water

MDPI

Article

Environmental and Economic Analysis on Sailing from Taiwan through Arctic Passages

Po-Hung Chen and Ta-Kang Liu *

Institute of Ocean Technology and Marine Affairs, National Cheng Kung University, 1 University Road, Tainan 70101, Taiwan; na8071025@ncku.edu.tw
* Correspondence: tkliu@mail.ncku.edu.tw; Tel.: +886-6-2757575 (ext. 63282)

Abstract: Maritime transportation is a key means for Taiwan to transport the cargo in the global trade. Global warming has led to two new navigation channels for arctic passages, the Northeast Passage and Northwest Passage. Research has increasingly addressed the unknown economic costs of these passages, and the increase of navigational activity in the Arctic Ocean has also resulted in CO_2 emissions. Taiwan has one of the leading merchant fleets in the world; however, study on this aspect in Taiwan is not available. We use Port of Taipei, Taiwan as the starting place to compare the two arctic shipping routes and developed a model to determine the shipping costs and as well the CO_2 emission. The results showed that a voyage from the Port of Taipei to the Port of Rotterdam through the Northeast Passage would be 2107 nautical miles shorter than voyage along the current sea route to Europe but 2% to 3% costlier; CO_2 emissions would be 3% lower. Sailing to New York Harbor through the Northwest Passage would shorten voyages by 2459 nautical miles and reduce both costs and CO_2 emissions by 7%. Therefore, if tolls were lowered or sailing speeds increased, sailing through the Arctic Passages could be a great opportunity for shipping industries and enable Taiwan to develop its shipping economy while protecting the marine environment.

Keywords: arctic passages; CO_2 emissions; Europe sea route; Americas sea route; maritime pollution

Citation: Chen, P.-H.; Liu, T.-K. Environmental and Economic Analysis on Sailing from Taiwan through Arctic Passages. *Water* **2022**, *14*, 2099. https://doi.org/10.3390/w14132099

Academic Editor: Marcel J.F. Stive

Received: 2 May 2022
Accepted: 28 June 2022
Published: 30 June 2022

1. Introduction

International maritime transportation occupies a critical position in global trade. Data from the United Nations Conference on Trade and Development (UNCTAD) indicate that maritime transportation accounts for 80% of the world's trade and facilitates the flow of global supply chains [1]. Increases in shipping have worsened emission problems, with 51% of CO_2 emissions in international trade coming from maritime transportation, 27% coming from air transportation, and 22% coming from land transportation [2]. The International Maritime Organization (IMO) conducted a study on global greenhouse gases and reported that from 2012 to 2018, total emissions of greenhouse gases in the shipping industry increased from 977 M tons to 1.076 G tons, with CO_2 emissions increasing from 962 M tons to 1.056 G tons [3]; consequently, maritime transportation has become a rapidly growing source of greenhouse gas emissions [4].

Global warming has resulted in a massive reduction in icebound surface in the Arctic Ocean [5], and the Sea surface temperature increases each year [6]. According to research data from the National Oceanic and Atmospheric Administration (NOAA), arctic temperatures increased twice as fast as the global average in 2020 [7] which also means the rate of ice melt will become faster, and sea level will rise rapidly [8]. Other studies on climate change have reminded the public that the Arctic may become ice free in the next 20 years [9]. The massive melting of ice has resulted in two new sea routes in the Arctic, the Northeast Passage and Northwest Passage. Satellite images taken in late August 2008 indicate that the Northeast and Northwest Passages were open simultaneously for the first time, sparking heated discussion worldwide. In July 2009, two freight ships belonging to Beluga Shipping GmbH, a German shipping company, set out from South Korea and sailed north through the Northeast Passage, which was typically sealed off by ice and unnavigable throughout the year, arriving safely in the Netherlands at Rotterdam [10]. This voyage is particularly notable in the history of Arctic shipping because it is an indirect announcement of the birth of a new commercial shipping route. The success of the voyage led to the gradual development of commercial transportation through the Arctic Ocean but also to ecological effects such as oil pollution and CO_2 emissions in the region [11]. Then, in November of 2020, the IMO approved an amendment to Annex I of the International Convention for the Prevention of Pollution from Ships (MARPOL) that prohibited ships from burning, using, or carrying heavy fuel oil (HFO) in Arctic waters [12]; this prohibition will take effect on 1 July 2024. However, ships registered with a country bordering the Arctic Ocean can continue to operate without the aforementioned restrictions within its country's waters until 1 July 2029. The IMO hopes to establish a legally binding system regulating carbon emissions by developing measures to reduce the use of HFO on ships, meet emission standards, and formulate carbon tax plans. They expect to achieve carbon neutrality in global shipping by 2050.

Given that Arctic shipping routes have become a foreseeable part in the future, countries have begun researching whether Arctic shipping routes are conducive to the shipping industry. Schøyen et al. [13] studied the transport of iron ore from Norway to China through the Northeast Passage by assuming icebreaking fees of US$380,000 for each trip and argued that the Northeast Passage is more economical than existing European shipping routes. Raza et al. [14] studied the transport of liquefied natural gas from Norway to Japan through the Northeast Passage and observed that the Northeast Passage would be more economical than existing European shipping routes by assuming a 50% reduction in icebreaking fees. Faury et al. [15] studied the feasibility of shipping petrol from Murmansk to South Korea via the Northeast Passage, the study applied Northeast Passage tariffs from 2014 and provided the upper and lower bounds for the ice conditions; the results indicated that the Northeast Passage was only more economical between July and November. Dimitrios et al. [16] studied oil tankers of various sizes traveling a range of distances through the Northeast Passage, and their analysis of fees and costs revealed that the Northeast Passage was more economical only when oil prices were high and icebreaking fees were discounted. Somanathan et al. [17] indicated that at the same cost, 38% more trips can be made from Yokohama to St. John's and 13% more trips can be made from Yokohama to Finland via the Northwest Passage. TurgutKoçak et al. [18] noted that although the Suez Canal is currently the most efficient route, but if the harsh conditions of the Arctic route are not taken into account, the Arctic Sea Route is more economical for Asian to European ports. Gleb et al. [19] found that after setting the costs and adding an evaluation of ice conditions, a combined route (Northeast Passage in summer, Suez Canal in winter) would be more advantageous than simply sailing though Suez Canal. Comparatively, there was 14% cost difference from Yokohama to Rotterdam and an 8% cost difference from Shanghai to Rotterdam. Lasserre [20] pointed out that if other factors are added, such as the ambiguity of the adjustable ice breaking costs, the unreliability of the Northeast Passage, and the amount of cargo carried, the Northeast Passage will not be as favorable as the traditional passages. Xu et al. [21] used the LNG ships to compare the differences between the Northeast Passage and the conventional shipping route and to calculate emissions. The results showed that under the limited operating and operational costs, the smaller LNG ships are more advantageous in the Northeast Passage. LNG ships can reduce emissions by 45.5–63% when sailing the Northeast Passage compared to a conventional fuel ship sailing the Suez Canal.

The global shipping experienced container shortages and port congestion caused by the global pandemic since 2020. However, due to the exceedingly high demand for foreign trade, Taiwan's international commercial ports handled approximately 750.04 M tons of cargo, a 6.7% increase from 2020 and a new historic high; container handling accounted for 73.6% of that weight [22]. Trade volume with Europe and the United States also increased continuously over the year. This data indicate that container ships are vital to Taiwan's shipping industry, economic development, and trade. As one of the leading merchant fleet owners in the world, however, study on the artic shipping in Taiwan is lacking. In 2021, Taiwan's total export volume was US$446.45 B, and the total import volume was US$381.17 B; marine shipping was accounted for the largest proportion of both [23]. From the literature of Arctic shipping route analysis, the starting places typically are located in Shanghai, Japan, and Korea and most of such analysis focused on a single route analysis and the information of greenhouse gas emission was limited. This was the first study in Taiwan's perspective to investigate whether the dual Arctic shipping routes, i.e., one leading to western Europe and the other leading to the eastern United States, can replace existing shipping routes. Existing routes referred to ships from Taiwan reach western Europe through the Suez Canal (hereafter referred to as "the Europe sea route") and the eastern United States through the Panama Canal (hereafter referred to as "the Americas sea route"). The Port of Taipei in Taiwan was used to conduct this case study. The economical and CO_2 emissions from container ships along various shipping routes were compared and whether the Arctic sea routes would be more economical was evaluated to facilitate economic development while protecting marine environments.

2. Research Method

In this case study, we developed a model to compare existing sea routes and the Arctic sea routes in terms of total transportation costs and CO_2 emissions produced by burning oil during the sea voyage. Two pairs of routes were compared in this study, i.e., the first pair for container ships departing from the Port of Taipei to New York Harbor in the United States through the Northwest Passage and the Americas sea route via Panama Canal; and the second pair for container ships also departing from Port of Taipei to the Port of Rotterdam in the Netherlands through the Northeast Passage and Europe sea route via Suez Canal. Figure 1 exhibits the block diagram in this case study.

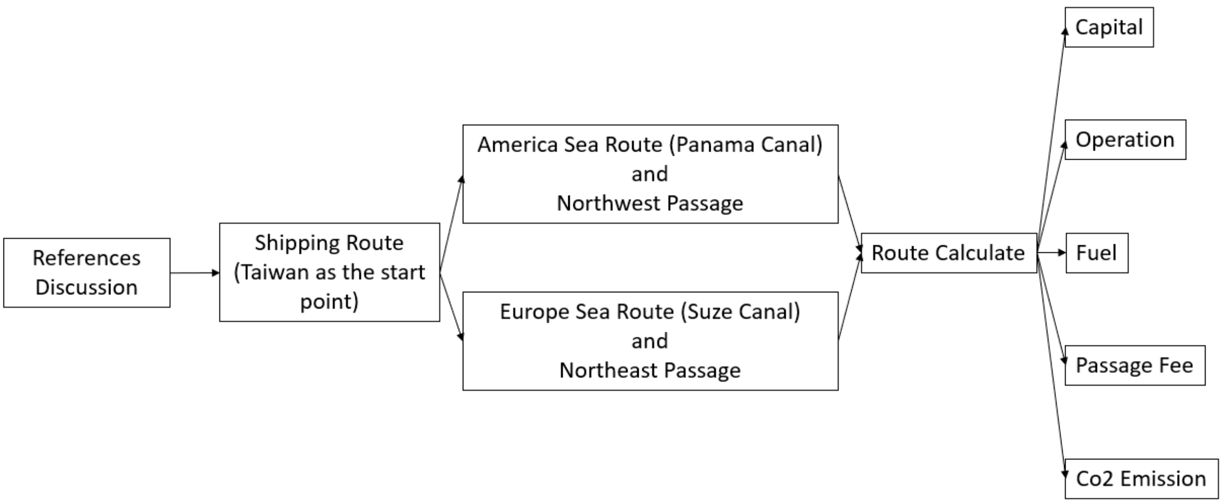

Figure 1. The block diagram of the procedure.

2.1. Ship Characteristics and Route Distance

The ships' size, speed, and ice class, which refers to requirements for travel through the Arctic Ocean, were studied. Since this study only examined summertime navigation, the required ice class was 1A (Arc4) [24]. An analysis of shipping volume along Arctic sea routes in 2020 provided information regarding ships that traveled through the Northeast Passage as reference [25]. This study examined two ships sizes: 1500-TEU container ships, which carry approximately 22,000 tons and are highly common, and 4500-TEU container ships, which carry approximately 50,000 tons and are the largest ships that can pass through the Arctic sea routes. One reason these ships were investigated is that container ships passing through the Northwest Passage typically have one harbor destination and do not stop at other harbors in transit; therefore, they do not need to be particularly large. Another reason is that the water depth is only 13 to 15 m in certain locations along the Arctic sea routes.

Speed is a major factor affecting cost. The speed of container ships in open waters is typically between 13 and 23 knots [26]. This study used a random number generator 10,000 times to obtain simulated container ship speeds in this range; an average open water speed of 15 knots was obtained. Canal speed was set to 4 knots on the basis of Panama Canal passage time [27]. Since the ships in this study sailed during the summer, the speed of travel through icy waters was assumed to be approximately 13 knots.

The most crucial factor affecting sailing costs and CO_2 emissions is the sailing schedule because it directly affects ships' fuel consumption, the crew's wages, and operational and maintenance costs. This study used PortDistance (Ver. 1.9.5, Marine Circle Ltd., Shanghai, China) to calculate the length of the sea routes.

2.2. Shipping Cost

In this study, shipping costs in Equation (1) consisted of cost of voyage operation C_{VO}, cost of voyage capital C_{VC}, cost of voyage fuel C_{VF}, and cost of voyage transit C_{VT}. This study developed an equation to calculate cost by modifying equations from Lu et al. [28] and Xu and Yin [29]. The first-hand real-world numbers were used instead of using rough estimate or adopting from second-hand references. Numbers used in the equations were best available based on real market price or obtained from container operators having arctic shipping experiences through personal communications whenever possible.

$$\text{Shipping Cost} = C_{VO} + C_{VC} + C_{VF} + C_{VT} \tag{1}$$

2.2.1. Cost of Voyage Operation (C_{VO})

C_{VO} represents the cost of a single voyage in terms of the crew's wages, maintenance fees and company management fees.

1. Daily maintenance: Annual maintenance fees typically account for 1.095% of shipbuilding costs [30]. Due to differences in design and specifications, the maintenance costs of ice-class ships can be 5% to 21% higher than those of normal container ships of the same size [15]; this study used the median of this range 13%.
2. Ship insurance: Insurances fees for a typical container ship account for approximately 0.343% of shipbuilding costs [30]. However, because the Arctic sea routes are not fully developed and entail adverse weather and navigation conditions, insurance companies typically list Arctic sea routes as high-risk routes. Consequently, the annual insurance fees for an Arctic sea route are 16.7% to 100% higher than those of a conventional route [31]. According to statistics, most insurance companies are reluctant to insure firms that do not have experience in Arctic shipping, and even for cooperated companies, the insurance fees are still 25% to 50% higher than the conventional route [32]; this study used the median of this range 37.5%.
3. Crew size and wages: Taiwan's medium-sized and large container ships are equipped with automated control systems and are crewed by approximately 20 people. According to the website Nautic Jobs, the average monthly wage for a crew member of an international container ship in 2021 was US$3359.6 [33]. However, ship operating companies have indicated that wages for crew members on Arctic sea routes are typically 10% to 20% higher than those for crew members on conventional sea routes because of the expertise required for ice-class ships and the dangers of Arctic sea routes [26]; this study used the median of this range, 15%.
4. Company management fees: Company management fees were calculated by referencing Drewry's [34] and 2020 reviews and forecasts of ship operating costs. Data from ship companies operating on Arctic sea routes have indicated that ice-class ships cost approximately 10% more to operate than does a typical ship [26].

2.2.2. Cost of Voyage Capital (C_{VC})

C_{VC} refers to the value of a ship and its depreciation after a single voyage. This study calculated this cost using the costs for constructing new ships in US dollars [30].

$$C_{VC} = \frac{C_{NV}}{VD_{Year} * 365} \sum_{i}^{Z} \left(\frac{D_{OW}}{24 * V_{OW}} + \frac{D_{IW,\,i}}{24 * V_{IW,\,i}} \right) \tag{2}$$

Here, C_{NV} represents the cost of constructing a new normal ship. Data from international ship firms (based on ready-made ships) have indicated that, a typical 1500-TEU container ship costs approximately US$23 M to build and that a typical 4500-TEU container ship costs approximately US$67 M to build. Navigating the Arctic Ocean requires ice-class container ships. Year of vessel depreciation Y_{VD} represents the depreciation period of the ship. Taiwan's Ministry of Finance requires that container ships have a minimum depreciation period of 18 years [35]. D_{OW} and $D_{IW,i}$ refer to the sailing distance (in nautical miles) on open waters and icy waters, respectively, with i being the minimum number of areas with icy waters. Z is the total number of areas with icy waters. The Northwest Passage has only one such area, but the Northeast Passage has seven. V_{OW} and $V_{IW,i}$ represent the sailing speeds (knots) on open waters and icy waters, respectively. The sailing speed on open waters was assumed to be the set sailing speed, and the sailing speed on icy waters was assumed to be the speed of the escort icebreaker.

2.2.3. Cost of Voyage Fuel (C_{VF})

C_{VF} is the fuel cost of a single voyage. Fuel consumption is determined by ship size, sailing speed, and navigation time [28].

$$C_{VF} = F_P * F_{CON} \sum_{i}^{Z} \left(\frac{D_{OW}}{24 * V_{OW}} + \frac{D_{IW,\,i}}{24 * V_{IW,\,i}} \right) \tag{3}$$

Fuel price F_p is the price of the HFO used by ships (USD/ton). Fuel consumption F_{CON} is the daily consumption of HFO in tons. The daily fuel consumption of a typical container ship varies between open and icy waters [26]. According to the Russian Maritime Register of Shipping, Ice Class 1A container ships consume 20% more fuel than do typical container ships of the same tonnage [36,37]. Between 2011 and 2019, the average price of marine fuel MF380 worldwide fluctuated between US$156/ton and US$743/ton [38]. This study used the price of MF380 which indicated by Taiwan's CPC Corporation in January 2022, which was US$656/ton [39].

2.2.4. Cost of Voyage Transit (C_{VT})

C_{VT} represents costs incurred during a voyage. Tolls for passing through the Panama Canal is charged bu TEU that can be accessed on the Panama Canal Authority website [27] (Table 1). The Northwest Passage, which corresponds to the Americas sea route, has no toll mechanism because Canada claims that this waterway is an inland sea, and the claim is not internationally recognized. Therefore, this study assumed that any tolls along the Northwest Passage would be similar to those in the Panama Canal. Tolls for passing through the Suez Canal toward Europe is charged by tons that can be accessed on the Suez Canal Authority website [38] (Table 1). Toll standards along the Northeast Passage, which corresponds to the Europe sea route, can be accessed on the Russian Northern Sea Route Administration website [40]; the original tolls are given in Rubles and were converted to US dollars by using the mean exchange rate from 2021 (US$1 = 73.647 Rubles) [41].

Combining (1)–(3) Equation (4).

$$\text{Shipping Cost} = \left(F_P * F_{CON} + \frac{C_{NV}}{VD_{Year} * 365}\right) \sum_{i}^{Z} \left(\frac{D_{OW}}{24 * V_{OW}} + \frac{D_{IW,\,i}}{24 * V_{IW,\,i}}\right) + C_{VO} + C_{VT} \tag{4}$$

Table 1. Sea route tolls through arctic passages and the existing Panama and Suez Canal.

Passage/Canal	Standard of the Toll
Panama Canal	Less than 1000 TEU = USD 60/TEU. Greater than or equal to 1000 TEU and less than 2000 TEU = USD 60/TEU. Greater than or equal to 2000 and less than 3500 TEU = USD 60/TEU. Greater than or equal to 3500 TEU = USD 60/TEU.
Northwest Passage	Assumed that similar to Panama Canal
Suez Canal	First 5000 tons = USD 7.88/tons. Next 5000 tons = USD 5.41/tons. Next 10,000 tons = USD 4.20/tons. Next 20,000 tons = USD 2.94/tons. Next 30,000 tons = USD 2.73/tons.
Northeast Passage	Ice Class: Arc4 or 1A. Season: Summer. Quantity zones: 7.

2.3. *Carbon Dioxide Emission*

Since the United Nations Framework Convention on Climate Change (UNFCCC) was first drafted, the maritime transportation industry has never been included in the agreement to reduce greenhouse gas emissions. However, with the increasing contribution of the maritime transportation industry to global emissions, the international community has begun to pay attention to reducing greenhouse gas emissions from the maritime transportation industry [42]. In 2006, the Intergovernmental Panel on Climate Change (IPCC) and European Environment Agency (EEA) provided a top-down method of calculating greenhouse gas emissions based on fuel and a bottom-up method based on activity level [43]. This study adopted the top-down method, which is based on CO_2 emissions from burning fuel. Total CO_2 emissions are obtained by multiplying a ship's fuel consumption by a corresponding emission factor. The accuracy of this method can be determined by comparing the results with ships' fuel consumption. This method is mainly used to calculate a country's CO_2 emissions. The equation is as follows:

$$\text{Marine } CO_2 \text{ emissions} = \text{Fuel consumption} * \text{Emission Factor} \quad (5)$$

The emission factor in this equation is based on the CO_2 emissions index released by the International Council on Clean Transportation (ICCT) in 2021. The emission factor of HFO was updated to 3.545 in 2021 [44].

3. Results and Discussion

3.1. *Distance of the Route*

This study compared the length of the Americas sea route and Europe sea route with that of the Northwest Passage and Northeast Passage, respectively. Figure 2 presents the ocean voyages from the Port of Taipei to New York Harbor. In the Americas sea route, ships depart from the Port of Taipei and travel across the Pacific Ocean through the Panama Canal and into the Caribbean Sea before arriving in New York Harbor; the length is approximately 10,842 nautical miles. To transport cargo via the Northwest Passage, ships depart from the Port of Taipei and travel through the Sea of Japan, the Bering Sea, and the Northwest Passage before arriving in the Northern Atlantic Ocean and docking at New York Harbor; the length is approximately 8383 nautical miles. The Americas sea route (through the Panama Canal) is 2459 nautical miles longer than the journey through the Northwest Passage, which creates considerable differences in sailing schedules.

Figure 2. Routes along the Americas sea route (black) and Northwest Passage (red and blue). The Northwest Passage comprises one area (blue).

Figure 3 presents the routes between the Port of Taipei and Port of Rotterdam. In the Europe sea route, ships depart from the Port of Taipei and travel southward through the Malacca Strait and Indian Ocean before passing through the Suez Canal into the Mediterranean Sea and sailing northward to arrive at the Port of Rotterdam; length is approximately 10,208 nautical miles. In the Northeast Passage, ships sail north from the Port of Taipei through the Sea of Japan and Bering Sea, passing through the Northeast Passage and reaching the Barents Sea before turning south and arriving at the Port of Rotterdam; the length is 8101 nautical miles. The Europe sea route (through the Suez Canal) is 2107 nautical miles longer than the journey through the Northeast Passage, which creates considerable differences in sailing schedules.

Figure 3. Routes along the Europe sea route (black) and Northeast Passage (red and blue). The Russian government zoned the Northeast Passage into seven areas (blue), which from east to west are the Chukchi Sea, North-eastern part of the East-Siberian Sea, South-western part of the East-Siberian Sea, Eastern part of the Laptev Sea, Western part of the Laptev Sea, North-eastern part of the Kara Sea, and South-western part of the Kara Sea.

3.2. Calculation of the Shipping Cost

3.2.1. Calculation of C_{VO}

By using the information in Section 2.2.1, we calculated that daily operating costs are approximately US$3726 for a typical 1500-TEU container ship, US$4291 for an ice-class container ship of the same size, US$6009 for a typical 4500-TEU container ship, and US$6956 for an ice-class ship of the same size (Table 2). Ice-class container ships cost more to operate per day than does a typical container ship of the same TEU. For the 1500-TEU size, ice-class container ships cost 13% more to operate than do typical container ships, with crew wages accounting for approximately 60% of daily operating costs. For the 4500-TEU size, ice-class container ship costs 14% more to operate than do typical container ships, with crew wages accounting for only 37% of daily operating costs and daily maintenance fees accounting for 33%.

Table 2. Voyage costs based on different tonnage and ice class of the vessel.

Daily Operating Costs (USD)	1500 TEU	1500 TEU (1A)	4500 TEU	4500 TEU (1A)
Maintenance	690	780	2010	2271
Crew wages	2240	2576	2240	2576
Insurance	216	297	630	866
Management	580	638	1130	1243
Total	3726	4291	6009	6956

3.2.2. Calculation of C_{VC}

By using the information in Section 2.2.2, we calculated that daily depreciation is US$3501 for a typical 1500-TEU container ship, US$3973 for an ice-class container ship of the same capacity, US$10,198 for a typical 4500-TEU container ship, and US$11,575 for an ice-class container ship of the same capacity (Table 3). For the 1500-TEU size, ice-class container ships depreciate by US$472 more per day than do typical container ships. For the 4500-TEU size, the ice class container ship depreciates US $1377 more per day than does the typical container ship.

Table 3. Shipbuilding costs and depreciation.

Cost (USD)	1500 TEU	1500 TEU(1A)	4500 TEU	4500 TEU (1A)
Shipbuilding Cost	23.0 M	26.1 M	67.0 M	76.0 M
Daily depreciation	3501	3973	10,198	11,575
CVC	101,634	93,146	296,065	271,339

By using (3), we calculated that the capital cost of each voyage is US$101,634 for a typical 1500-TEU container ship, US$93,146 for an ice-class 1500-TEU container ship, US$296,065 for a typical 4500-TEU container ship, and US$271,339 for an ice-class 4500-TEU container ship (Table 3). Due to differences in voyage time, the ice-class container ships have lower capital costs per voyage. The capital cost of ice-class ships is US$8488 less than that of typical container ships for the 1500-TEU size and US$24,726 less for the 4500-TEU size.

3.2.3. Calculation of C_{VF}

Using the information from Sections 2.1 and 2.2.3, we calculated that typical 1500- TEU and 4500-TEU container ships sailing via the Europe sea route consume 639 and 1408 tons of fuel per voyage, respectively, whereas ice-class container ships of the same sizes consume 619 and 1364 tons of fuel per voyage, respectively, when sailing via the Northeast Passage. Typical 1500-TEU and 4500-TEU container ships sailing via the Americas sea route consume 670 and 1477 tons of fuel per voyage, respectively, whereas ice-class container ships of the same sizes consume 624 and 1375 tons of fuel per voyage, respectively, when sailing via the Northwest Passage (Table 4).

Table 4. Fuel consumption along different sea routes.

Fuel Consumption (Tons)	Panama Canal and Northwest Passage	Differences	Suez Canal and Northeast Passage	Differences
1500 TEU 1500 TEU(1A)	639 619	20	670 624	46
4500 TEU 4500 TEU(1A)	1408 1364	44	1477 1375	102

Although ice-class container ships consume more fuel per day, because the Arctic passages are shorter than the Europe and Americas sea routes, the ice-class container ships consume less total fuel per voyage than do typical container ships. For 1500-TEU container ships, fuel consumption along the Northeast Passage is approximately 20 tons less than that along the Europe sea route, and fuel consumption along the Northwest Passage is approximately 46 tons less than that along the Americas sea route. For 4500-TEU container ships, fuel consumption volumes along the Northeast and Northwest Passages are approximately 44 and 102 tons less than those along Europe sea route and Americas sea route, respectively.

3.2.4. Calculation of C_{VT}

The passage fees for 1500-TEU (22,000-ton) and 4500-TEU (50,000-ton) container ships were calculated using the information in Section 2.2.4 (Table 5). Since the Northwest Passage is not open, the study assumed its tolls would be similar to the fees for crossing the Panama Canal; therefore, no meaningful differences were observed. For a 1500-TEU container ship, crossing the Suez Canal costs US$114,330, and crossing the Northeast Passage costs US$160,124, whereas the costs for a 4500-TEU container ship are US$194,550 and $303,366, respectively. The fees to pass through the Northeast Passage are approximately 29% higher than those for the Suez Canal for a 1500-TEU container ship and 36% higher for a 4500-TEU container ship.

Table 5. Tolls and transit fees along different sea routes.

Passage Fees (USD)	22,000-Ton/1500 TEU Container Ships	50,000-Ton/4500 TEU Container Ships
Panama Canal	90,000	277,000
Northwest Passage	90,000 *	277,000 *
Suez Canal	114,330	194,550
Northeast Passage	160,124	303,366

Note: * Similar to Panama Canal.

3.3. Calculation of the CO_2 Emission

After the length and fuel consumption for each shipping route were determined, the CO_2 emissions of each route were calculated (Figure 4). Along the Europe sea route, a typical 1500-TEU container ship emits 2264 tons of carbon, and a typical 4500-TEU container ship emits 4992 tons. Along the Northeast Passage, an ice-class 1500-TEU container ship emits 2194 tons, and an ice-class 4500-TEU container ship emits 4837 tons. Ice-class 1500-TEU container ships sailing through the Northeast Passage emit approximately 70 tons of CO_2 less than do typical 1500-TEU container ships navigating along the Europe sea route and through the Suez Canal; when the ship capacity is 4500-TEU, ice-class container ships emit approximately 155 tons of CO_2 less than do typical container ships. Both sizes of ice-class ships emit 3% less CO_2 overall.

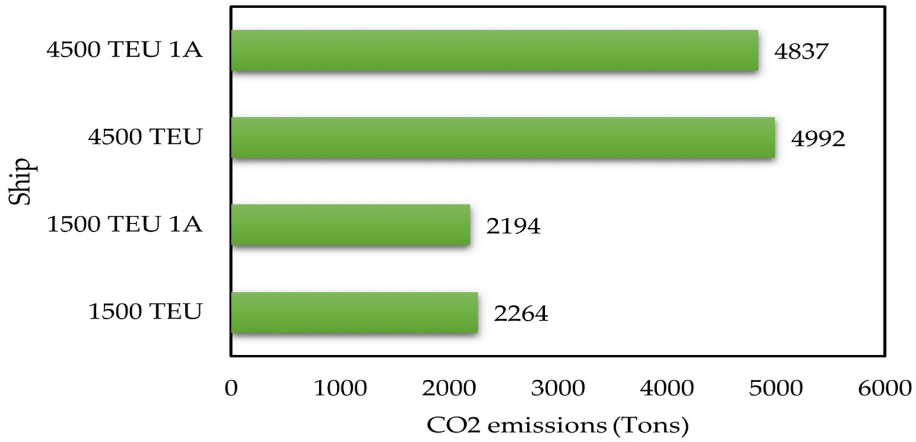

Figure 4. Comparison of CO_2 emissions for Europe sea route and Northeast Passage.

Figure 5 presents the CO_2 emissions along the Americas sea route (through the Panama Canal) and the Northwest Passage. For the Americas sea route, a typical 1500-TEU container ship emits approximately 2375 tons of CO_2, and a typical 4500-TEU container ship emits 5236 tons of CO_2. Along the Northwest Passage, their ice-class counterparts emit 2211 and 4874 tons of CO_2, respectively. An ice-class 1500-TEU container ship sailing through the Northwest Passage emits approximately 164 tons of CO_2 less than does a typical 1500-TEU container ship sailing along the Americas sea route through the Panama Canal; when the ship capacity is 4500 TEU, an ice-class container ship emits approximately 362 tons less than does a typical container ship. Both sizes of ice-class ships emit 7% less CO_2 overall.

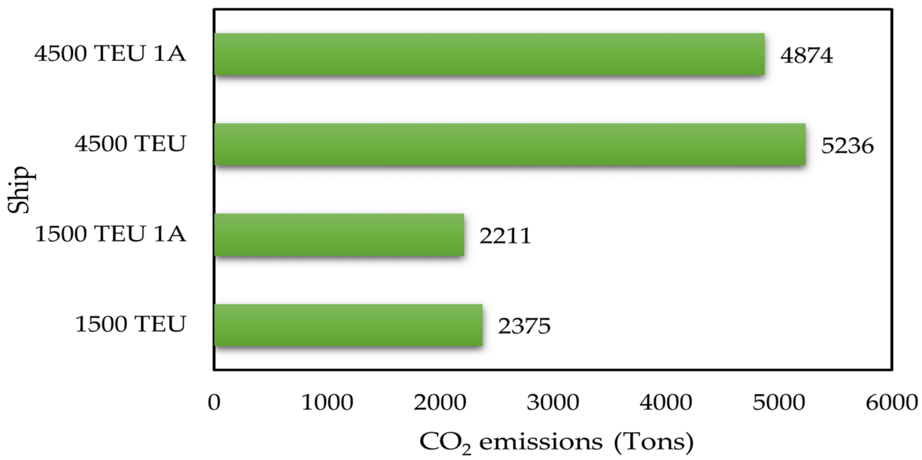

Figure 5. Comparison of CO_2 emissions for Americas sea route and Northwest Passage.

3.4. Discussion

Figure 6 presents the total costs for each voyage. Sailing along the Europe sea route costs approximately US$743,123 for a typical 1500-TEU container ship and US$1,588,760 for a typical 4500-TEU container ship. Sailing through the Northeast Passage costs approximately US$759,842 for an ice-class 1500-TEU container ship and US$1,632,788 for an ice-class 4500-TEU container ship. For the 1500-TEU size, the cost of sailing an ice-class container ship through the Northeast Passage is 2% higher than that of sailing a typical container ship along the Europe sea route. For the 4500-TEU size, sailing an ice-class container ship through the Northeast Passage costs approximately 3% more than does traveling along the Europe sea route.

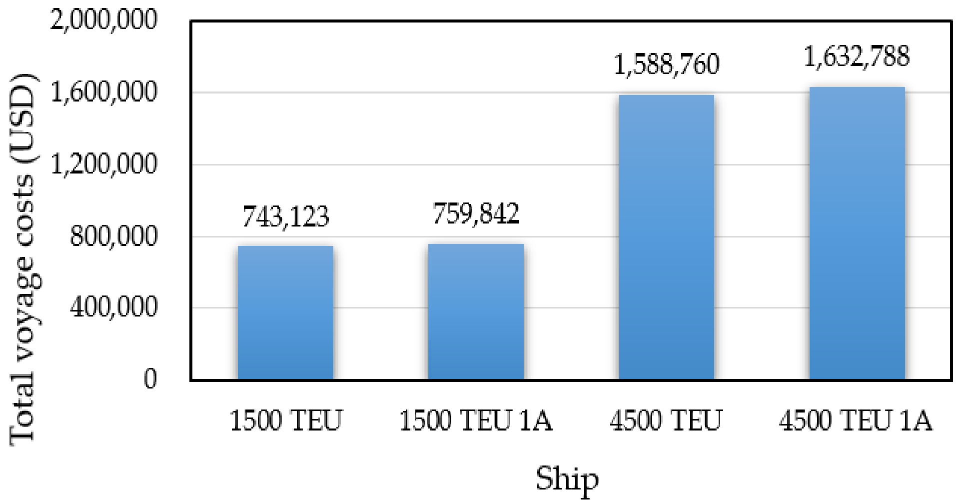

Figure 6. Total voyage costs for the Europe sea route and Northeast Passage.

An analysis of individual voyage costs indicated that sailing an ice-class container ship through the Northeast Passage costs less than does sailing a typical container ship along the Europe sea route, except for tolls. The high tolls for transit through the Northeast Passage directly causes the total cost of a single voyage through the Northeast Passage to be higher than the total cost of a single voyage along the Europe sea route (Figure 7).

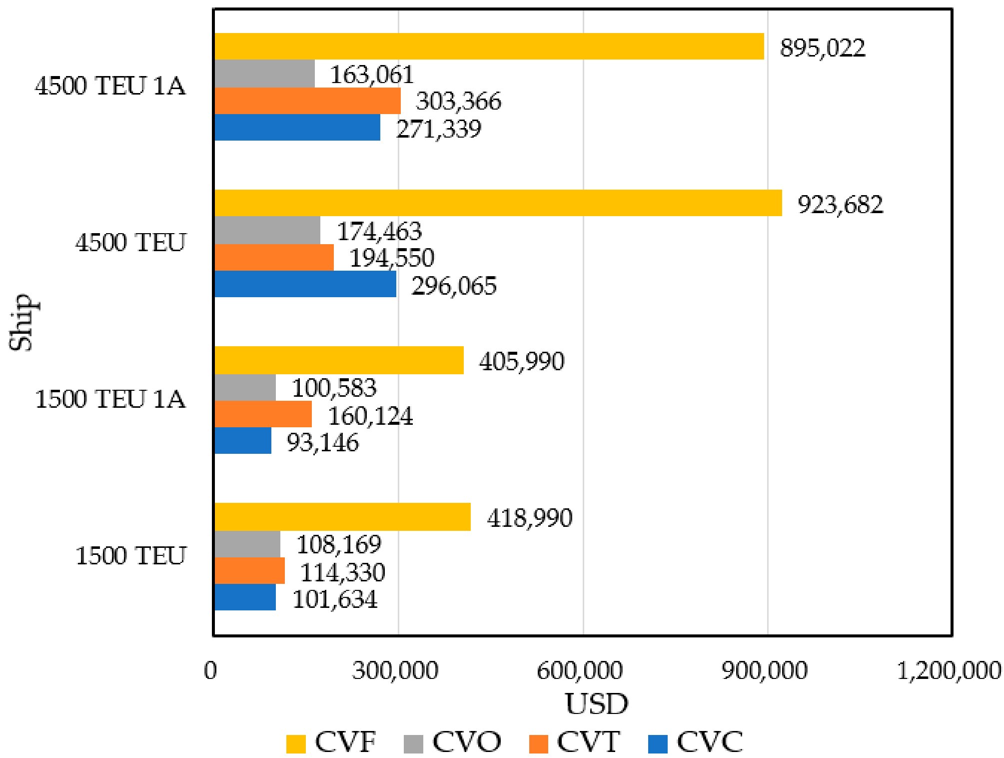

Figure 7. Voyages cost analysis for Europe sea route and Northeast Passage.

If the tolls for traveling through the Northeast Passage were lowered by 10% for ice-class 1500-TEU container ships and by 15% for ice-class 4500-TEU container ships, the total cost for traveling to the Port of Rotterdam via the Northeast Passage would be lower than that for traveling along the Europe sea route. By assuming the Northeast Passage tolls were not reduced, this study observed that if the speed of sailing in the Northeast Passage were increased to match that of sailing in normal waters, the total cost of traveling through the Northeast Passage would be less than that of traveling along the Europe sea route. Research on melting ice in the Arctic at the current rate indicates that this assumption is within the realm of possibility.

Figure 8 presents the costs of traveling to New York Harbor. The total cost of one voyage along the Americas sea route is approximately US$749,597 for a typical 1500-TEU container ship and US$1,732,510 for a typical 4500-TEU container ship. The total cost of one voyage through the Northwest Passage is approximately US$694,301 for an ice-class 1500-TEU container ship and US$1,609,581 for an ice-class 4500-TEU container ship. Sailing along the Americas sea route is approximately 7% more expensive than sailing through the Northwest Passage for both 1500-TEU and 4500-TEU container ships.

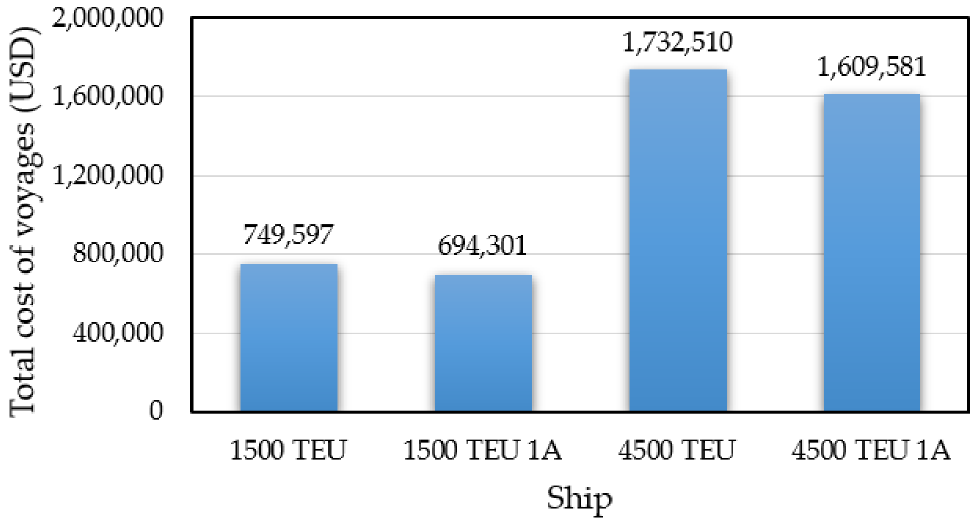

Figure 8. Total voyages cost for Americas sea route and the Northwest Passage.

Figure 9 presents an analysis of the costs of sailing along the Americas sea route and through the Northwest Passage. Since the Northwest Passage is not open and has no established toll system, this study assumed it had the same tolls as the Panama Canal. This in combination with the short length of the Northwest Passage makes it lower cost than the Americas sea route. If the Northwest Passage were open for sailing, tolls would become a major factor affecting cost. The analysis revealed that if tolls were increased by 55% for an ice-class 1500-TEU container ship and by 43% for an ice-class 4500-TEU container ship, the total cost of sailing through the Northwest Passage would still be lower than the current cost of sailing through the Americas sea route.

The results are similar to those of Raza et al. [14], Faury et al. [15], and Dimitrios et al. [16]. These studies indicated that icebreaking fees are the main factor determining whether passage through the Northeast Passage would be advantageous. Faury et al. [15] noted that sailing speed is also a determinant, which is consistent with the results of this study. Dimitrios et al. [16] observed that in addition to icebreaking fees, high fuel prices, the US–Ruble exchange rate, and voyage length determine the economic benefits of sailing through the Northeast Passage. The results of this study differed from those of Schøyen et al. [13]; despite analyzing similar sailing distances, Schøyen et al. used lower sailing speeds and higher icebreaking fees. However, the Northeast Passage is more advantageous than the Europe sea route because they assumed that both sea routes would take 30 days; slower sailing speeds would enable ice-class container ships to reduce fuel consumption considerably [13]. In addition, Schøyen et al. assumed oil prices to be US$1000 which exceeds market prices substantially. As indicated previously, the Arctic sea routes are more advantageous when oil prices increase. The results for the calculation of CO_2 emissions are similar to one of the conclusions of Xu et al. [21] that the Northeast Passage does reduce emissions. However, although the economic analysis of both the Northeast Passage and the Northwest Passage was carried out in Xu et al. [21], but only the Northeast Passage calculated carbon emission calculation, and the comparison was made between LNG ships and general ships.

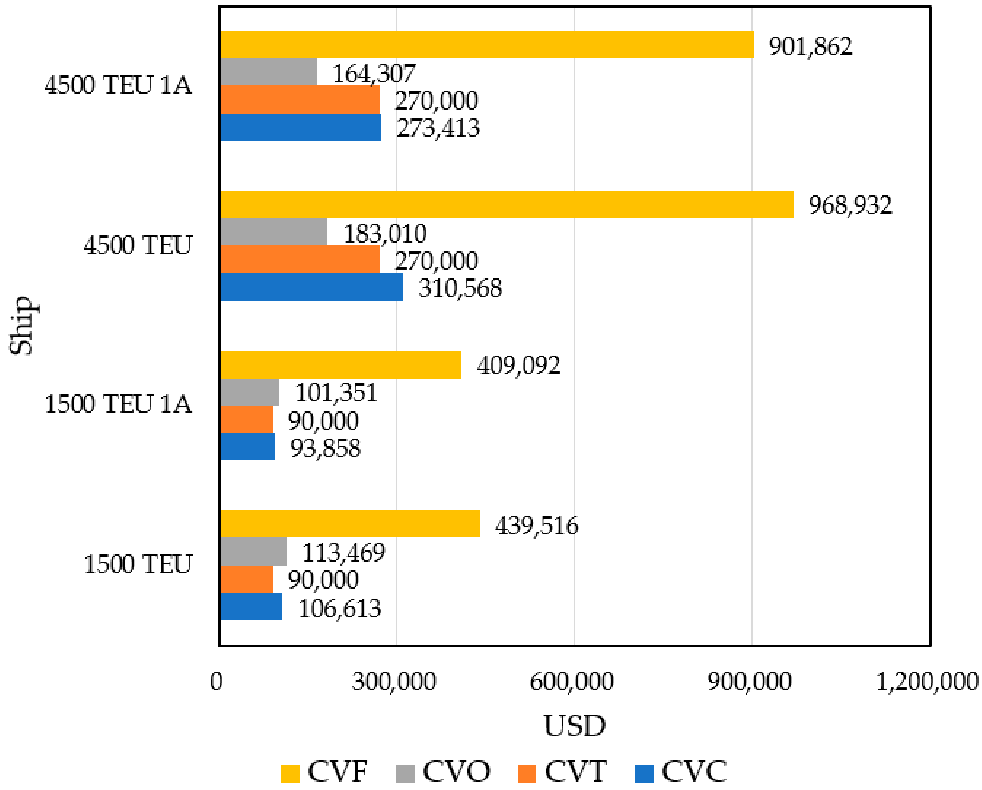

Figure 9. Voyages cost analysis for Americas sea route and the Northwest Passage.

Container ships sailing along sea routes to Europe and the Americas spend more than 80% of time at sea. If the Arctic becomes ice free, ice-class container ships will be able to make approximately 13 voyages along the Northeast Passage per year. On the basis of the information in Section 3.3, each ice-class 1500-TEU container ship can reduce carbon emissions by 876 tons per year, whereas each ice-class 4500-TEU container ship can reduce carbon emissions by 1930 tons. Under similar ice-free conditions in the Arctic, ice-class container ships can make approximately 12 voyages through the Northwest Passage per year. This would reduce carbon emissions by approximately 2032 tons per ice-class 1500-TEU container ship and by 4480 tons per ice-class 4500-TEU container ship each year. In 2021, the International Chamber of Shipping (ICS) expressed an intention to enact a carbon tax to reduce CO_2 emissions from maritime transportation. The IMO agreed to revise its greenhouse gas strategy in 2023 [45] and expects to implement new measures to reduce emissions by 2025; a carbon tax is also being discussed. These measures will affect not only shipping companies but also national economies [46]. The global atmospheric CO_2 concentration has steadily increased, resulting in increases in global temperature, including temperatures in areas of northwestern Russia near the entrance to the Arctic Ocean [47]. Currently the research of annual increases in CO_2 levels in the Arctic Circle is lacking, the data on single-voyage CO_2 emissions for typical and ice-class container ships (1500-TEU and 4500-TEU) from this study can be used as reference to calculate the CO_2 emissions produced by navigating in the Arctic Circle. There are very few studies on the effects of species and biodiversity caused by the discharge of pollutants in the Arctic Ocean shipping routes, because it's difficult to study the ecological impacts in the Arctic Circle and the lack of ecological models [48]. In these rare studies, the aquatic toxicity data of Arctic species are also lacking for oil pollution and can only be replaced by experimental models [49]. At most, water quality sampling was used to predict impacts, with no data on actual biological effects [50]. Although it is true that shipping via the Arctic Sea Routes can reduce overall emissions, it does not seem feasible to achieve the 2050 carbon neutrality target by navigating the Arctic Sea Route, and more technology and exploration is needed, for example reducing the sailing speed [51], or the use of the clean fuel (LNG) [52]. It is necessary to pay attention on how to acquire a balance between the new Arctic shipping routes and the protection of the marine environment.

4. Conclusions

The results indicate that the cost of sailing through the Arctic passages is affected by tolls, speed, and oil prices, with tolls being the most crucial factor. A 10% to 15% reduction in icebreaking fees would lower the total cost of sailing through the Northeast Passage to less than that of sailing along the Europe sea route. In addition, the tolls for sailing through the Northwest Passage could be 55% more than those for sailing through the Panama Canal for ice-class 1500-TEU container ships and 43% more for ice-class 4500-TEU container ships while the total costs could remain lower than those for sailing along the Americas sea route. In the future, the loan and financial study can be useful to analyze the case of shipping companies with multiple ships, because those company's value and calculation are based on the optimal total value of free cash flows to equity for each level of the starting capital and the number of acquired vessels [53]. A single voyage through the Northeast Passage emits 3% less CO_2 than does a single voyage along the existing Europe sea route, whereas a single voyage through the Northwest Passage emits 7% less CO_2 than does a voyage along the Americas sea route. Consequently, sailing through the Arctic Passages reduces carbon emissions and thereby slows global warming. Therefore, the Arctic Passages can be utilized to develop maritime transportation and reduce carbon emissions in a cost-effective manner.

Author Contributions: Contributions: Conceptualization T.-K.L.; methodology, P.-H.C. and T.-K.L.; hardware and software, P.-H.C.; validation, T.-K.L. and P.-H.C.; writing—original draft preparation, P.-H.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors want to express sincere thanks to the people from vessel operator including the Caption and Chief engineer for their assistance of vessel operation details.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations' Conference on Trade and Development (UNCTAD). *Review of Maritime Transport 2020*; United Nations Publications: New York, NY, USA, 2020.
2. Cristea, A.; Hummels, D.; Puzzello, L.; Avetisyan, M. Trade and the greenhouse gas emissions from international freight transport. *J. Environ. Econom. Manag.* **2013**, *65*, 153–173. [CrossRef]
3. IMO. *Fourth IMO GHG Study 2020-Final Report Note by the Secretariat*; IMO: London, UK, 2020.
4. Brandt, J.; Silver, J.D.; Christensen, J.H.; Andersen, M.S.; Bønløkke, J.H.; Sigsgaard, T.; Geels, C.; Gross, A.; Hansen, A.B.; Hansen, K.M.; et al. Assessment of past, present and future health-cost externalities of air pollution in Europe and the contribution from international ship traffic using the EVA model system. *Atmos. Chem. Phys.* **2013**, *13*, 7747–7764. [CrossRef]
5. Lei, R.; Xie, H.; Wang, J.; Leppäranta, M.; Jónsdóttir, I.; Zhang, Z. Changes in sea ice conditions along the Arctic Northeast Passage from 1979 to 2012. *Cold Reg. Sci. Technol.* **2015**, *119*, 132–144. [CrossRef]
6. Hays, B. NOAA: Arctic Warming at Twice the Rate of the Rest of the Planet, UPI. 2018. Available online: https://www.upi.com/Science_News/2018/12/12/NOAA-Arctic-warming-at-twice-the-rate-of-the-rest-of-the-Planet/5141544580754/ (accessed on 18 July 2020).
7. Carvalho, K.S.; Wang, S. Sea surface temperature variability in the Arctic Ocean and its marginal seas in a changing climate: Patterns and mechanisms. *Glob. Planet. Chang.* **2020**, *193*, 103265. [CrossRef]
8. Xia, Y.; Bex, V.; Midgley, P.M. *Climate Change 2013: The Physical Science Basis*; Cambridge University Press: Cambridge, MA, USA, 2013. [CrossRef]

9. Diebolda, F.X.; Rudebusch, G.D. Probability assessments of an ice-free Arctic: Comparing statistical and climate model projections. *J. Econom.* 2021, *in press*. [CrossRef]
10. Beluga Shipping. Available online: https://en.wikipedia.org/wiki/Beluga_Shipping (accessed on 12 December 2021).
11. Arctic Council. *Arctic Marine Shipping Assessment (AMSA) 2009 Report*; Arctic Council: Tromsø, Norway, 2009.
12. IMO. *Sub-Committee on Pollution Prevention and Response (PPR 7), 17–21 February 2020*; IMO: London, UK, 2020.
13. Schøyen, H.; Bråthen, S. The Northern sea route versus the Suez Canal: Cases from bulk shipping. *J. Transp. Geogr.* **2011**, *19*, 977–983. [CrossRef]
14. Raza, Z.; Schøyens, H. The commercial potential for LNG shipping between Europe and Asia via the Northern Sea Route. *J. Marit. Res.* **2014**, *11*, 67–79.
15. Faury, O.; Cariou, P. The Northern Sea Route competitiveness for oil tankers. *Transp. Res. Part A Policy Pract.* **2016**, *94*, 461–469. [CrossRef]
16. Theocharis, D.; Rodrigues, V.S.; Pettit, S.; Haider, J. Feasibility of the Northern Sea Route: The role of distance, fuel prices, ice breaking fees and ship size for the product tanker market. *Transport. Res. Part E Logist. Transport. Rev.* **2019**, *129*, 111–135. [CrossRef]
17. Somanathan, S.; Flynn, P.; Szymanski, J. The Northwest Passage: A simulation. *Transp. Res. Part A Policy Pract.* **2009**, *43*, 127–135. [CrossRef]
18. TurgutKoçak, S.; Yercan, F. Comparative cost-effectiveness analysis of Arctic and international shipping routes: A Fuzzy Analytic Hierarchy Process. *Transp. Policy* **2021**, *114*, 147–164. [CrossRef]
19. Gleb, S.; Jin, J.G. Evaluating the feasibility of combined use of the Northern Sea Route and the Suez Canal Route considering ice parameters. *Transp. Res. Part A Policy Pract.* **2021**, *147*, 350–369. [CrossRef]
20. Lasserre, F. Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector. *Transp. Res. Part A Policy Pract.* **2014**, *66*, 144–161. [CrossRef]
21. Xu, H.; Yang, D. LNG-fuelled container ship sailing on the Arctic Sea: Economic and emission assessment. *Transp. Res. Part D Trans. Environ.* **2020**, *87*, 102556. [CrossRef]
22. Directorate General of Budget, Accounting and Statistics, Executive Yuan, ROC. 2021. International Port Cargo Lifting Volume. Available online: https://www.dgbas.gov.tw/public/Data/2210143122YUOZUPXC.pdf (accessed on 28 January 2022).
23. Export & Import Value List. Bureau of Foreign Trade, MOEA, R.O.C. 2021. Available online: https://cuswebo.trade.gov.tw/FSCE030F/FSCE030F (accessed on 28 January 2022).
24. IMO. MEPC.268(68) (Adopted on 15 May 2015). Designation of the South-West Coral Sea as an Extension of the Great Barrier Reef and Torres Strait Particularly Sensitive Sea Area. Available online: https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/MEPC-2014-15.aspx (accessed on 12 September 2021).
25. Northern Sea Route information Office. Analysis of Shipping Traffic in the NSR Waters in 2020. Available online: https://arctic-lio.com/analysys-of-shipping-traffic-in-the-nsr-waters-in-2020/ (accessed on 8 February 2022).
26. Anonymous; An Anonymous Officer from One of the Major Container Operator Companies. Personal Communication.
27. Panama Canal Authority. Available online: https://pancanal.com/eng/op/tariff/index.html (accessed on 10 February 2022).
28. Lu, D.; Park, G.K.; Choi, K.; Oh, S. An economic analysis of container shipping through Canadian Northwest passage. *Int. J. E Navigat. Marit. Econ.* **2014**, *1*, 60–72. [CrossRef]
29. Xu, H.; Yin, Z. The optimal icebreaking tariffs and the economic performance of tramp shipping on the Northern Sea Route. *Transp. Res. Part A Policy Pract.* **2021**, *49*, 76–97. [CrossRef]
30. Jiang, M.; Hu, M.; Leibrecht, M. Profitability of container shipping via the Arctic Northeast passage: A simulation and regression analysis. *Mar. Policy* **2021**, *133*, 104738. [CrossRef]
31. Lasserre, F. Simulations of shipping along Arctic routes: Comparison, analysis and economic perspectives. *Polar Rec.* **2014**, *51*, 239–259. [CrossRef]
32. Sarrabezoles, A.; Lasserre, F.; Hagouagn'rin, Z. Arctic shipping insurance: Towards a harmonisation of practices and costs? *Polar Rec.* **2016**, *52*, 393–398. [CrossRef]
33. Container Ship Crew Salary Guide 2021. Available online: https://www.nauticjobs.com/blog/2020/10/30/container-ship-crew-salary-guide-2021/ (accessed on 13 February 2022).
34. Drewry. *Ship Operating Costs Annual Review and Forecast 2019/20*; Drewry Shipping Consultants: London, UK, 2019.
35. Enter the Existing Ship Schedule. In *The Law of the Ship*; Maritime Port Bureau; MOTC: Taiwan, 2019. Available online: https://www.motcmpb.gov.tw/Information/Detail/4f6b83b4-11e9-4673-8cd2-00d58caa7682?SiteId=1&NodeId=54 (accessed on 16 December 2021).
36. Russia Maritime Register of Shipping Website. Available online: https://rs-class.org/ (accessed on 10 February 2022).
37. Clarkson Shipping Fuel Price. Available online: https://www.clarksons.com/ (accessed on 7 January 2022).
38. SUEZ Canal Authority. Available online: https://www.suezcanal.gov.eg/English/Navigation/Tolls/Pages/TollsTable.aspx (accessed on 7 January 2022).
39. Marine Fuel Price of CPC, ROC. Available online: https://www.cpc.com.tw/cp.aspx?n=44 (accessed on 13 February 2022).
40. Russian Northern Sea Route Administration. Available online: http://www.nsra.ru/en/ledokolnaya_i_ledovaya_lotsmanskaya_provodka/raschet_stoimosti_ledokolnoy_provodki_v_akvatorii_smp.html (accessed on 19 November 2021).

41. Exchange Rate USD/RUB. 2021. Available online: https://invest.cnyes.com/forex/detail/USDRUB/history (accessed on 15 May 2022).
42. IMO. *UN Body Adopts Climate Change Strategy for Shipping*; IMO: London, UK, 2018.
43. Xue, Y.L. Carbon Dioxide (CO_2) emissions from ocean-going vessels and estimation methods. *Ship Shipp. Newsl.* **2014**, *124*, 2–12.
44. Comer, B.; Osipova, L. *Accounting for Well-to-wake Carbon Dioxide Equivalent Emissions in Maritime Transportation Climate Policies*; ICCT: Washington, DC, USA, 2021.
45. International Chamber of Shipping, 6 September 2021. International Chamber of Shipping Sets Out Plans for Global Carbon Levy to Expedite Industry Decarbonization. Available online: https://www.ics-shipping.org/press-release/international-chamber-of-shipping-sets-out-plans-for-global-carbon-levy/ (accessed on 10 January 2022).
46. Lee, T.C.; Chang, Y.T.; Lee, P.T.W. Economy-wide impact analysis of a carbon tax on international container shipping. *Transp. Res. Part A Policy Pract.* **2013**, *58*, 87–102. [CrossRef]
47. Samenow, J. It Was 84 Degrees near the Arctic Ocean This Weekend as Carbon Dioxide Hit Its Highest Level in Human History. Available online: https://www.washingtonpost.com/weather/2019/05/14/it-was-degrees-near-arctic-ocean-this-weekend-carbon-dioxide-hit-its-highest-level-human-history/ (accessed on 15 February 2022).
48. Kikuchi, T.; Nishino, S.; Fujiwara, A.; Onodera, J.; Yamamoto, K.M.; Mizobata, K.; Fukamachi, Y.; Watanabe, E. Status and trends of Arctic Ocean Environmental Change and its Impacts on Marine Biogeochemistry: Findings from the ArCS Project. *Polar Sci.* **2021**, *27*, 100639. [CrossRef]
49. Fahd, F.; Yang, M.; Khan, F.; Veitch, B. A food chain-based ecological risk assessment model for oil spills in the Arctic environment. *Mar. Pollut. Bull.* **2021**, *166*, 112164. [CrossRef]
50. Vincent, W.F.; Whyte, L.G.; Lovejoy, C.; Greer, C.W.; Laurion, I.; Suttle, C.A.; Corbeil, J.; Mueller, D.R. Arctic microbial ecosystems and impacts of extreme warming during the International Polar Year. *Polar Sci.* **2009**, *3*, 171–180. [CrossRef]
51. Tran, N.K.; Lam, J.S.L. Effects of container ship speed on CO2 emission, cargo lead time and supply chain cost. *Research in Transp. Bus. Manag.* **2022**, *43*, 100723. [CrossRef]
52. Hoang, A.T.; Foley, A.M.; Nižetić, S.; Huang, Z.; Ong, H.C.; Ölçer, A.I.; Pham, V.V.; Nguyen, X.P. Energy-related approach for reduction of CO_2 emissions: A critical strategy on the port-to-ship pathway. *J. Clean. Prod.* **2022**, *355*, 131772. [CrossRef]
53. Bazaluk, O.; Zhykharieva, V.; Vlasenko, O.; Nitsenko, V.; Streimikiene, D.; Balezentis, T. Optimization of the Equity in Formation of Investment Portfolio of a Shipping Company. *Mathematics* **2022**, *10*, 363. [CrossRef]