some potential measures from both the coastal government and the shipowners, as well as the economic impacts of these measures, are considered in this paper. We analyze the daily navigation profits and the corresponding BC emissions after these measures are adopted. Since equipment-related cost is usually regarded as fixed and cannot be calculated on a daily basis, this paper also proposes an equipment investment payback period to access the time needed to achieve a balance between the investments and the profits of applying the equipment. A case of a dry bulk carrier navigating through the Northwest Passage is presented for concrete quantitative analysis. The results indicate that wind propulsion system can help shipowners mitigate the largest amount of BC emission. Wind-driven generators, which are used for auxiliary generating system, are the most economic-beneficial to shipowners under the current technology environment. Besides, we found that BC emission tax rate set by coastal governments plays an important role in the selection of different measures by shipowners.

**Keywords:** Black carbon, Arctic, Shipping, Polar Code Area, Northwest Passage

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## **Chapter 1      Introduction**

In recent years, climate change has caused a substantial melting of sea ice in the Arctic area, which can potentially turn the Arctic water from a previously restricted area for scientific research into international shipping lanes. This new development draws attention to the environmental impacts of such shipping activities on the fragile ecosystem of the Arctic. In particular, black carbon (BC), which consists of tiny particles produced by incomplete combustion of fossil fuels and biomass (Levitsky, 2011), has become the largest source of pollution in the Arctic area (Quinn et al., 2007). It is estimated to be the second largest contributor of global warming, only after carbon dioxide. Moreover, BC deposits in snow-covered regions, such as the Arctic, can also have warming effects by reducing surface albedo and promoting snowmelt (Quinn et al., 2007; McConnel et al., 2007). A study in the Siberian Arctic shows that transport using fossil fuel, especially heavy oil, as the main power source likely has contributed the most to the BC emission in Northeast Passage, more than gas flaring, power plants and open fires combined (Winiger et al., 2017). This phenomenon leads to the conflicts between shipping corporations and environmentalists, as well as between Arctic coastal countries and the tropical countries which have no economic interests in Arctic but meanwhile would suffer a lot from the global warming. Therefore, it is necessary to study the options to reduce BC emission in the Arctic, and how the shipping activities on the Arctic Passage would be affected once a mandatory regulation regarding BC emission restriction is taken into action among all Arctic area.

Apart from BC, greenhouse gas (GHG),  $\text{SO}_x$ ,  $\text{NO}_x$  and Particulate Matter (PM) are also considered as the air pollutions that can accelerate the rate of sea ice melting in the Arctic. According to the notes by the International Maritime Organization (IMO) to the UNFCCC Talanoa Dialogue (2018), regulation methods of different ship emission types proposed by IMO are shown in Table 1:

Table 1 Different ship emission types and their regulation methods

<i>Ship emission types</i>	<i>Regulation methods</i>
<i>Greenhouse gas (GHG)</i>	The total annual GHG emissions from international shipping shall be reduced by at least 50% by 2050 compared to 2008.
<i>Sulfur Oxides (SO<sub>x</sub>) and Particulate Matter (PM)</i>	The sulfur limit outside an Emission Control Area (ECA) established to limit SO <sub>x</sub> and PM emissions has fallen from 3.50% m/m to 0.50% m/m since 1 January 2020.
<i>Nitrogen Oxides (NO<sub>x</sub>)</i>	Different levels (Tiers) of NO <sub>x</sub> control apply based on the ship construction date and within any particular Tier the actual limit value is determined from the engine's rated speed. The marine diesel engine installed on a ship constructed on or after 1 January 2016 shall comply with the Tier III NO <sub>x</sub> standards, which is the most stringent limit, while operating in ECAs.
<i>Black Carbon (BC)</i>	IMO is currently in the process of collecting BC data from Member States and international organizations, and hasn't identified the most appropriate method for measuring Black Carbon emissions from international shipping yet.

Source: Notes by the International Maritime Organization (IMO) to the UNFCCC Talanoa Dialogue (2018)

Table 1 shows that IMO is still trying to figure out how to measure BC emissions, not to mention the appropriate control measures to reduce the impact of BC emissions, while the emissions of other air pollutions have already been regulated in detail. Thus, in order to fill this void, it is very crucial to propose some actions to mitigate BC emissions in the Arctic.

In 2004, the Arctic Marine Shipping Assessment (AMSA) was adopted by the Arctic Council's Working Group on the Protection of the Arctic Marine Environment (PAME) to focus on marine safety and marine environmental protection. This report highlights an unprecedented shift in the Arctic, including larger Arctic ocean passages and longer



sailing seasons due to the dramatic increase in greenhouse gas emissions over the region and the limited resilience of sea ice. This transformation will increase the efficiency of the Arctic shipping routes to some extent, and the number of vessels built specifically for Arctic navigation will also increase exponentially. Therefore, a legally binding Arctic polar rule that effectively coordinates and strengthens the international standards recommended by AMSA, including ship construction, equipment, crew training and operating standards, needs to be established (Arctic Council, 2009).

Although there are already some supporting regulations in response to AMSA Report, such as the Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic, a set of global Arctic shipping safety and environmental rules has not been formed yet (Scassola, 2013). Against this background, a Polar Code of navigation in Arctic region regulating the expected growth of vessel traffic in polar waters and addressing the risks posed by polar environmental conditions to safe navigation and environmental integrity is being developed by IMO (Anderson, 2012).

Considering the huge impacts of BC emission on the environmental protection of these coastal states and the rate at which sea ice melts resulting in route safety and length of navigable seasons, how to achieve the balance between restricting BC emissions and maximizing the economic benefits of Arctic Passages is worth studying, provided that the Polar Code is mandatorily enforced by the shipments who want to take advantage of Arctic routes to shorten the navigation distance. The objective of this paper is to construct a cost model to figure out the economic effects of different measures restricting or even banning BC emissions produced from cargo ships' fossil fuel burning in the Polar Code area.

The paper is organized as follows. Section 2 presents relevant literature review, while Section 3 details the decision model used in our analysis. Section 4 presents a case study for the analysis to be implemented. Section 5 gives out results of the analysis and the corresponding discussion. Section 6 contains concluding remarks.

## **Chapter 2      Literature review**

So far, there are few papers discussing the impacts of restricting BC emissions on the transport capacity and potential development of all shipping routes in the Arctic region, let alone the economic impacts on the shipping companies who are the main stakeholders of using these Arctic passages for cargo transportation. However, it is very important and practical to let the shipping companies know whether the measures of restricting BC emissions would greatly increase the transportation cost considering the timeliness requirements of the customers as well as the maturity of other alternative routes, such as the Suez and Panama Canals.

Among all papers referring to BC emissions in Arctic area, a large proportion of them focus on the sources or the environmental consequences of black carbon deposit in Arctic snow and sea ice. To assess the within-snow BC concentrations and the radiative effect caused from BC depositions, an aerosol model is applied by Jiao et al (2014). The results of their simulations show that there are more BC deposits in snow in Russia and Norway and less BC concentrations elsewhere in the Arctic than expected. Ren et al. (2019) verify that fossil fuel combustion is the largest contribution of the BC in the Arctic Ocean sediments based on a carbon isotopic mass balance model, and the measures to reduce BC emissions should be on the agenda since BC has become a significant confluence of CO<sub>2</sub> in the Arctic Ocean atmosphere as well as the global carbon cycle. Ikeda et al. (2017) also prove this conclusion by examining the pathways and efficiencies of long-distance BC transport from different emission sources to the Arctic.

Because of the complexity of emission sources and the diversity of transmission routes of climate pollution (Arnold et al., 2016), monitoring and controlling all sources of air pollution in the Arctic area is a very challenging and costly task. As one of the most efficient ways to simultaneously benefit both air quality and climate in the Arctic area (Zhang et al., 2018), the measures of reducing BC emissions, especially reducing fossil

fuel combustion produced mostly from the power engines of cargo transportation, have caught IMO's attention (Brewer, 2019). Brewer also finds that in terms of economic cost-effectiveness, potential policies at all levels associated with mitigating BC emission would affect shipping companies' decisions on whether to continue the Arctic shipping routes a lot. Since there are few researches discussing the exact economic effect of restricting BC emissions on Arctic cargo shipping, the contribution of this paper is to fill this gap and provide a practical piece of academic advice for the shipping companies.

### Chapter 3 The decision model

The model consists of four main equations. The first one is used to describe the power requirement of freighters using fossil fuel driven engine when traveling through the Arctic area, considering hull characteristics, sea ice conditions and auxiliary generating system on board. The second equation measures BC emission as a function of engine technology, required power and black carbon emission time in each voyage. It can provide a more intuitive picture of the amount of BC emissions that would be mitigated if various restriction measures are applied. The third one describes the proportion of BC emissions mitigated from different measures. The value of this parameter is supposed to be set by IMO. The last series of equations describe some economic factors of the freighter when traveling through the Polar Code Area. In order to compare the impact on the total transportation cost before and after the implementation of measures to mitigate BC emissions, we need to assume that vessel characteristics and each voyage distance remain the same in the same period of time.

The power model consists of the power of the freighter for propulsion  $P_s$ , the power needed for ice break  $P_{ice}$  and the power of the necessary auxiliary system  $P_{aux}$ , as expressed by equation (Lewis, 1998; Lloyd, 1998; Lindstad et al., 2014, 2016):

$$P = P_s + P_{ice} + P_{aux} \quad (1)$$

where  $P_s$  has a close relationship with the average speed in nautical miles per hour across the Polar Code Area  $v$  and engine load. Specifically, when the engine load remains constant,  $P_s$  can be approximated as being positively correlated with  $v$ . Similarly,  $P_{ice}$  can also be regarded as being positively related to vessel's speed at the sea ice limit  $v_{ice}$ . Therefore, the relationship between  $P_s$  and  $P_{ice}$  can be expressed as  $\frac{P_s}{P_{ice}} = \frac{v}{v_{ice}}$ .

The BC emission  $e$  can be calculated as (Lindstad & Sandaas, 2014):

$$e = \frac{d * P * K_{bc}}{v} \quad (2)$$

in the condition of using fossil fuel oil as the vessel's power energy, where  $d$  is the total navigation distance through Polar Code Area, and  $K_{bc}$  is the emission factor for black carbon as a function of engine load, which is a decreasing function of engine load. When engine load remains unchanged,  $K_{bc}$  is a constant value. Obviously, the amount of BC emission has a very close relationship with the type of power energy. Although the power required of a vessel for propulsion depends on the engine parameters and usually remains the same alongside the whole trip, different power energy types can determine whether there are BC emissions produced from engine while doing work. For example, when shipowner decides to use biodiesel in substitution of fossil fuel oil as the main energy for freighter propulsion, there will be no BC emissions from the whole power  $P$ , although the fuel cost will be much more expensive than using fossil fuel.

Since the potential policy of restricting BC emissions in the Polar Code Area is proposed by IMO, the proportion of BC intended to mitigate will also be set by them. The coastal governments and shipowners have to take measures to cope with this policy and meanwhile get profits as much as possible by trying to figure out the optimal solution. Whether the measures described in next section are feasible depend on the proportion of BC emissions reduction set by IMO, and how much emissions these measures are able to mitigate. Therefore, it is very significant to assume a parameter that can reflect this ratio:

$$\beta = 1 - \frac{e_i}{e_0} * 100\% \quad (i = 1, 2, \dots, n) \quad (3)$$

Here,  $\beta$  means the proportion of BC emissions IMO decides to mitigate;  $e_0$  is the original BC emissions before any policies or measures taken into practice; and  $e_i$  is the BC emissions resulted from each measure carried out by governments or shipowners. In this study, there are four main measures mentioned, so  $n$  equals 4 in this paper.

In cargo shipping, what shipowners usually consider with the purpose of maximizing their profit when using fossil fuel oil as the main power energy is the Time Charter Equivalent per day (Evans and Marlow, 1990):

$$TCE = \frac{R * W}{\frac{d}{24 * v}} - p_{fuel}[k * (24 * v)^{\gamma} + F_{aux}] - C^* - C_a \quad (4)$$

where  $TCE$  is the daily time charter equivalent;  $R$  is the freight rate;  $W$  is the deadweight available for cargo;  $p_{fuel}$  is the fuel price per ton;  $k$  is a freighter-specific constant of proportionality;  $F_{aux}$  is the fuel consumption per day for the auxiliary system;  $C^*$  is the potential black carbon emission cost on a daily basis; and  $C_a$  represent other related expenses such as generating equipment investment cost, maintenance cost, crew wages, potential icebreaker fees, insurance and financial cost specially referring to the amortization expenses incurred by the total investment expenses. It is commonly acknowledged that  $k$  has a close relationship with ship's design speed ( $V_{ds}$ ) and the fuel consumption at design speed ( $F_{ds}$ ) so that  $k = \frac{F_{ds}}{(24 * V_{ds})^3}$  (Psaraftis and Kontovas, 2013, 2014). Meanwhile, under the condition of using fossil fuel oil as the power energy, fuel consumption is closely associated with cargo displacement, navigation speed and total transporting distance (Chang, 2012). When the displacement is constant, the fuel consumption in an hour  $F$  is proportional to the speed  $V^3$ . When navigation speed is constant, the relationship between  $F$  and cargo displacement  $D$  is:  $F \propto D^{2/3}$  (Zeraatgar Hamid and Hossein, 2019; Schiller et al., 2017; Bialystocki and Konovessis, 2016; Tillig et al., 2018). Therefore,  $\gamma$  can be valued as 3 in this model assuming that freighters won't stop at the port to unload the cargo when travelling through Polar Code Area.

In the short run and in a pure competition market, both freight rate and fuel prices are exogeneous and thus outside the ship companies' control. Therefore, towards the cargo ships which use heavy fuel oil as the main power, the only adjustable variables in order to maximize the profit is the ships' full load and the speed along the Arctic routes. The

optimal speed is then obtained when  $\frac{dTCE}{dv} = 0$ , equal to:

$$v^* = \frac{1}{24} \sqrt{\frac{RW}{3pkd}} \quad (5)$$

However, towards the cargo ships which use alternative energies, this value is not their optimal speed because the initial speed is different when the main engines are resting. Frankly speaking, these alternatives can provide some additional speed other than the original speed.

Apart from the TCE, another cost factor varied from different alternatives but affecting shipowners' decision to use alternative energy sources is the equipment investment cost  $C^o$ , defined as all the alternative equipment-related costs that have no relationship with vessel speed and navigation time, but are largely dependent on power required of these vessels. There are four sections of this equipment investment cost considered in this study:

**Purchasing cost:** The cost of purchasing alternatives-related equipment, such as biodiesel engine, wind turbines, water-electrolytic devices for hydrogen fuel cells or others, can be regarded as a fixed market price depending on the power required by freighters. The installation cost is included into this section.

**Maintenance cost:** This cost is usually measured between 1% and 10% of the initial purchasing cost, depending on the type of alternatives equipment.

**Financial cost:** This cost of equipment is usually calculated with an investment amortization period of 20 years at 6% interest (Chen et al., 2011).

**Equipment-related operational expenditure:** This cost concludes equipment insurance, potential crew training fee and others. It is regarded normally as a fixed value shown in Table 1 in this study.

When researching the economic effects of this equipment investment  $C^o$  to the decision about whether shipowners should apply alternatives in substitution of fossil oil, it's very hard to do it on a daily basis, because  $C^o$  is only determined by engine

power required of the freighters for propulsion and operation. Therefore, to include this factor into the discussion, we decide to introduce a variable called equipment investment payback period  $\delta$ :

$$\delta = \frac{C^o}{TCE} \quad (6)$$

Here  $\delta$  means how many days the shipowners need to have a balance between their investments in alternatives equipment and their profits of cargo transportation through the Arctic routes, considering a potential BC emissions restriction policy that would be drafted in the whole Polar Code Area. The larger  $\delta$  is, more days it will take shipowners and less economic competitive this concerning alternative energy is.



## Chapter 4 Case study

In this section, we present a case study to discuss how different BC emission restricting measures affect TCE and  $\delta$ , including charging BC emission tax and using alternative energies. It focuses on dry bulk vessel using low sulphur fuel oil (LSFO) with a sulphur content of 0.5% when traveling through the Polar Code Area. This choice is based on the fact that the dry bulkers have occupied 40% of the total world sea freight market (Lindstad et al., 2012) and are the main vessel type transporting through the Northwest Passage (NWP) (NORDREG, 2014). Compared with HSFO, LSFO is chosen because it can reduce BC emissions by an average of 30% that may reach 80% when complemented with scrubbers although it can greatly increase the transportation cost (Lack & Corbett, 2012). Another reason for this choice is that HFO will be banned completely from the Canadian Arctic by 2024 according to the latest regulations issued by the Canadian federal government, who is instead in favor of lighter distillate fuels as the substitution. LSFO, which has been desulfurized and thus is no longer under the category of HFO (Zhu et al., 2020), is expected to be widely used in the Polar Code Area. Table 2 presents the main characteristics of typical Panamax dry bulk vessels.

In previous research associated with black carbon emission factors,  $K_{bc}$  is valued as 0.067 gram per kWh based on the high Sulphur fuel oil (HSFO) with a Sulphur content of 2.7% (Buhaug et al., 2009; Peters et al., 2011). When vessels consuming LSFO with a 0.5% Sulphur content instead of HSFO,  $K_{bc}$  is usually valued as 0.05 with high engine load and 0.2 with low engine load (Lindstad et al., 2016).

The selected navigation lane is going through the Northwest Passage (NWP) from the eastern to the western section of Canada. The reason is that under the influence of the polar easterly winds, vessels sailing from east to west are following the wind (Yoshihiro, 2010). It can ensure that there is enough wind for the entire voyage. Figure 1 shows the most-used route based on the vessels' daily positions records for the NORDREG zone and the ice coverage density alongside this route. Although it is true that some models

predict sea ice will completely disappear from the Arctic Area during mid-century,

Table 2 Vessel characteristics

<b>Panamax dry bulk vessel</b>	
<b><i>DWT (ton)</i><sup>1</sup></b>	<b>80000</b>
<b><i>Design speed (kts) (<math>V_{ds}</math>)</i><sup>1</sup></b>	<b>15</b>
<b><i>Speed at the vessel ice limit (kts)</i><sup>2</sup></b>	<b>3</b>
<b><i>Installed power for main engine (<math>P_s + P_{ice}</math>)(kW)</i><sup>1</sup></b>	<b>10500</b>
<b><i>Power for auxiliary systems in navigation (<math>P_{aux}</math>) (kW)</i><sup>1</sup></b>	<b>600</b>
<b><i>Main engine daily fuel consumption at design speed (ton /day) (<math>F_{ds}</math>)</i><sup>3</sup></b>	<b>45</b>
<b><i>Auxiliary system daily fuel consumption at design speed (ton /day) (<math>F_{aux}</math>)</i><sup>3</sup></b>	<b>3.5</b>
<b><i>Bunker price, LSFO (06/03/2020 in Rotterdam) (<math>p_{fuel}</math>) (USD /ton)</i><sup>4</sup></b>	<b>393.5</b>
<b><i>Operational expenditure (USD/day)</i><sup>2</sup></b>	<b>10400</b>
<b><i>Freight rate (USD/ton) (<math>R</math>)</i><sup>3</sup></b>	<b>12</b>
Sources: <sup>1</sup> Lindstad et al., (2014); <sup>2</sup> Lasserre (2014) ;	
<sup>3</sup> Clarksons Database (2018); <sup>4</sup> Rotterdam Bunker Prices (2020)	

there are still over 1 million km<sup>2</sup> sea ice covered in the Canadian Arctic Area during summer, occupying about 25% of the whole ocean area (Smith & Stephenson, 2013). During winter, the coverage density can only be much larger. Since our study topic is about the BC emissions restriction measures and suppose relevant policies would be proposed in the near future, it is necessary to consider the ice coverage factor. Therefore, we assume 25% of the freighters navigation route through NWP is covered with sea ice. Bulklers can only move forward at the lowest speed of 3 nm/h and still have to consume  $P_{ice}$  driven by fossil fuel when traveling through the ice-covered area, while in ice-free open water, bulklers can travel at the optimal speed  $v^*$  and can replace fossil fuel with alternatives as the main power energy. The ice-covered sea distance  $d_{ice}$  is 195

nm and the open water distance  $d_{ow}$  is 585 nm.

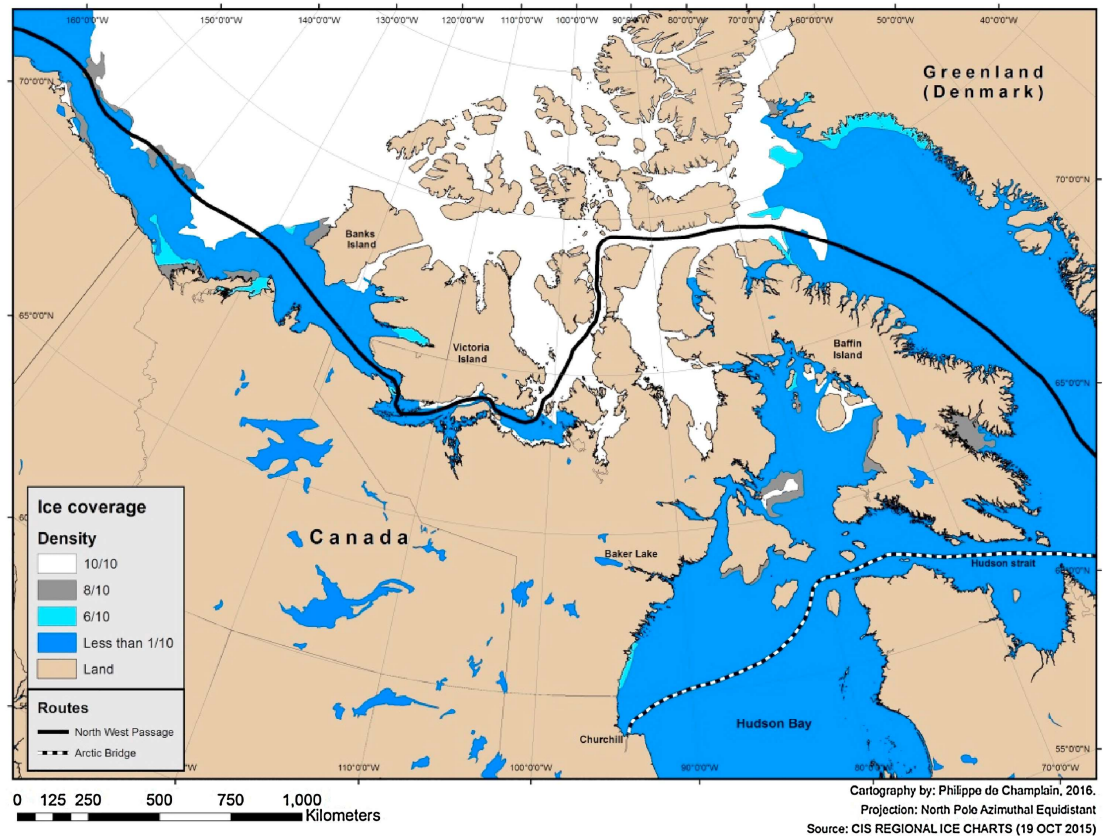


Figure 1 Most-used route through NWP and ice coverage density alongside this route, 19 October, 2015.

Source: Canadian Ice Service Arctic Regional Sea Ice Charts. (2015). National Snow & Ice Data Center.

Although shipping industry is widely considered as the most efficient goods transporting mode, especially in the area of bulk goods transported over long distances, the amount of GHGs including BC emitted by these freighters is to a large extent underestimated (Boone, 2012). According to the report released by International Centre for Trade and Sustainable Development (ICTSD), the shipping industry carries more than 90 percent of the world's goods, resulting to the fact that the total GHGs emissions from international shipping industry have already exceeded those emissions from most countries listed in annex I to the Kyoto protocol (Friedrich et al., 2007). With regard to the contribution of cargo shipping industry to total BC emission, the amount is also

largely underestimated. According to the research findings by Corbett et al. (2010), it seems that BC emissions originated from international cargo shipping are about 71000 to 160000 metric tons annual, approximately equal to 15% of total Particulate Matter emitted from cargo shipping and about 2% of total global BC emissions from all sources. The consequence is even more severe in terms of Arctic shipping since Corbett et al also find that the proportion of BC emissions from Arctic shipping in the global BC emissions inventory will rise from 0.6% in 2004 to over 2.3% in 2050. Among all BC pollution sources in the Arctic area, tugboats are thought to be the biggest polluters, while large oil tankers and container ships are thought to be emitting twice as much as originally thought (Lack et al., 2008). As a result, the warming of Arctic area will be largely accelerated if BC amounts are not controlled and mitigated through some restriction measures in the aspect of Arctic cargo shipping industry.

Based on equation (3), the original BC emissions taking sea ice coverage factor into consideration before any policies or measures taken into practice can be expressed as:

$$e_0 = \left( \frac{d_{ice} * P}{v_{ice}} + \frac{d_{ow} * P}{v_{ow}} \right) * K_{bc} \quad (7)$$

The following parts focus on some potentially feasible measures to mitigate BC emissions and how they will affect TCE of bulkers if being taken into practice.

#### **4.1 Coastal government's measure: Charge BC emission tax**

The most practical and straightforward measure that can be carried out into Polar Code is to charge BC emission tax for Arctic shipping. Although there is more pressure on the IMO to enforce a ban on heavy fuel, which is the most widely used fuel in goods shipping nowadays in the Arctic, and to ask the shipowners to use cleaner alternative energies mandatorily, it is not easy for all coastal countries to reach an agreement of alternative energy standards, especially the opposition of Russia for instance (Over the Circle, 2018). Among all three routes across Arctic Ocean, Northern Sea Route (NSR)

passes mostly through Russian and Norwegian controlled waters while Northwest Passage (NWP) mostly through Canadian-controlled waters. The third one is through the North Pole, which is still fully covered with thick ice and cannot be developed and utilized in the foreseeable future. The complexity of ownership of arctic waters makes it more difficult to reach a consensus between IMO and all coastal countries.

However, it is possible that IMO can propose a mandatory standard of the reduction of BC emissions in the Polar Code Area<sup>1</sup>. To cope with this regulation, all coastal countries and shipowners have to find alternative measures. In order to minimize the emission tax cost, shipowners have to adopt cleaner energies to reduce BC emissions with or without the introduction of a BC tax charged by governments. In other words, the introduction of a BC tax by coastal governments in response to this IMO's regulation cannot help to reduce emissions, if they do not reach an agreement on the emission rate during their meetings. It is more possible that IMO and governments will discuss together about everything related to BC in the Arctic Area, and finally have an agreement on both the regulations and the corresponding measures. Therefore, we assume that charging BC emissions tax is an enforcement measure attached to the policy of restricting BC emissions in the Polar Code Area proposed by IMO, although only coastal governments have the right to impose a completely new tax. Therefore, immediately when IMO proposes this policy, all coastal governments will start to charge emission tax with the same emission rate mandatorily.

In this case study, BC emission tax will be charged by the Canadian government mandatorily due to the navigation lane selected (which is NWP). Since shipowners' decision on the choice of power energy does not have direct relationship with BC emission tax, they can still use LSFO to navigate through NWP as long as they are willing to pay the tax. Therefore, in this section, we build models under the condition

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<sup>1</sup> There is indeed a possibility that imposing a tax on BC will cause the confusion with the taxes on other pollutants such as carbon,  $SO_x$ ,  $NO_x$  and PM emissions because of its uniqueness (not a specific type of gas that is dominated by one chemical element and hard to measure its emissions accurately). But we believe that these possible concerns deserve to be discussed in a brand-new paper. Otherwise, the content of this article will be very jumbled and will not highlight the main research question this article was originally intended to solve.

that shipowners would not take actions in substituting LSFO when coming across this emission tax. Moreover, in the following episodes discussing the economic effects of different alternative energies, BC emission tax will be considered as the mandatory measures shipowners have to comply, but simultaneously shipowners would find the most suitable alternatives to replace LSFO as their measures to cope with the IMO's policy of restricting BC emissions.

Normally, emission tax is positively correlated with BC emissions. Therefore, taking the sea ice coverage factor into consideration, in the case of bulkers traveling through NWP, daily BC emission tax  $C^*_{bc}$  can be expressed as:

$$C^*_{bc} = k_{bc} * \frac{ev}{d} = k_{bc} K_{bc} * \frac{\frac{d_{ow}P}{v_{ow}} + \frac{d_{ice}P}{v_{ice}}}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} \quad (8)$$

Here  $k_{bc}$  is the emission tax rate set by the Canadian government.

Combining the equation (2), (4), (7) with ice coverage factor, TCE after charging BC emission tax comes to:

$$TCE_{tax} = \frac{RW}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} - p_{fuel} [k * \frac{v_{ow}^3 \frac{d_{ow}}{24 * v_{ow}} + v_{ice}^3 \frac{d_{ice}}{24 * v_{ice}}}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} + F_{aux}] - C^*_{bc} \quad (9)$$

## 4.2 Shipowner's measures: Alternative energies

This is the most effective and immediate measure to slow down the warming process in the Arctic and has been generally regarded as the most ideal solution to ban BC emissions by environmentalists because it can block BC emissions from the root source once implemented. To help preventing BC pollution and other air pollution caused by GHGs and sulfides, the obligations and challenges of the maritime sector are to find

alternatives to petroleum-based fuels (Fernández Soto et al., 2010; Ren and Lutzen, 2017).

Although there are difficulties in promoting alternative energies, the urgency of preventing BC emissions and mitigating climate warming in the Arctic area requires this most efficient measure to be discussed. Moreover, the shipping companies need to know exactly how this measure would cost them. Therefore, it is valuable to consider different alternative energies in our model. According to Schenker's research (2007), the alternatives can be classified as seven categories: sails, kites, biodiesel, wind driven generators, photovoltaic panels, hydrogen fuel cells and nuclear power. To study the economic effects of these alternatives towards shipping companies, we assume there are no technical problems in installing the corresponding devices into the ships, and all freighters driven by these alternatives can navigate through the Arctic routes smoothly and safely.

#### **4.2.1 Wind propulsion system**

As one of the most environmental-friendly energies, natural wind has already been proven that can propel freighters forward in the past. There have been several studies discussing the application prospects of offshore wind power in the field of maritime propulsion, such as on sail assisted ships (Milić & Klarin., 2016; Li et al., 2020) and on marine horizontal-axis wind turbine assembly (Barkla., 1984; Talluri et al., 2016). It has not been widely used recently, nevertheless, because compared with fossil fuel, the conversion of traditional wind energy into kinetic energy is relatively inefficient, resulting in a greater negative impact on the cost and timeliness of ocean transportation. However, with the increasing attention to marine and air pollution and the increasingly mature research on the improvement of sails, the application prospect of wind-driven system is getting wider and wider. Especially in the Arctic area where the wind is abundant, wind-powered freighters are already technically feasible (Amiadji et al.,

2017). The research results from Lee et al. (2016) concluded that 15-25% of existing propulsion could be replaced by a wing sail, thereby saving an equal proportion of fossil fuel. Through the use of natural wind power, sails can assist with freighters traveling without consuming too much fuel by the ship's main engine. Another kind of sails that deserves to be considered is kite sails. The main difference between wing sails system and kite system is the efficiency of converting wind energy into kinetic energy. According to Fernández Soto et al. (2010), they describe the working principle of kites as followed:

*“Their efficiency is based on the high altitude at which they operate, where wind speeds are much greater than on the sea surface. This produces greater thrust forces using the same sail area associated with traditional sails. The area of the kites used to tow cargo vessels varies between approximately 150 and 600 m<sup>2</sup>. They are attached to the vessel by means of a cable to the so-called towing point (normally situated forward of the forecastle), and hence to the winch, which will release or pull the cable depending on the thrust required. A computer on the bridge processes all the information received by the system's sensors and controls the skysail accordingly”.*

Based on such description, it seems that the kite system is more efficient and have the potential to become more widespread along the freighters navigating through Polar Code Area because of the high altitude than the traditioned sail. Besides, compared with sails installation, kite system seems to be more easily installed so that the fixed cost associated with this procedure will be much lower. To sum up, this system is more practical and deserves more attention from Arctic shipping companies in terms of economic factors and the efficiency of fuel burning.

Since the wind propulsion systems are technically feasible to replace the main engine powered by fossil oil in the near future, it is reasonable to suppose that freighters can completely be driven by sails in ice-free water. However, there is no scientific evidence showing that the kinetic energy generated by wind energy can be large enough to break the ice. Besides, the freighter's auxiliary power system cannot benefit from a wind propulsion system either. Therefore, in this study, freighters still have to consume LSFO



for internal power generation and travel through ice-covered area while using wind propulsion systems when navigating in open water. The BC emission  $e$  will decline a lot due to the fact that there will be no pollution issues when using sails. Hence, the equation of  $e$  can be expressed as:

$$e = \left( \frac{d_{ice}(P_{ice} + P_{aux})}{v_{ice}} + \frac{d_{ow}P_{aux}}{v_{ow}} \right) * K_{bc} \quad (10)$$

In this case, based on equations (3) and (7), the mitigating proportion of BC emissions  $\beta$  equals to:

$$\beta = 1 - \frac{d_{ice}P_{ice}v_{ow} + d_{ice}P_{aux}v_{ow} + d_{ow}P_{aux}v_{ice}}{d_{ice}Pv_{ow} + d_{ow}Pv_{ice}} * 100\% \quad (11)$$

Combined with the governments' potential mandatory measure of charging emission tax,  $TCE$  after utilizing wind propulsion system can be addressed as:

$$TCE_{wind} = \frac{RW}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} - p_{fuel}[k(24 * v_{ice})^3 + F_{aux}] - \frac{k_{bc} * e}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} \quad (12)$$

Here, average speed in ice-free water  $v_{ow}$  is closely related to the wind speed of the day. In fact, the measurement of  $v_{ow}$  not only depends on wind speed  $v_w$ , but also has a close relationship with shape of the sails, angle of the wind attack, density of the air that passed the sails, towing cable tension and the angle sails against ship. The calculation of  $v_{max}$  under the wind condition can be very complicated from an aerodynamic standpoint. In order to simplify computational difficulty,  $v_{max}$  will be approximated as a value not exceeding the wind speed. Here,  $v_w$  will be valued as 13.6 kts (Przybylak et al., 2003), the average wind speed in October.<sup>2</sup> Therefore,  $v_{ow} \leq 13.6$  under this condition.

No matter what kind of wing propulsion systems shipowner decides to use, wind sails

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<sup>2</sup> We choose October to correspond to the information in Figure 1, which shows the most-used route through NWP and ice coverage density alongside this route in October. Since both navigation route and ice-free waters distance in this case derived from this figure, I think choosing the average wind speed in October can make this case more convincing.

or kite sails, additional sails equipment investment cost  $C^o$  needs to be taken into consideration. Table 3 shows the specification data of wind propulsion systems which are feasibly applied into freighter navigation through the NWP, and the calculation of  $C^o$ .

Table 3 Specification data of wind propulsion systems and the calculation of  $C^o$

System	Wind sail	Kite sail
<b>System and assembly cost (USD)</b>	5030000	1140000
<b>Maintenance cost (USD)</b>	503000	128000
<b>Financial cost (USD)</b>	3621600	820800
<b>Operational expenditure (USD)</b>	$10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$	$10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$
<b>Equipment investment cost (USD)</b>	$9154600 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$	$2088800 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$

Source: Fernandez Soto et al., (2010)

Based on these calculations, equipment investment payback period  $\delta = \frac{C^o}{TCE}$  can be easily got. The results and relative discussions are shown in the next sections.

#### 4.2.2 Biodiesel

Biodiesel has rapidly gained interests among scientists as the most potential alternative of fossil fuel in recent years because of its renewable and versatile characteristics. It can be obtained from a wide range of sources, such as animal fat and discarded cooking oil. Besides, biodiesel can help reducing harmful gases, including BC produced from the auxiliary power system. Firoz's study shows that biodiesel can deduct 78% of GHGs

compared to conventional diesel fuel (Firoz, 2017). Although biodiesel has a lot of advantages, it has many limitations and shortcomings. All benefits and disadvantages are shown in Table 4.

Table 4 All benefits and shortcomings of biodiesel

	<i>Characteristics</i>		<i>Explanations</i>
<i>advantages</i>	Renewable		The source of biodiesel is limitless.
	Versatile		Biodiesel can be obtained from a wide range of sources depending on the geographical location.
	Easily used		Biodiesel can be used in any conventional diesel engines as 100% or mixed with other petroleum diesel without engine modification (Mohd Noor et al., 2018).
	Lower emissions	GHGs	78% of GHGs can be deducted using biodiesel (Firoz, 2017).
	Biodegradable		Biodiesel can biodegrade in watery solutions with a rate reaching 85%-88% in a 28-day period (Firoz, 2017).
	Non-toxic and safe		Biodiesel doesn't contain any poisonous substance such as sulfur or aromatics. It also has a higher flash point than petroleum diesel, making it less flammable.
	Positive balance	energy	The energy balance is positive, with a ratio of 1 (input)/ 2.5 (output) based on Fernández Soto's study (2010).

<i>Shortcomings</i>	Higher viscosity and density	High biodiesel viscosity and density values can sometimes cause corrosion of engine, especially its fuel injection system if biodiesel is run on for a long time (Tesfa et al., 2010).
	High production cost and high market price	Currently, the production cost of biodiesel is slightly higher than conventional petroleum diesel cost.
	Lower energy content	Biodiesel has less energy content than petroleum diesel, resulting to the fact that the consumption of biodiesel is much more than that of petroleum diesel. Specifically, ,1163 liters of biodiesel are needed to substitute 1,000 liters of diesel oil for support of the same engine power (Fernández Soto et al., 2010).
	Higher $NO_x$	Although biodiesel can largely mitigate BC emissions in the Arctic area, it will emit $NO_x$ more than petroleum diesel instead, increasing the possibility of acid rain in the Arctic area ((Mohd Noor at al., 2018).

Based on the Table 4, we can find that cost is the most critical factor limiting whether biodiesel can replace petroleum fuels, such as heavy oil which is mostly used among Arctic cargo transportation currently. Apart from the higher production cost and market price, higher viscosity and density can cost biodiesel users more maintenance expenditure than petroleum diesel users, because former engine has to be repaired more frequently in prevention of corrosion (Woo et al., 2016). Therefore, it is necessary to calculate how much more a dry bulk vessel has to spend taking all these factors into consideration, compared with other alternative energies when studying the application

prospect of biodiesel in Polar Code Area.

The present biodiesel is mainly applied into automotive engines. Although it has been proven that with the similar Carbon Numbers, biodiesel can be used in place of fossil fuel as the engine power energy (Mythili et al., 2014), the application of biodiesel in vessel propulsion system is still very few, mostly because marine-based and land-based fuel systems and operational environment are different and there is no specific international marine-grade biodiesel standard so far (Lin, 2013). Consequently, when selecting suitable biodiesel for freighters, we can only refer to relevant research materials. Ng et al. (2010) found that although pure biodiesel can be used without modification to the original engine structure, its high kinematic viscosity is detrimental to the quality of the combustion spray. Moreover, due to the high temperature of fuel pour point and cloud point, the direct use of pure biodiesel will also affect the engine's low temperature start-up performance, causing a certain risk of sudden engine failure and loss of power during the voyage (Prucol et al., 2014). In terms of cargo transportation through the Polar Code Area where climate and navigating conditions are more severe, it is very hard to apply B100 (which means pure biodiesel) to the main energy for propulsion, although B100 can significantly reduce BC emissions. A more realistic measure is to apply B100 to auxiliary generating system while still using LSFO as the main power energy for freighter propulsion. Based on this discussion, BC emission  $e$ , mitigating proportion of emissions  $\beta$  and  $TCE$  after using B100 are expressed as follows:

$$e = \left( \frac{d_{ice}(P_s + P_{ice})}{v_{ice}} + \frac{d_{ow} * P_s}{v_{ow}} \right) * K_{bc} \quad (13)$$

$$\beta = 1 - \frac{d_{ice}P_s v_{ow} + d_{ice}P_{ice} v_{ow} + d_{ow}P_s v_{ice}}{d_{ice}P v_{ow} + d_{ow}P v_{ice}} * 100\% \quad (14)$$

$$TCE = \frac{RW}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} - p_{fuel} k \left( \frac{v_{ow}^3 \frac{d_{ow}}{24 * v_{ow}} + v_{ice}^3 \frac{d_{ice}}{24 * v_{ice}}}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} \right) - 1.163 * p_{bio} F_{aux} - \frac{k_{bc} * e}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} \quad (15)$$

Here,  $p_{bio}$  of B100 biodiesel is valued as 605.6 USD/ton (Bourbon, 2020).

Under such conditions, the optimal open water speed  $v^*$  exists and can be obtained through  $\frac{dTCE}{dv_{ow}} = 0$ , so as for  $TCE_{max}$ . Since the characteristic of easily used means biodiesel can be blended with fossil diesel oil without engine modification, there are no other specific biodiesel equipment needed other than the original diesel engine equipment, thus can help shipowners save a lot in terms of  $C^o$ . The calculation result of  $C^o$  is shown in Table 6.

#### 4.2.3 Other zero pollution alternative energies

In this section, other zero pollution alternative energies include wind driven generators, photovoltaic panels and hydrogen fuel cells, all of which come from the natural environment and have almost negligible side effects (Pain, 2017). When applied into vessel navigation, this kind of alternative energies is widely used to generate electricity for auxiliary systems, such as the ship's lighting system, instead of being used to provide propulsion under the current technological condition. Therefore, with the main power engine still driven by fossil fuel oil, these alternatives contribute little to the restriction of BC emissions in the Arctic area. In spite of this, the economic analysis of using these energies to generate internal electricity is still valuable because these zero pollution alternative energies have always been widely discussed as the promising alternatives to fossil fuel oil in power generation system on board. To restrict BC emissions originally produced from the burning of fossil fuel oil used for power

generation within the ships, this kind of alternatives has the potential to replace fossil fuel.

Since the main power engine of the freighter for propulsion is still driven by LSFO in this case, and this kind of alternatives will not produce more BC emissions when generating electricity, the basic equations of BC carbon  $e$ , mitigating proportion of emissions  $\beta$  and  $TCE$  are almost the same among these alternatives:

$$e = \left( \frac{d_{ice}(P_s + P_{ice})}{v_{ice}} + \frac{d_{ow}P_s}{v_{ow}} \right) * K_{bc} \quad (16)$$

$$\beta = 1 - \frac{d_{ice}P_s v_{ow} + d_{ice}P_{ice} v_{ow} + d_{ow}P_s v_{ice}}{d_{ice}P v_{ow} + d_{ow}P v_{ice}} * 100\% \quad (17)$$

$$TCE = \frac{RW}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} - p_{fuel} k \left( \frac{v_{ow}^3 \frac{d_{ow}}{24 * v_{ow}} + v_{ice}^3 \frac{d_{ice}}{24 * v_{ice}}}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} \right) - \frac{k_{bc} * e}{\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}}} \quad (18)$$

Here,  $TCE_{max}$  can be obtained when  $\frac{dTCE}{dv_{ow}} = 0$ . Apparently, their equipment investment cost  $C^o$  are different, so as their equipment investment payback period  $\delta$  are. Actually, since all these alternative energies applied in marine are still in the stage of development and the related technologies have not undergone enough test to prove that they can adapt to the complexity of Arctic shipping, their  $C^o$  are relatively higher than any other alternatives mentioned in the preceding paragraphs. In the next few paragraphs, I will discuss the potential applications of each alternative energy on the auxiliary generating system of freighters navigating through NWP.

Wind-driven generator is used to convert natural wind energy into auxiliary electrical energy, different from sails system which is used to provide propulsion power. Its application on vessels navigating through Arctic Area is very attracting considering that the wind force is greater not only at sea than on land, but also at higher latitudes. We don't need to worry that freighter's auxiliary generating system would have stopped

working if there are no adequate wind conditions in the Arctic Area. However, the most influential characteristic of wind-driven generator for whether it can be applied into freighters is that all wind turbines have to be installed on the vessel's open deck. It means some kinds of vessels with cargos stowed on open decks, such as container ships, cannot apply this technology to their auxiliary generating system. Nor would it be installed on other special-purpose vessels, such as passenger ships, chemical tankers and gas carriers. It can be installed, however, on bulk carriers and oil tankers through the Arctic Area because in this case, the wind turbines can be installed symmetrically on the port and starboard sides of the ship (Wu, 2014; Fernández Soto et al., 2010).

There are two significant applications in vessels, generating electricity alone with larger blade parameters and higher axis rotation, or as part of a hybrid energy system, working in combination with hydrogen fuel cells. For the first application, these wind generators need to be specially designed and developed to provide a bulk carrier whose power for auxiliary engine is as large as 600kW, and have enough spare space for cargos as well. Most popular theory is to install two bucket foundations with offshore wind turbines and increase air pressure inside the bucket foundations to increase the stability (Zhang et al., 2015). Meanwhile, this theory also proves that the ballast in the ship has little effect on the movement of the ship, while increasing draft will decrease the stability. Therefore, every novel freighter equipped with wind generator systems is not allowed to be refitted to increase the ship's draft. For the second application, wind turbines do not have to be designed specially and can merely need to provide enough electricity for water electrolysis. The most common type of wind turbine in this application is HAWT (horizontal-axis wind turbine). It's the same type as that used in the wind field on land. To increase the stability and safety of the freighters navigating through the NWP under the complicated climate and sea conditions, several turbines with less power are more practical than a large wind turbine with longer blade diameters. Therefore, associated with hydrogen fuel cells as well, the equipment investment cost  $C^o$  of wind-driven generators of second application is much higher than that of first application. Their  $C^o$  calculations are shown in Table 6.



Similar with wind-driven generators and sail systems, photovoltaic panels also convert a renewable energy into auxiliary electrical energy, in this case this energy coming from sun. Photovoltaic power generation has become a mature technology that directly converts light energy into electricity by utilizing the photovoltaic effect of semiconductor interface. When solar cells being packaged and protected in series to form a large area of solar cell modules (Bollinger & Gillingham., 2012), the whole photovoltaic panels can provide enough electricity for vessel's auxiliary system, and this unique technology can make the components beautiful, strong and snow resistant. Therefore, we don't need to worry about the safety of installing photovoltaic panels on freighters through the Arctic Area. Besides, there are also other advantages that can make this alternative energy feasibly applied in vessels. First, excellent low light effect of photovoltaic panels can make it possible to absorb light energy and convert it into electricity even during the night or on a snowy day (Marczyński et al., 2019). Second, the characteristics of high conversion rate and high output efficiency help solar panels store and generate electricity more efficiently. However, similar with wind-driven generators, the most challenging problem of this alternatives, besides navigating at night or on snowy days, is that all photovoltaic panels have to be equipped on the open deck, making it only possible to be applied into bulk carriers or oil tankers through the Arctic Area.

There're also two applications of photovoltaic panels, generating enough electricity for auxiliary system, or used to work in combination with hydrogen fuel cells. The equipment investment cost analysis of these two applications is also similar with that of wind-driven generators. It is estimated that the first application will cost much less than second application associated with hydrogen fuel cells. The calculation results are shown in Table 6.

Hydrogen fuel cell is a power generation device that converts the chemical energy of hydrogen and oxygen directly into electricity. The basic principle is the reverse reaction of electrolysis of water. Hydrogen and oxygen are supplied to the anode and the cathode respectively. After the diffusion of hydrogen through the anode and the reaction of

electrolyte, electrons are released to the cathode through the external load (Bögel et al., 2018). The key technology of hydrogen fuel cell is that the electrode is made of special porous material, which is also the reason why equipment investment cost  $C^0$  of this cell is very expensive compared to other alternatives. The main advantages and disadvantages of hydrogen fuel cell when applied into the auxiliary generating system of a vessel are shown below:

Advantages:

1. Hydrogen stocks are limitless. It can be produced by electrolysis of water and any hydrocarbon, such as natural gas, methanol, ethanol, biogas, etc.
2. It can be part of hybrid systems. If hydrogen is produced from renewable sources (photovoltaic panels, wind power, etc.), the whole cycle is completely free of harmful emissions.
3. It is proved that the efficiency of yielding electricity from hydrogen fuel cell is two to three times more than from an internal combustion engine (Díaz et al., 2018).
4. The level of noise produced is much less than a quarter of that produced by diesel generators.

Disadvantages:

1. Under the current technology environment, the estimated equipment investment cost of hydrogen fuel cells is much higher than any other alternative energies.
2. There are still certain risks for freighters in storage and in terms of persistence and resistance to extreme weather in the Arctic Area, since whether this technology can adapt to the complicated weather conditions through the Arctic Area is still in the theoretical stages and has not undergone enough testing (Chade et al., 2015).

The characteristics of limitless hydrogen stocks and zero harmful emissions make hydrogen fuel cell the most ideal power energy for vessels navigating through the Arctic Area, once IMO decides to draft a policy banning black carbon emissions in the whole Polar Code Area in the near future. Combined with photovoltaic panels or wind power, the whole hybrid system has the potential to be in substitution of marine petroleum diesel oil completely not only in the aspect of auxiliary generating system, but in main engine for propulsion as well. The largest obstacle is the equipment investment cost  $C^o$ . Apart from high purchasing cost and high financial cost of hydrogen fuel cell devices, the production of hydrogen has to make shipowners purchase wind-driven turbines or photovoltaic panels as well. The specification data and corresponding results are shown in Table 6.

#### **4.3 Nuclear-powered vessels**

Besides all alternative energies mentioned in detail above, nuclear power is also another substitution to fossil fuels. Recent research has developed a small modular Pressurised Water Reactor specially to meet the requirements of large container ships (Peakman et al., 2019). However, while nuclear-powered ships have been operating successfully at sea for decades, most of them belong to the naval systems and the rest are largely derived from naval vessels as well, such as icebreakers (Spyrou, 2006; Bukharin, 2006; Peakman et al., 2019).

There are numerous reasons to explain this phenomenon. First, the fuel types utilised in naval systems have considerable disadvantages when used in the commercial environment, mainly because of their relatively high cost compared to conventional fuels. Second, to achieve long core life, highly enriched uranium is a necessity because of the low uranium densities, greatly increasing safety hazards and fuel storage difficulties (IAEA, 2003; Ingersoll, 2009). Although technical solutions have been developed to ensure the safety of nuclear waste disposal, finding a country willing to

host these nuclear wastes is very politically complicated considering the oppositions towards nuclear power within many countries (Gupta 2018). Moreover, these oppositions may restrict vessels to enter these countries' waters and ports. Another potential problem will be the needs and costs associated with trained personnel capable of operating nuclear reactors on board, as well as reactor behaviour in the event of a collision, sinking and grounding of the vessel (Häyrynen, 2003). All these issues make the application of nuclear power in commercial cargo ships still immature.

Therefore, we will not include nuclear powered vessels in the calculations in this article.

## Chapter 5 Results and Discussions

To clarify the parameters and variables in this study, Table 5 summarizes the explanations of all parameters and variables used in our models as well as their values or functional form adopted in the case study.

Table 5 All parameters and variables in this study

Parameters or variables	Explanations	Values or interrelationships
$P$	<i>The whole power bulk needed<sup>1</sup></i>	11100 kW
$P_s$	<i>Power needed for propulsion</i>	$10500 * \frac{v_{ow}}{3+v_{ow}}$ kW
$P_{ice}$	<i>Power needed for ice break</i>	$10500 * \frac{3}{3+v_{ow}}$ kW
$P_{aux}$	<i>Power needed for auxiliary generating system<sup>1</sup></i>	600 kW
$v_{ow}$	<i>Vessel speed in open water</i>	Unknown
$v_{ice}$	<i>Vessel speed at the ice limit<sup>2</sup></i>	3 kts
$v_w$	<i>Average wind speed in October<sup>3</sup></i>	13.6 kts
$d_{ow}$	<i>Open water navigation distance</i>	585 nm
$d_{ice}$	<i>Ice-covered navigation distance</i>	195 nm
$K_{bc}$	<i>Emission factor for black carbon as a function of engine load</i>	0.05 with high engine load
$\beta$	<i>Proportion of emission reduction intended</i>	$\beta = 1 - \frac{e_i}{e_0} * 100\%$ Set by IMO

$k_{bc}$	<i>BC emission tax rate</i>	Set by governments
$R$	<i>Freight rate</i> <sup>4</sup>	12 USD/ton
$W$	<i>Deadweight available for cargo</i> <sup>1</sup>	80000 ton
$k$	<i>A freighter-specific constant of proportionality</i>	$k = \frac{F_{ds}}{(24 * V_{ds})^3} = \frac{45}{360^3}$
$F_{aux}$	<i>Fuel consumption per day of the auxiliary system</i> <sup>4</sup>	3.5 ton/day
$p_{fuel}$	<i>Bunker price, LSFO</i> <sup>5</sup>	393.5 USD/ton
$p_{bio}$	<i>Bunker price, pure biodiesel</i> <sup>6</sup>	605.6 USD/ton
$C^o$	<i>Equipment investment cost</i>	Shown in Table 3 and 6

Sources: <sup>1</sup>Lindstad et al., (2014); <sup>2</sup>Lasserre (2014); <sup>3</sup>Przybylak et al., (2003);

<sup>4</sup>Clarksons Database (2018); <sup>5</sup>Rotterdam Bunker Prices (2020);

<sup>6</sup>Alternative Fuel Price Report, 2020

## 5.1 The effects of different measures on BC emission mitigation

Based on equations (10), (13) and (16), we can find that all these alternatives can be classified as two categories in terms of their contributions on the mitigation of BC emissions, alternatives used for propulsion and alternatives used for auxiliary generating system. The first category includes wind sails and kite sails, while biodiesel, wind-driven generators, photovoltaic panels and hydrogen fuel cells belong to the second category. Figure 2 presents that in the current technology environment, the amount of BC emissions generated by replacing fossil diesel oil with different alternative energies accounts for the proportion of the original BC emissions.

From this image, both wind sails and kite sails have better environmental effects on the mitigation of BC emissions in the Polar Code Area. Since vessel's speed in open water after applying wind propulsion system satisfies the inequation  $v_{ow} \leq v_w = 13.6 \text{ kts}$ , this measure can help shipowners mitigate up to about 85% of BC emissions when freighter can navigate in ice-free water as fast as the wind at that time. Contrary to this, it seems alternatives used for auxiliary generating system cannot reduce too much BC emissions, and the faster freighter travels in ice-free water is, the fewer emissions they can reduce. It is easy to understand because these alternatives have not been proven to be technologically adaptable for propulsion system, which is the biggest BC emissions contributor among different parts of a freighter, under the unique climate conditions in the Arctic Area.

However, this result does not imply that wind propulsion system is the best solution for shipowners to cope with the potential BC emission restriction. Continuous technological improvements in zero-pollution energy, such as photovoltaic panels and hydrogen fuel cells, can be reasonably foreseeable in the near future. They have the potential to replace fossil diesel oil in both propulsion system and auxiliary generating system, except for ice break which may still need power large enough driven by fossil diesel oil or liquefied natural gas (LNG). The shortcoming of both wind sails and kite sails not being able to transfer wind energy into electricity will make them emit more BC emissions than any other alternatives in the future. Therefore, we need to analyze the economic effects of these alternatives on shipowners, although currently, wind propulsion system seems to be the optimal solution in terms of restricting BC emissions.

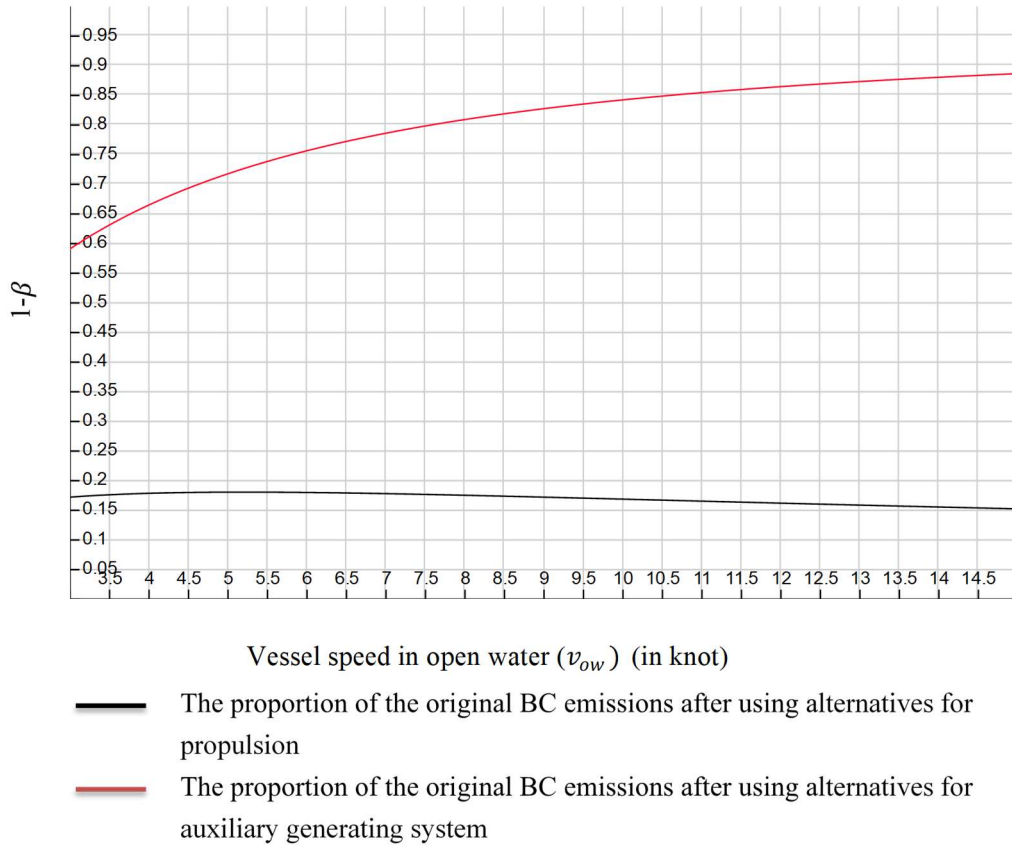


Figure 2 The effect of using different alternative energies to reduce BC emissions

## 5.2 Economic effects of shipowner's choice of measures to limit BC emissions

In order to have a more intuitive comparison of the economic gap between taking all these measures aimed at restricting BC emissions in the whole Polar Code Area before and after, we decide to include the calculations of  $TCE$ ,  $C^o$  and  $\delta$  towards the original freighters whose main propulsion engine and auxiliary generating system are still driven by LSFO. The equipment investment cost  $C^o$  of this LSFO-driven vessel is also shown in Table 6.



Table 6 Equipment investment cost ( $C^o$ )

	Purchasing cost (USD)	Maintenance cost (USD)	Financial cost (USD)	Equipment-related operational expenditure (USD)	Total OPEX and CAPEX ( $C^o$ ) (USD)
LSFO	30000	9000	216000	$10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$	$255000 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$
Biodiesel	30000	15000	216000		$261000 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$
Wind driven generators	528000	16200	380160		$924360 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$
Photovoltaic panels	4020000	40200	2894400		$6954600 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$
Hydrogen fuel cells + wind driven generators	4128000	34200	2972160		$7134360 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$
Hydrogen fuel cells + photovoltaic panels	7620000	58200	5486400		$13164600 + 10400 * (\frac{d_{ow}}{24 * v_{ow}} + \frac{d_{ice}}{24 * v_{ice}})$

Within this discussion, the BC emission rate  $k_{bc}$  set by the Canadian government is a

constant value. The emission tax is an external compulsory cost which is not controlled by every vessel which has the intention to travel through the NWP to shorten their total transportation distance. Therefore, to simplify the difficulty of calculation, we assume that BC emission will be taxed at the same rate as  $CO_2$  temporarily by the Canadian government, which means  $k_{bc} = 23 \text{ USD/ton}$  based on Carbon Pricing Dashboard from The World Bank (2020) in this section.

### 5.2.1 Daily Time Charter Equivalent of different power energies

Substituting the known values into the equations (9), (12), (15) and (18), Figure 3 shows *TCE* of a bulk carrier in the function of vessel's speed in open water  $v_{ow}$ , after the Canadian government and the shipowners taking measures to restrict BC emissions. From this image, we found that under the current technology environment, shipowners using zero-pollution energies, such as photovoltaic panels and hydrogen fuel cells, make the most daily profit compared to other alternatives when traveling at the same open water speed in the Polar Code Area. Biodiesel, in contrast, is the least economic-beneficial alternative energy and shipowners even have no profits if freighters navigating at the open water speed of 15kts. Under the condition of BC emission tax being charged by the Canadian government mandatorily, the average daily profit from the wind propulsion system will be only slightly less than that from the original fossil diesel oil.

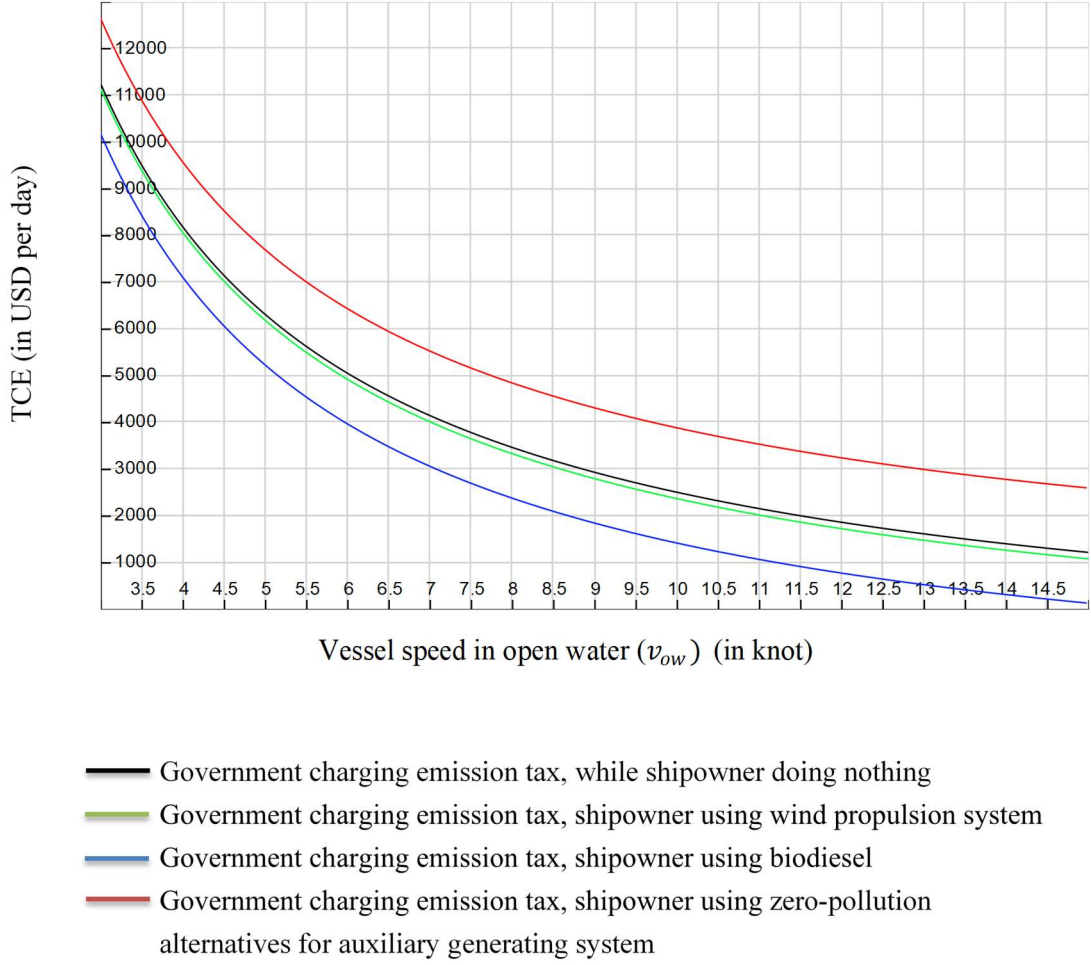


Figure 3 Time Charter Equivalent in USD/day of different measures as a function of speed in the open water

By comparison fossil diesel oil and wind propulsion system, both of which are equally capable of acting on vessel's main engine to provide propulsion, it is very confusing that they can result to almost the same **TCE** to shipowners because it has already been proven that using wind propulsion can help to mitigate up to 85% of BC emissions, thus will cost shipowners fewer taxes. However, when we re-check their TCE equations (8), (11) in detail and substitute all known values into these equations, we can find the answers. The key points to this phenomenon are the freighter-specific constant of proportionality  $k$  and vessel's average speed navigating through the whole Polar Code Area. According to previous work on this coefficient,  $k$  is defined based on vessel's design speed,  $k = \frac{F_{ds}}{(24 \cdot V_{ds})^3}$ . In this study,  $v_{ds}$  is valued as 15kts, which is the most

common design speed of a freighter when it was just out of the factory. This equation also reveals that small differences in speed, however, can trigger a multiplier effect on fuel consumption. The peculiarities of the NWP mean that freighters have to travel 195nm among the ice-coved area at a speed of only 3kts, one fourth of the total mileage. The consequence of this reality is that freighter's average speed of traveling through NWP have to be much lower than its design speed. Since the fuel consumption of main engine satisfies the equation  $F = k * (24\bar{v})^3$ , the daily fuel consumption of propulsion system is much lower than expected when traveling through NWP. Compared with the fixed fuel consumption of auxiliary generating system  $F_{aux}$ , fuel consumption from main engine will occupy very little of the whole consumption. Hence, the replacement of vessel's auxiliary generating system power energy will have much larger economic effect on vessel's whole fuel cost than that of propulsion system when shipowner decides to travel through NWP. In fact, this finding can be applied to the entire arctic route, as long as there are still a large percentage of ice-covered sea area in the Polar Code Area.

Although it seems that zero pollution alternatives can help shipowners have the maximum daily profit according to Figure 3, we still cannot draw a conclusion that shipowners can benefit the most from transferring fossil fuel into zero-pollution energies due to the existence of equipment investment cost. Therefore, we will calculate  $C^o$  using the same BC emission tax rate set by the Canadian government and discuss its effects by comparing equipment investment payback period  $\delta$  of different power energies in the following subsection.

### 5.2.2 $C^o$ and $\delta$ of different power energies

The Combination of the equation (6) with the calculation results shown in Table 2 and Table 6 comes to the images presented below as Figure 4,5,6 and 7:

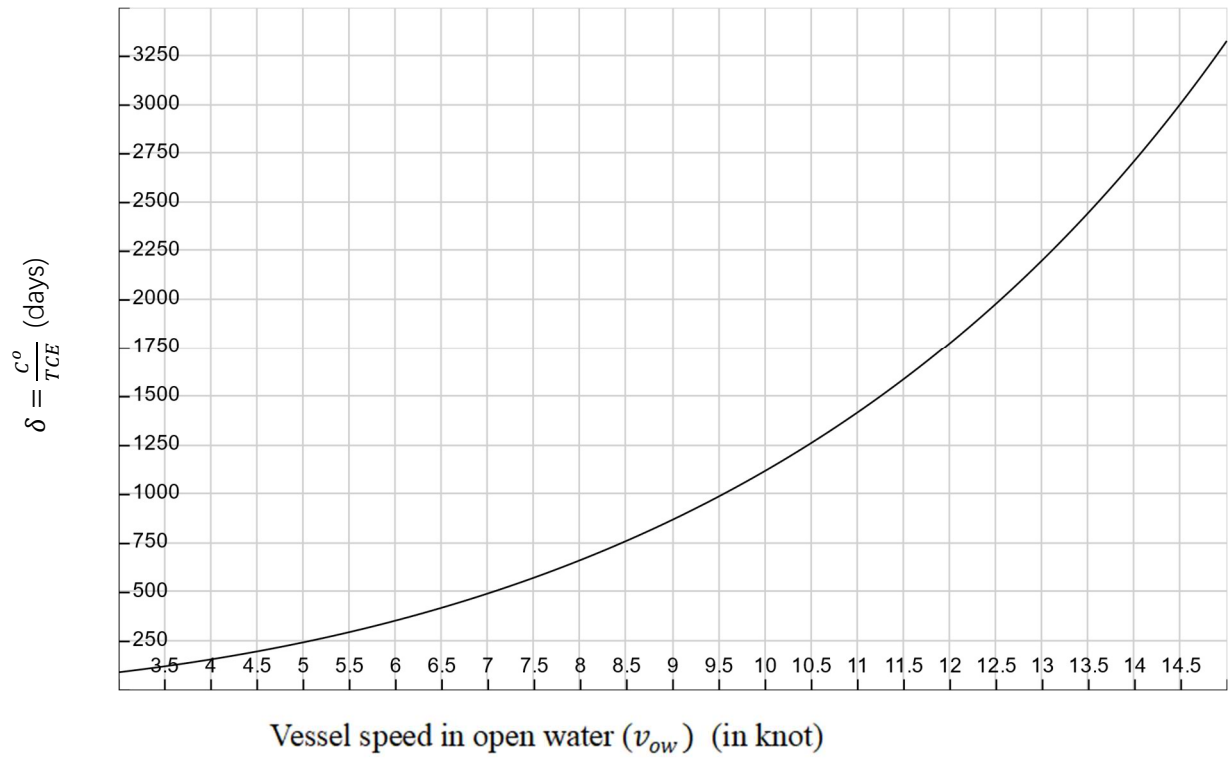


Figure 4 Equipment investment payback period of shipowners still using fossil diesel oil

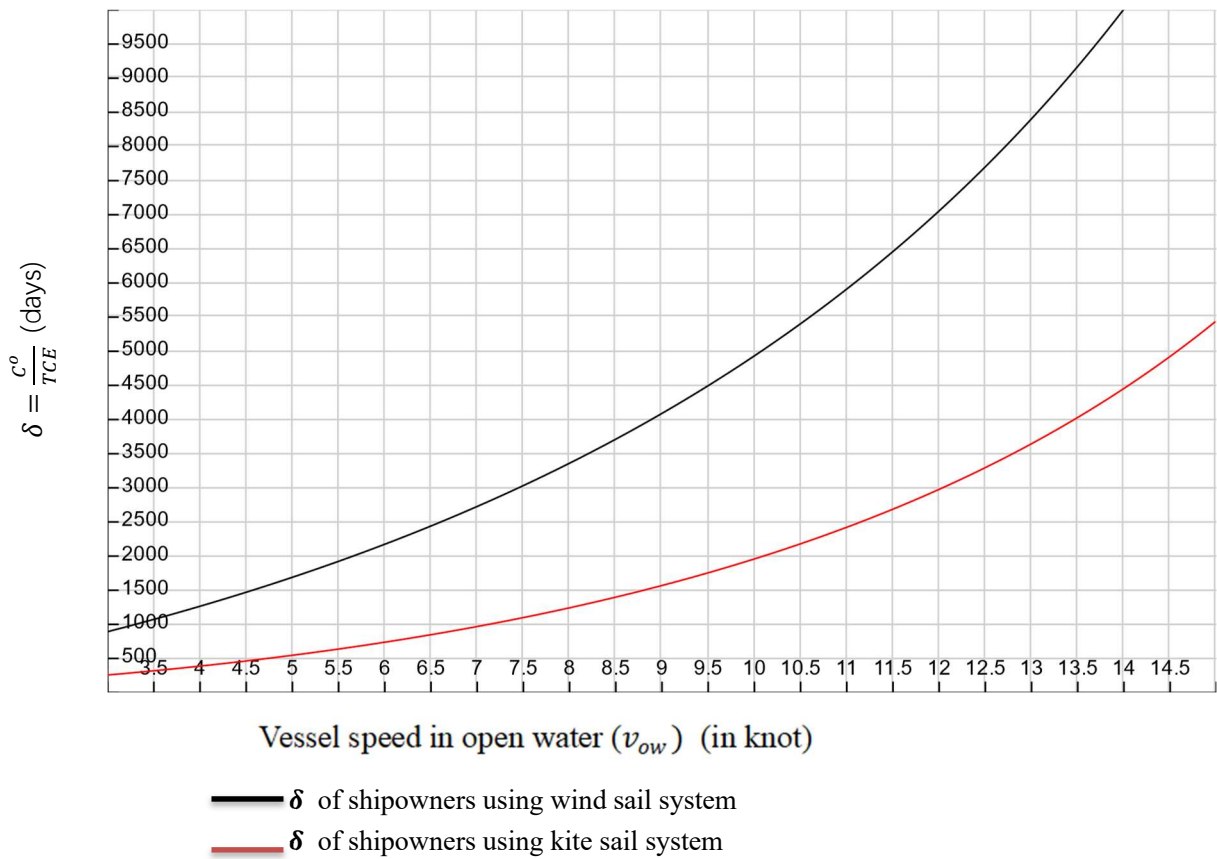


Figure 5 Equipment investment payback period of shipowners using wind propulsion system

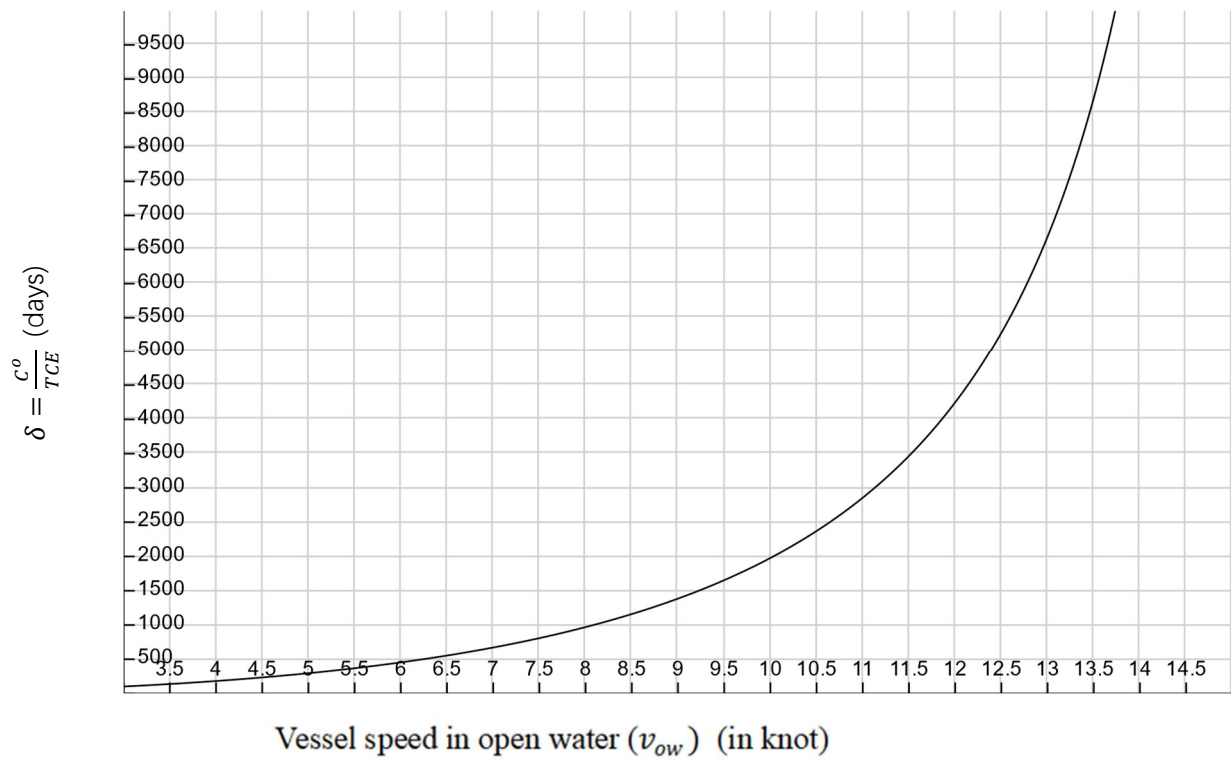


Figure 6 Equipment investment payback period of shipowners using biodiesel

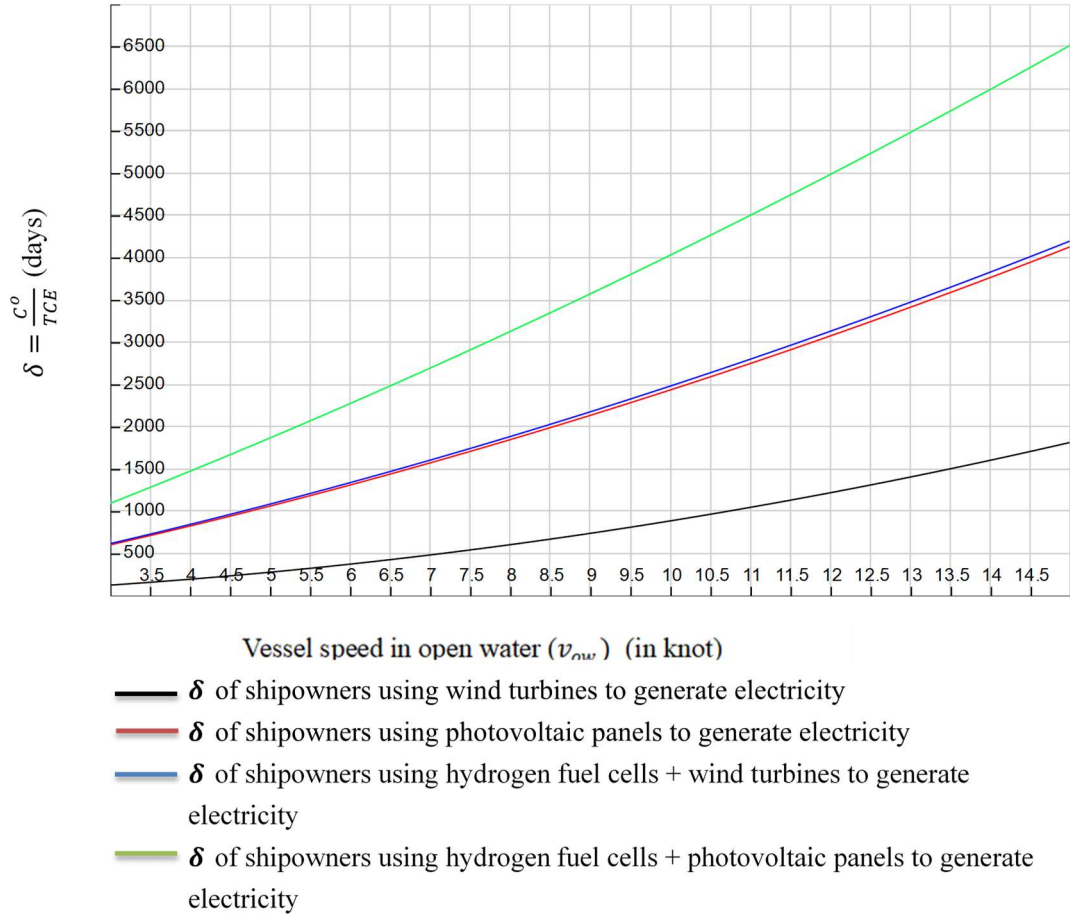


Figure 7 Equipment investment payback period of shipowners using zero-pollution alternatives for auxiliary generating system

The similarity of all these four images is that the higher the freighter's open water speed, the longer the waiting time for shipowners to expect a return, although the slopes of these energies are all different. It is an interesting finding because in our subjective impression, the higher the vessel's open water speed means the less time the freighter needs to complete the whole journey, the higher the transport efficiency, and thus the greater the profit of a single trip. However, all four images in this study show that vessels traveling at a fast speed will dramatically increase more fuel cost and BC emission tax cost than the saving opportunity cost resulted from the high transportation efficiency if they choose to navigate through the Polar Code Area. Traveling at a low speed, thus, can not only mitigate BC emissions, but also help shipowners achieve profitability earlier. No matter which energy shipowners choose to use as main engine's

power energy or the source of auxiliary system to generate electricity, it is a good choice to let the freighter travel in the Arctic Area as slowly as possible while meeting the time requirement of transportation.

As for some measures which can help shipowners acquire the same daily profit when traveling through NWP, specifically referred to both wind sails and kite sails as well as four different zero-pollution alternatives, it is apparent that lower equipment-related cost of kite sails and wind turbines can also help shipowners get the return from their investments much earlier, thus making them the better choice to be applied into main engine propulsion system and auxiliary generating system respectively in terms of economic impacts (Figure 5 and Figure 7). Moreover, since wind-driven generators cannot be applied for propulsion system, photovoltaic panels and hydrogen fuel cells still have the potential to be more economic-beneficial to shipowners in the near future when they can technically replace fossil diesel oil for both vessel's propulsion system and auxiliary generating system because of their characteristics of emitting almost zero harmful pollutions and thus zero fuel cost and emission tax fee at that time. Another potential development direction is the combination of different energies, such as installing both kite sails and wind turbines on board to make the most of wind energy. By combining the various energy advantages, the freighter can maximize daily profits *TCE* while shortening the investment return period  $\delta$  at the same time when traveling through the whole Polar Code Area. The only obstacle of this measure is that this kind of combination will have to occupy large part of the open deck, resulting to the consequence that freighters will not be able to carry too many cargoes.

In contrast of all different energies with the same open water speed, including the original LSFO, we found that installing wind-driven generators and still using fossil diesel oil always cost shipowners the shortest and the second shortest periods of return on investment no matter what the vessel's open water speed is. The sequence of other investment payback periods, however, changes frequently. Specifically, when freighter travels with the open water speed lower than 10kts, biodiesel has the third shortest payback period no more than five years although it also has the lowest TCE of all



energies. When open water speed is up to 12.5kts, wind sails have the third shortest investment payback period, and when  $v_{ow}$  of a vessel is really close to vessel's design speed, photovoltaic panels become the third.

### 5.3 Economic effects of governments' measure to limit BC emissions

Charging emission tax is the only mandatory measure coastal governments can do to limit BC emissions indirectly by raising vessel's transportation cost and thus reducing the number of ships choosing the Arctic route. To simplify the calculation difficulty, we decide to discuss the effects of emission tax rate on the choice of shipowners towards different power energies in the base of freighters traveling with the same open water speed. In this case,  $v_{ow}$  is valued as 9kts.

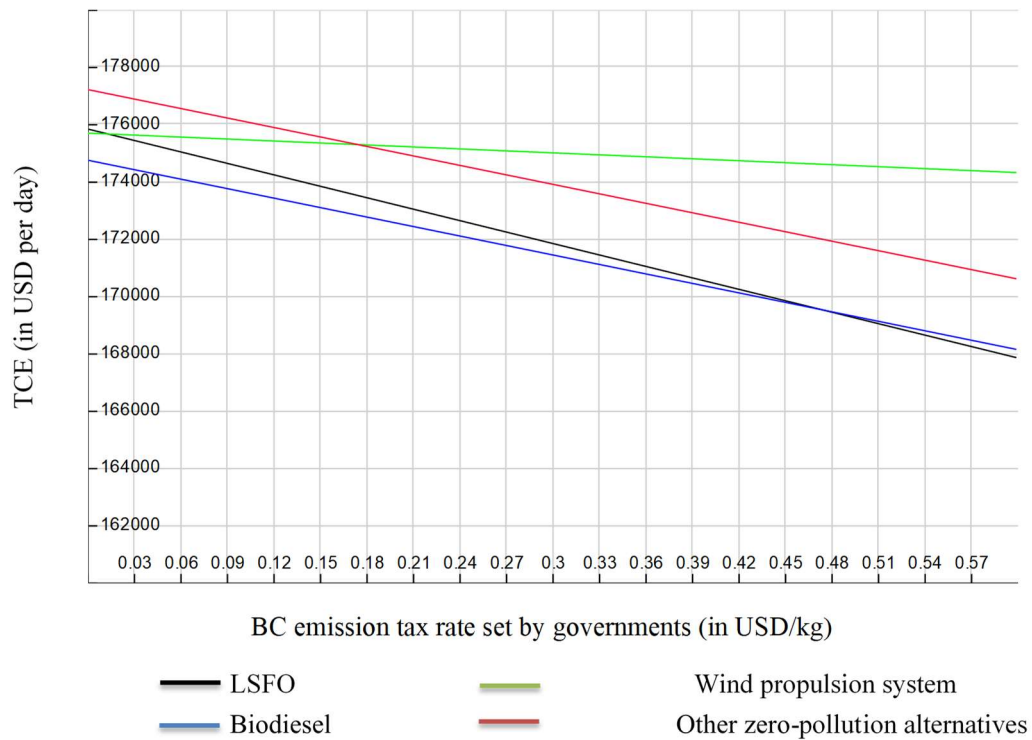


Figure 8 The effects of BC emission tax rate on  $TCE$  of different power energies when  $v_{ow}$  is valued as 9kts

According to Figure 8, LSFO is the energy source most affected by different BC emission tax rates, followed by biodiesel and other zero-pollution alternatives including wind-driven generators, photovoltaic panels and hydrogen fuel cells. Wind propulsion system is the energy least affected by this tax rate differences. It is easy to understand because wind propulsion system can mitigate the largest amounts of BC emission.

In terms of the specific value of emission tax rate, other zero-pollution alternatives can help shipowners acquire the highest daily profits when tax rate is lower than 0.18 USD/kg. Although using biodiesel in substitution of LSFO doesn't produce BC emission, it can only help shipowners acquire more profits than LSFO when emission tax rate is larger than 0.45 USD/kg, due to the expensive market price of biodiesel.

Since we do not know IMO's basis for pricing the emission tax rate, we cannot determine the range of the tax rate. Suppose BC emission tax rate is valued close to the market price of an internationally accepted carbon tax, zero-pollution alternatives applied into auxiliary generating system will benefit the most compared to other power energies. However, if IMO and all coastal governments tend to stop BC emissions completely in the Polar Code Area and thus will set a very high emission tax rate, the combination of wind propulsion for vessel's propulsion system and wind-driven generators is the best choice for shipowners who still plan to travel through the Polar Code Area to reduce the total navigation distance.

## Chapter 6 Conclusion

This study aims to figure out the economic effects of shipowners' different measures of restricting BC emissions under the background of potential policy proposed by IMO and coastal countries. Combining all the results shown above, including the impacts of different power energies on TCE, the proportion of mitigating BC emission resulted from these shipowners' measures and emission tax rate factor, we can come to following conclusions.

If the BC emission restriction policy proposed by IMO does not come up with a specific figure of the reduction in BC emissions, or requires vessels which decide to travel through the Polar Code Area to mitigate the emissions for only 60% of the initial BC emissions, it is a better choice for shipowners to replace LSFO into alternatives in parts of vessel's auxiliary generating system first. Among different available alternative energies, wind-driven generators are the most economic-beneficial to shipowners currently. If IMO decides to propose a policy that strictly restricts BC emissions derived from vessels in the Polar Code Area into no more than 60% of the initial emissions, there are two measures available for shipowners to select under the current technology environment. The first one is that they have to adopt wind propulsion system in substitution of fossil diesel oil as the main energy for vessel's propulsion system and use zero-pollution alternatives for auxiliary generating system. Although BC emission can be minimized to the greatest extent and fuel cost can be saved a lot, the combination of these two systems will occupy a large space of the vessel's open deck, so that there will be no enough room for cargoes. The whole profits of each voyage will be much lower than expected. The second measure recommended under this condition is that shipowners use wind propulsion system for vessel's propulsion system while still apply LSFO into auxiliary generating system on the ground of economic effects of different energies. Considering the effects of mandatorily charged BC emission tax by governments, kite sails are the best choice to help shipowners acquire higher daily

profits and meanwhile shorten their investment payback period. If both IMO and coastal governments decide to stop BC emissions completely in the Polar Code Area by setting a very high tax rate, the combination of kite sails for vessel's propulsion system and wind-driven generators is the best choice for shipowners under the current technology environment.

Although the initial equipment-related investments of photovoltaic panels and hydrogen fuel cells are the highest among all these energies and the investment payback periods are pretty long, these zero-pollution alternatives are, in fact, the most promising energies to be used in the future, not only because they have the technological potential to replace fossil oil entirely from propulsion system to auxiliary generating system, but also for the reason that they can provide pretty high profits for shipowners in the long term. Besides, vessel's open water speed plays a very important role in the economic effects of these alternatives towards the potential IMO's policy of restricting BC emissions in the Polar Code Area. This study shows that shipowners can emit less BC emissions and meanwhile get a high daily profit if freighters navigate with a low speed. Therefore, it is suggested that freighters should travel in the Arctic Area as slowly as possible under the premise of satisfying the timeliness of transportation.

In general, when shipowners decide to travel through the Arctic Area under the consideration of shorter total navigation distance and higher transportation efficiency, the use of alternative energies for vessel's either propulsion system or auxiliary generating system as these shipowners' measures to cope with IMO and coastal governments' policy on the BC emission restriction is more profitable in the long term than the use of the conventional diesel oil, except for the biodiesel which largely depends on whether the market price of biodiesel can be decreased a lot. Besides IMO's policy to restrict BC emissions, coastal governments' regulations of setting BC emission tax rate will also influence the choice of shipowners a lot. Governments trying to manage the trade-off between mitigating BC emissions among the Polar Code Area and maximizing the economic benefits of arctic shipping routes will be very challenging.

In recent decades, while there has been an increase in economic activities in the Arctic area, whether Arctic shipping deserves to be defended is still in dispute because the pollutants emitted from these vessels, especially black carbon, can accelerate the melting of icebergs and make the Arctic environment more fragile (Arnold et al., 2016). Understanding such, this research about various BC emission mitigation measures and their economic impacts on vessels navigating through NWP would have practical implications since the case study shows that it might be possible to find a balance between economic activities and emissions control. The next step is to prove the universality of the existence of such a balance through collecting detailed data on BC emissions and discussing other scenarios such as different navigation seasons, different vessel sizes, sea ice thickness in different routes etc. We believe that this research can serve as the first attempt on constructing an integrated model considering both BC emission and economic factors and provide useful insight for future studies concerning relevant topics.

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