UNIVERSITY OF GOTHENBURG

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THE IMPLICATIONS OF HEAVY FUEL OIL BAN IN ARCTIC WATERS FOR SUSTAINABLE ARCTIC SHIPPING

Systematic Literature Review

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Popular Scientific Summary

Global warming and consequential climate change have raised the temperature in the polar regions of the earth. Therefore, the regional warming of the Arctic leads to the accelerated decline of sea ice levels resulting in new international shipping routes for maritime transportation. However, although the shipping industry plays a vital role in the global economy and cargo transport, it can create detrimental impacts on the marine environment. As the shipping industry mainly uses heavy fuel oil (HFO), which is a relatively cheap fuel but a dirty residual one, for the propulsion of marine vessels, the use and carriage of HFO by ships present serious environmental concerns such as the emissions of harmful pollutants, toxic compounds and the risk of oil spills. As the Arctic region is regarded as an ecologically vulnerable area due to its highly sensitive marine ecosystems, it is of vital importance to protect the region from the negative impacts of shipping activities. Moreover, the environmental risks from Arctic shipping might affect the local communities and Arctic indigenous people. Therefore, an HFO ban in Arctic waters has become a hot topic, and it was agreed upon the draft to phase out the use and carriage of HFO by ships in 2020. This study reviewed 34 publications to explore the environmental, societal and economic implications of the use and carriage of HFO by ships in Arctic waters and the impacts of the Arctic HFO ban. It was found that the larger vessels were more likely to use HFO, and hence, the use and carriage of HFO by ships were relatively high in Arctic waters. Therefore, the potential Arctic HFO ban could significantly reduce the associated ecological and socio-economic risks of Arctic shipping. Although the shipping industry will need to switch from a low-price HFO to more expensive alternative fuels, it is worth the transition because the clean-up costs of HFO could be relatively high in case of oil spills. However, as the currently available alternative fuels to HFO would not eliminate the associated environmental problems of Arctic shipping, further research should focus on the development of cleaner fuels.

Abstract

The increased temperature in the polar regions is one of the significant impacts of global warming and consequential climate change. In the Arctic, regional warming leads to the accelerated loss of sea ice caps, which has opened up new international shipping routes. Consequently, the associated risks of shipping operations raise concerns about the sustainability of the Arctic region. One of the serious issues of Arctic shipping is the use and carriage of heavy fuel oil (HFO) by ships due to the release of air emissions and potential oil spills. Hence, it has been discussed to phase out the use and carriage of HFO by ships in Arctic waters, and as a result, it was agreed upon the draft amendment of the Arctic HFO ban. Therefore, this study conducted a systematic literature review to investigate the impacts of the potential Arctic HFO ban under the sustainable development framework. There are 34 reviewed papers selected for this study to explore the implications of the Arctic HFO ban for the sustainable development of Arctic shipping. It was found that the environmental and socio-economic risks were significantly high because of the relatively larger consumption and carriage of HFO by ships in Arctic waters. A switch from HFO to distillate fuels by ships would be beneficial for the sustainability of the region and the sustainable development of Arctic shipping. However, it is necessary to develop further research on the development of alternative fuels other than distillate fuels.

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List of Abbreviations

AIS	Automatic Identification System
ASMA	Arctic Shipping Marine Assessment
BC	Black Carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DKK	Danish Krone
ECAs	Emission Control Areas
EEZ	Exclusive Economic Zone
GHGs	Greenhouse Gases
HFO	Heavy Fuel Oil
ICCT	International Council on Clean Transportation
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
LNG	Liquified Natural Gas
LSFO	Low Sulphur Fuel Oil
MARPOL	The International Convention for the Prevention of Pollution from Ships
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
N_2O	Nitrous Oxide
NEP	Northeast Passage
NMVOC	Non-methane Volatile Organic Compound
NORDREG	Northern Canada Vessel Traffic Services Zone
NO_X	Nitrogen oxides
NSR	Northern Sea Route
NWP	Northwest Passage
OC	Organic Carbon
PAME	Protection of the Arctic Marine Environment
PM	Particulate Matter
Polar Code	International Code for Ships Operating in Polar Waters
PPR	Pollution Prevention and Response
SD	System Dynamics

SDGs	Sustainable Development Goals
SDG14	Sustainable Development Goal 14
SO_2	Sulphur dioxide
SO_X	Sulphur Oxide
TSR	Transpolar Sea Route
U.S.	The United States
UN	United Nations
USD	United States Dollar
VOC	Volatile Organic Compound

List of Figures and Tables

1. Introduction

Global warming and consequential climate change have been affecting the world resulting in significant alterations to the environment. The warming of the Arctic and Antarctic, which are the polar regions of the earth, is one of the considerable impacts of climate change. According to the Intergovernmental Panel on Climate Change and an Arctic Council working group, it was reported by the Arctic Monitoring and Assessment Programme that there may be ice-free summer in the Arctic region by mid-century (Bai & Chircop, 2020; IPCC, 2019). As a result, the increased temperature in the Arctic leads to the accelerated decline of the sea ice cap (Mukherjee & Liu, 2018), and this tendency has opened up new international shipping routes in the Arctic for maritime transportation. Consequently, it is also expected to increase shipping activities and maritime operations in the future Arctic (Deggim, 2018).

However, the potential increased maritime operations also raise concerns for the Arctic region because the impacts of shipping on the atmospheric and aquatic marine environment are of significance and well-documented (Moldanová et al., 2022). Moreover, it is noted that the environmental risks posed by shipping operations can vary depending on the nature of marine environments and the sensitivities of the affected regions (Chircop, 2020). The Arctic region is regarded as an ecologically vulnerable area due to its extreme climatic conditions and highly sensitive marine ecosystems (Roy & Comer, 2017). Therefore, the opening up of the Arctic shipping routes and the likely increased shipping activities can pose significant challenges to the fragile Arctic marine environment and Arctic communities (Sun, 2019).

Even though seaborne transportation plays a vital role in the economic sector and global trade carrying more than 80% of world cargo by volume (Xing et al., 2020), it heavily depends on fossil fuel (Wan et al., 2018). The use of fossil fuel by ships results in significant negative impacts on the marine environment, and the most commonly used type of fossil fuel by the shipping industry is heavy fuel oil (HFO) because of its wider availability and lower cost than other forms of fossil fuels (Comer et al., 2016). When it comes to Arctic shipping, the use and carriage of HFO as fuel by vessels is one of the major concerns (Bai & Chircop, 2020) because not only does the burning of HFO release atmospheric pollutants and greenhouse gases (GHGs) which tend to trap heat in the atmosphere such as carbon dioxide (CO_2), methane (CH_4) and Nitrous Oxide (N_2O), but the potential oil spill of HFO is also a serious threat for the polar regions (Sun, 2019).

Since 2011, the carriage of HFO as cargo, ballast, or carriage and use by ships was completely banned in Antarctic waters (Deggim, 2018). Therefore, the international community has also been engaged in the issue of such a ban on the use and carriage of HFO for ship operations in Arctic waters (Bai & Chircop, 2020). However, the work of the Arctic HFO ban for maritime transportation has been delayed to reach the mandatory provision for shipping operations. This is because the Arctic Ocean is surrounded by continents with numerous coastal seas and several stakeholders being engaged in the issue. Hence, the potential ban of HFO in the Arctic region presents challenges concerning social and economic consequences despite the environmental risks posed by HFO.

1.1 Background

With regard to the regulatory framework for international shipping, the International Maritime Organisation (IMO) which is a specialised agency of the United Nations (UN) has the authority to create global regulatory measures and provisions to ensure safety, security and the protection of the marine environment (Deggim, 2018). Due to the fact that the increase in maritime transportation and shipping operations in polar regions pose threats to highly sensitive areas of the Arctic and Antarctic regions, the IMO adopted the mandatory International Code for Ships Operating in Polar Waters (Polar Code) (Sun, 2019). The Polar Code entered into force in January 2017, and it addresses a range of safety and environmental risks posed by shipping operations to the polar marine environments.

Despite the Polar Code adoption which is a major achievement for the protection of the unique and fragile polar waters (Chircop, 2020), the only reference mentioned about HFO for the Arctic region is Part 2-B of the Polar Code, which is an encouragement to the vessels operating in Arctic waters to apply the regulation of HFO ban for the Antarctic region (Bai & Chircop, 2020). As HFO is significantly harmful to the Arctic region and Arctic marine ecosystems, the potential ban of the use and carriage of HFO by ships has been discussed by many organisations, researchers and local communities (van Luijk et al., 2020). The development of the regulation for the potential ban of HFO by ships in Arctic waters has seen significant improvements over the last few years. Several proposals have been made to the IMO to implement a mandatory HFO ban in Arctic waters (Sun, 2019).

In February 2020, the draft amendment of the Arctic HFO ban for the carriage and use of HFO was agreed upon at the seventh session of the IMO sub-committee on the Pollution Prevention and Response (PPR 7) (Comer et al., 2020). Regarding the proposed ban of HFO in Arctic waters, it is only prohibited on the use and carriage for use as fuel of HFO by ships, while the transportation of HFO by ships as cargo is not included (IMO, 2020). This is different from the mandatory ban of HFO in Antarctic waters where HFO is completely prohibited for maritime operations. Therefore, it would be of great value to explore the effects of the proposed HFO ban in the Arctic region and provide the necessary information on the potential impacts on the development of Arctic shipping. The draft amendment for the prohibition on the use and carriage of HFO by ships in Arctic waters is presented in Appendix.

1.2 Disposition

This thesis is organised with six sections, beginning with the Section 1 to introduce the background of thesis. Section 2 presents the navigational context of Arctic shipping and theoretical framework of sustainable shipping. Section 3 explains the methodology and the application of methods in this thesis. Synthesis of results and findings are presented in Section 4. Section 5 analyses and discusses the results. Section 6 concludes this thesis by answering the research questions and discusses further research considerations.

2. Arctic Navigational Context and Theoretical Framework

This section will introduce the navigational shipping routes and operating vessels in Arctic waters. Then it will explore the use of marine fuel oils, particularly the use of HFO, by ships along with the regulatory framework of the shipping industry. It will conclude by explaining the sustainable framework tool which is used to assess the potential ban of HFO in Arctic waters and sustainable Arctic shipping.

2.1 Arctic Shipping Routes and Navigational Vessels

Due to the diminishing sea ice level in the Arctic region, it has become an opportunity for the shipping industry to enhance accessibility and the possibility to navigate in Arctic waters for maritime activities. According to the Arctic Marine Shipping Assessment (AMSA) 2009 report by the Arctic Council, there are four modes of shipping operations and voyages undertaken in the Arctic Ocean which are:

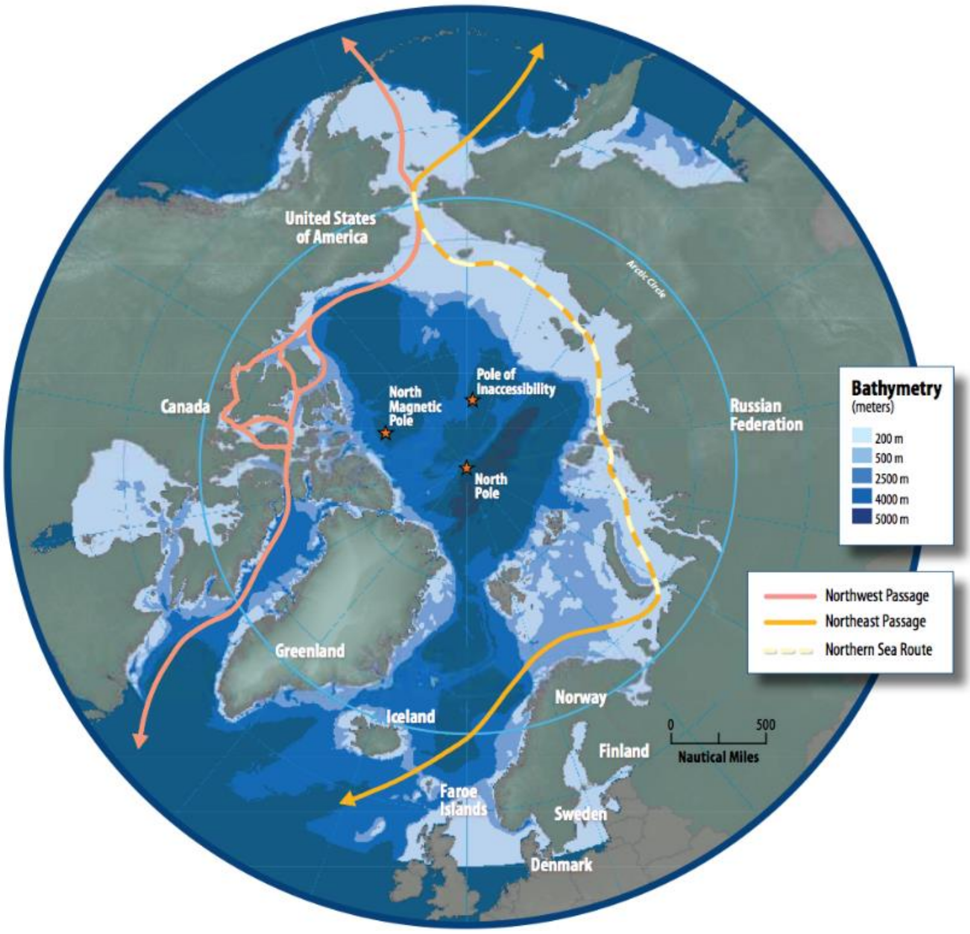
- destinational transport which is a navigational voyage to the Arctic
- intra-arctic transport which is a voyage between the two Arctic states
- trans-arctic transport which is a voyage across the Arctic Ocean
- cabotage which is a domestic voyage between the two ports of an Arctic state (Ellis & Brigham, 2009).

Regarding the shipping routes in the Arctic Ocean, there are, in general, three principal Arctic transit routes namely Northeast Passage (NEP), Northwest Passage (NWP) and Northern Sea Route (NSR) as illustrated in Figure 1. Among these shipping routes, Chircop (2020) mentioned that the most economically feasible and fastest growing route is the NEP which includes the NSR through Russian Federation waters, while the NWP, largely through Canadian waters, has fewer shipping operations than NSR. Sun (2019) also pointed out that whereas the NSR witnesses the highest number of voyages within the Arctic for both transpolar passages and destinational traffic, the trans-navigation through the Canadian Arctic waters remains less accessible compared to the NSR, and most of the maritime operations are domestic and destinational to support the Northern communities.

Another possible route is the Transpolar Sea Route (TSR) which directly links the Strait of Bering and the Arctic Ocean of Murmansk through the central part of the Arctic, but it is just a hypothetical route due to the lack of information about ice-free conditions (Rodrigue, 2020). According to the AMSA classification, the navigating vessels that operate in Arctic waters are bulk carriers, fishing vessels, general cargo, government vessels and icebreakers, oil and gas exploration vessels, passenger ships, pleasure craft, tankers, tug/barge (van Luijk et al., 2020).

Figure 1

Navigational Routes in Arctic Waters



Note. Adapted from *Arctic Marine Shipping Assessment 2009 Report* by Ellis, B., & Brigham, L., 2009, Arctic Council, p. 17.

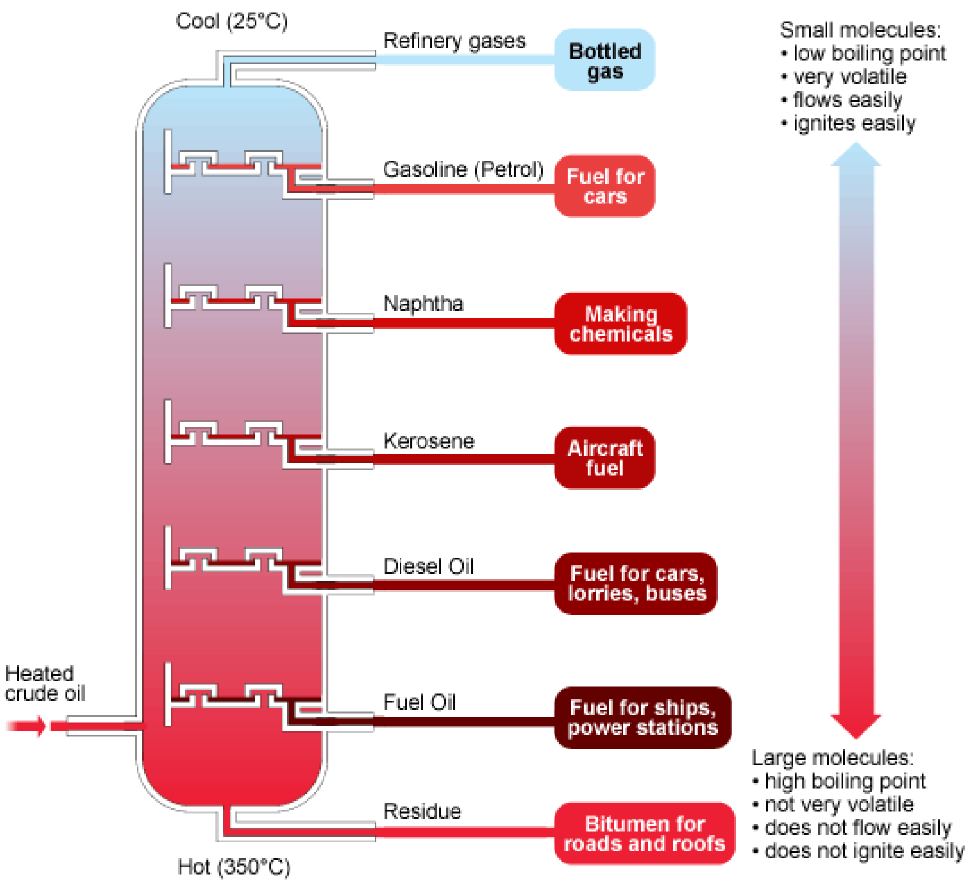
2.2 Marine Fuels

According to the report by DNV (2011), HFO is defined in several terms such as bunker oil, bunker fuel oil, residual fuel and heavy diesel oil so that it covers a broad range of different marine residual fuels and some distillate fuels. Moreover, the other names of HFO which are used to describe this range of products are residual fuel oil, bunker fuel, bunker C, fuel oil No. 6, industrial fuel oil, marine fuel oil and black oil (Ford, 2012). The common features of these terms are that they all are used as terminology to be used onboard ships and are distinct from other forms of refined products and crude oil (Fritt-Rasmussen et al., 2018). The definition of HFO defined by the IMO is as follows:

> crude oil having a density, at 15 °C, higher than 900 kg/m3; oil, other than crude oil, having a density at 15 °C, higher than 900 kg/m3 or a kinematic viscosity, at 50 °C higher than 180 mm2/s; or bitumen, tar, and their emulsions. (DNV, 2011, p. 45)

Figure 2

Refinery Process of Crude Oil



Note. The figure shows the distillation of crude oil to produce different types of fuel oils. Adapted from *Global Trading*, 2022. https://globaltrading.com/heavy-fuel-oil.php

As illustrated in Figure 2, HFO can be defined as the leftover after the distillation process because distillate fuel, which is often referred to as marine gas oil (MGO) and marine diesel oil (MDO), is the purified version of crude oil and residual fuel (van Luijk et al., 2020). Comer et al. (2020) argued that HFO being the leftover from the oil refining process is the reason why it can only be used by ships and becomes the preferred fuel for maritime transport. However, in some cases, HFO is produced by the mixture of residual and distillate fuels, though there is no standard for the blending process of residual fuel and distillate fuel to produce HFO (Fritt-Rasmussen, 2018). This type of HFO which is the product of a combination of residual and distillate fuel is often called intermediate fuel oil (IFO) (van Luijk et al., 2020). Therefore, the quality of HFO for both physical and chemical properties can vary depending on the distillation process and the mixing process of residual and distillate fuels. Table 1 demonstrates the terminology used to describe marine fuel oils.

Table 1

Marine Fuel Oil Terminology

Marine Fuel Oil Name	Composition	Type
Bunker C/Fuel oil No.6	Residual oil	HFO
Intermediate Fuel Oil (IFO) 380	Residual oil (~98%) blended with distillate	HFO
Intermediate Fuel Oil (IFO) 180	Residual oil (~88%) blended with distillate	HFO
Low Sulphur marine fuel oils (LSFO)	Residual oil blended with distillate (higher ratio of distillate to residual)	HFO derivative
Marine diesel oil (MDO)/ Fuel oil No.2	Distillate fuel that may have traces of residual oil	Distillate
Marine gas oil (MGO)	100% distillate	Distillate

Note. Adapted from *Phasing Out the Use and Carriage for Use of Heavy Fuel Oil in the Canadian Arctic: Impacts to Northern Communities* by DeCola, E., Robertson, T., Fisher, M., & Blair, L., 2018. p. 3.

2.3 Regulation of Marine Fuel Use for Arctic Shipping

The International Convention for the Prevention of Pollution from Ships (MARPOL) is a comprehensive international convention developed by the IMO in order to prevent pollution of the marine environment from shipping operations and accidental causes by ships (IMO, 2022). Because the Arctic Ocean is subject to the global regime for the law of the sea, ships operating in Arctic waters must comply with all the relevant international rules and IMO regulations, including the specific regional rules and standards adopted in the Polar Code (Sun, 2020). Amongst 6 technical Annexes of MARPOL, the two applicable Annexes of fuel use are Annex I which is the Regulation for the Prevention of Pollution by Oil and Annex VI which is the prevention of air pollution from Ships.

Currently, there is no regulation of fuel oil use and carriage restriction in the Arctic area according to Annex I. There is only one domestic regulation developed by Norway to prevent the use of HFO by ships in certain areas around Svalbard in the Arctic (Sun, 2019). As Annex VI is to reduce air pollution from ships, the fuel oil quality used by ships becomes important to comply with the regulation, especially for sulphur oxide (SO_x) emission. The Emission control areas (ECAs) areas are specially designated by the IMO to limit the emission level with a more stringent control, and hence the sulphur content limit is 0.1% in the ECA (IMO, 2022). The current ECA areas are the Baltic Sea, the North Sea and North American waters but do not include Arctic waters (Chircop, 2020). The latest development of Annex VI is 0.5% of the global sulphur cap which means that all vessels operating outside designated control areas (ECA) must use fuel oil with a sulphur content of not more than 0.5% since 1st January 2020 (Sun, 2020).

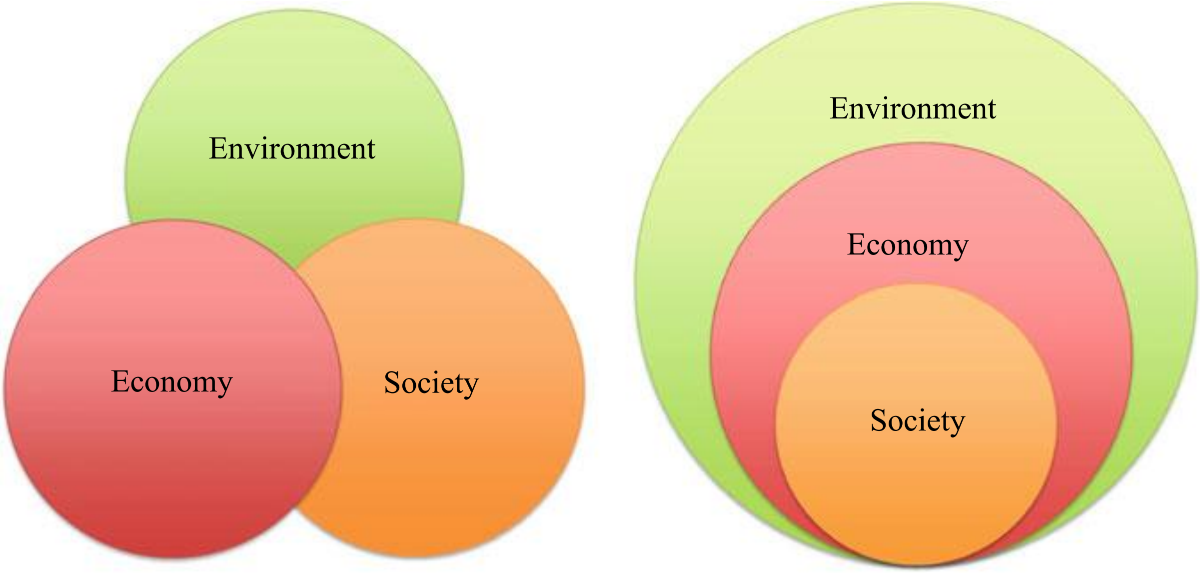
2.4 Sustainable Development Framework of the Shipping Industry

The general sustainability concept was first introduced in 1987 at the UN General Assembly, and sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Pongrácz, 2020, p.3). According to Shaker (2015), the concept of sustainability could be argued to be a human-ecosystem equilibrium state. However, this notion of sustainability is viewed by many people as cannot be achievable because of the inherent unsustainability of unlimited growth in a closed system (Pongrácz, 2020). As stated in Carter & Jennings (2002), the environment, diversity, safety, human rights and philanthropy are the underlying dimensions of the concept of sustainability.

The triple bottom line approach of the term sustainability reported by Cheng et al. (2015) requires the simultaneous balancing of three dimensions, namely economic, environmental, and social dimensions in policy, decisions, and general management of any organizational function. Andersson et al. (2016) illustrated that environmental, social and economic are commonly regarded as the three pillars of sustainable development as shown in Figure 3.

Figure 3

Visualisation of Sustainable Development



Note. The figure demonstrates two different visualisations of sustainable development showing the three pillars of sustainable development as overlapping circles. The first one on the left is one of the most common views of sustainable development, and the second one on the right is another perspective of viewing that it is not sustainable development if it is not ecologically sustainable. Adapted from *Shipping and the Environment* by Andersson et al., 2016. Shipping and the Environment. p. 12.

In September 2015, the UN adopted the 2030 Agenda for sustainable development goals (SDGs) and its 169 targets. Among the 17 goals, the aim of sustainable development goal 14 (SDG14) is toward the conservation and sustainable use of oceans, seas and marine resources for sustainable development. With regard to the sustainable management of marine ecosystems, the UN 2030 Agenda for sustainable development emphasized the need to strengthen resilience across human and natural systems in order to avoid significant adverse impacts and strengthen their resilience (Pongrácz, 2020). As SDG14 is to advance the sustainable use and conservation of the oceans, the maritime transport plays a vital role in addressing the global sustainability imperative and sustainable mandates due to its strategic economic and social importance to the global economy, along with the efficient mode of transport (estimated in tonne-miles) by the shipping industry (Fasoulis & Kurt, 2019; Psaraftis, 2019).

However, despite its attribute to global trade, the shipping industry also raises concern about the negative externalities such as the contribution of GHGs emissions, air pollution (Wan et al., 2016; Wu et al., 2020) and potential environmental impacts on the marine environment such as accidental or operational marine pollution (Chang & Danao, 2017). Benamara et al. (2019) observed that it is necessary to balance varied and potentially competing economic, social and environmental objectives in order to enhance sustainability in transport. Thus, it is imperative to manage the sustainable performance of maritime transport by taking into account the environmental and social aspects as important as the economic dimension. Accordingly, the environmental concerns of Arctic shipping need to be addressed to enhance the idea of sustainability concept by means of an economically efficient, socially equitable and environmentally sound development (Benamara et al., 2019).

2.4.1 Sustainable Arctic Shipping

As it is expected to increase shipping activities in Arctic waters in the future, particularly for regional shipping activities, sustainable conduct has become a concerning issue (Keil, 2018). Not only does Arctic shipping offer advantages for global economic growth thanks to shorter routes than traditional passages but it can also promote trade and link communities and societies. Keil (2018) pointed out that although the actors of Arctic shipping have a general consensus about sustainable Arctic shipping, there are still conflicts when it comes to certain concrete referent objects. One of the examples that Keil (2018) mentioned is the issue of the use of HFO in the Arctic Ocean because the environmental organisations illustrate the current use of HFO in Arctic waters as an unsustainable practice due to the potential severe risks to the marine environment, whereas the local communities and the shipping operators are in favour of using relatively cheap marine fuel oil to emphasise on economic gains and market achievements.

With respect to the sustainable Arctic shipping, the ban on usage and carriage of HFO in the Arctic region is primarily motivated by the detrimental environmental impacts by means of potential marine fuel oil spills and atmospheric pollution which can be harmful to both the environment and human health (Lack, 2016; van Luijk et al., 2020). Moreover, the combustion of HFO can produce GHGs emissions and black carbon (BC) which is a short-lived climate pollutant which is comprised of a significant portion of particulate matter (PM) that acts as a powerful regional climate change accelerator (Sun, 2019). Regarding the inter-related socio-economic and cultural impacts of the use and carriage of HFO by ships and the proposed ban, the cost and profits of using HFO and the transition away from HFO will have the likely impacts in both beneficial and adverse ways on the global transportation costs as well as on local communities and indigenous people.

2.5 Research Purpose and Questions

Thanks to the increased interest by the scientific community and different organisations, there has been a growth of research papers about Arctic shipping over the last years (Theocharis et al., 2018). Meng et al. (2017) reviewed 25 studies of Arctic shipping from navigational and commercial perspectives. Theocharis et al. (2018) conducted a systematic literature review of comparative studies evaluating Arctic shipping and shipping routes from economic and environmental perspectives. Zhang et al. (2019) reviewed studies on black carbon emissions from Arctic shipping and assessed technical and operational solutions and policy implications to mitigate environmental impacts. However, to date, there has not been any comprehensive systematic literature review evaluating the overall impacts of HFO usage and carriage by Arctic shipping under the sustainability framework.

As the proposed ban of HFO for Arctic shipping was agreed upon, it is important to reveal and compile the current knowledge of the impacts of HFO usage and carriage by ships in Arctic waters. Moreover, it would be necessary to identify the factors concerning the roadmap of an HFO-free Arctic for the shipping industry in order to understand the complexity of the Arctic HFO ban for the sustainable development of Arctic shipping and the decision-making process. Therefore, the aim of this study is to explore the implications of the Arctic HFO ban and how the potential ban of HFO in Arctic waters will affect the sustainability of the Arctic region. For this purpose, the main research question is formulated as:

How will the regulatory initiative ban on the use and carriage of HFO in Arctic waters be supportive of the sustainable development of Arctic shipping?

To address the main research question, the three complementary research questions are formulated as:

1. What are the scale and scope of HFO usage and carriage by ships in Arctic waters and the associated environmental and socio-economic impacts of Arctic shipping?

2. How will the current global regulatory measures and the proposed ban of HFO in Arctic waters play a role in the sustainable development of Arctic shipping?

3. What will be the major challenges and necessary knowledge gaps to become the HFO-free Arctic for the sustainability of the Arctic region?

2.5.1 Scope

The Arctic is most typically defined by the Arctic Circle, 66° 33′ 44” North, which is the Northernmost latitude (Pongrácz, 2020). Moreover, another definition of the Arctic is the IMO Arctic which is defined by the Polar Code so that shipping activities in this area are subject to the international Arctic safety and environmental regulations (Comer et al., 2017). The IMO Arctic boundary generally follows the 60-degrees-North line of latitude across the Bering Sea and the Canadian Arctic Archipelago, then turns to the north from the south of Greenland to exclude Iceland and the Norwegian coast on the Scandinavian peninsula (Sun, 2019).

Despite different delimitations of the Arctic boundary, the geographical scope of this study is not limited to one specific Arctic definition and will focus on the shipping activities in the Arctic region that will apply to the sustainability of the Arctic region and sustainable development of Arctic shipping. The thematic scope will include the implications of HFO usage and carriage by ships in Arctic waters and the impacts of the potential HFO ban with the associated principal ecological and socio-economic impacts caused by the use and carriage of HFO by ships in Arctic waters.

3. Methodology

This section will provide the justification and rationale of the chosen methodology for this study and present the methodological design to describe the characteristics of the approach. Moreover, it will describe the protocol of the research including different phases of the methodological framework which are used for this study.

3.1 Methodological Framework

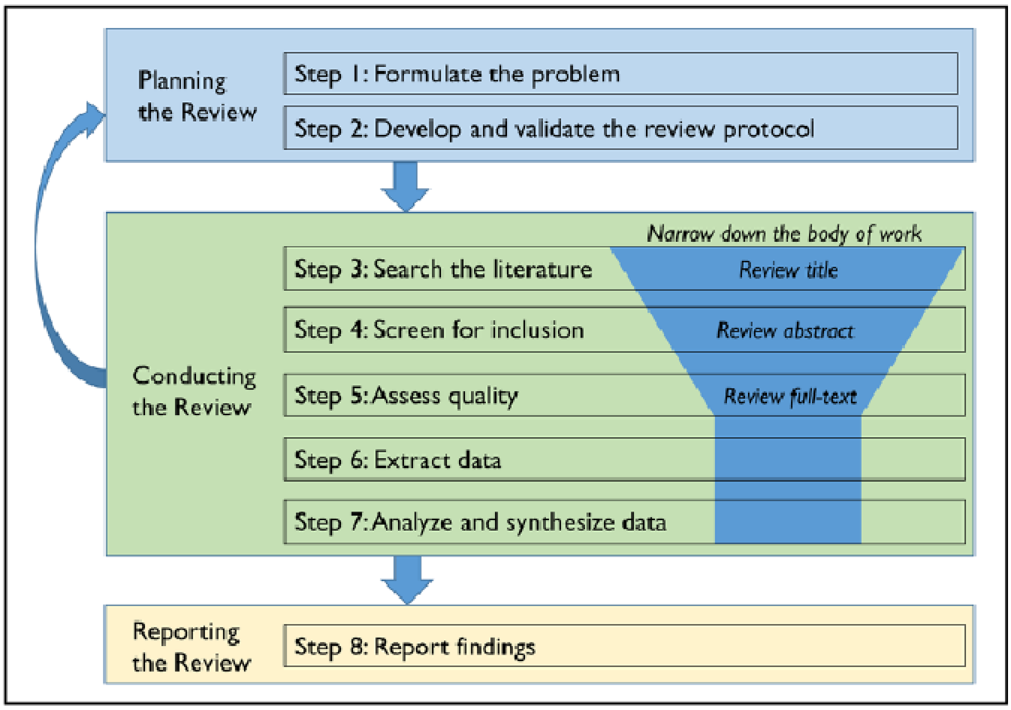
This study aims to review and find out the relevant studies on the issue of HFO ban in Arctic waters to support the sustainability of the Arctic region and sustainable development of Arctic shipping. The key research goal of conducting a review of the literature is to provide the best evidence for informing policy and practice in any respective academic discipline and community (Tranfield et al., 2003). Xiao & Watson (2019) noted that a literature review is essential to academic research as knowledge advancement must be built on prior existing work, and thus, undertaking a literature review will appraise the up-to-date knowledge of the discipline and will lead to identifying the knowledge gaps to explore.

According to Jesson et al. (2011), systematic reviews are reviews with a clearly stated purpose, a research question with a defined search approach which also states inclusion and exclusion selection criteria to produce an appraisal of articles. Systematic reviews differ from traditional reviews as the process of systematic reviews is replicable, scientific and transparent with detailed technology so that it can minimise bias through exhaustive literature searches of published and unpublished studies with an audit trail based on the reviewer's decision, procedures and conclusions (Cook et al., 1997; Tranfield et al., 2003).

As illustrated in Figure 4, the methodological characteristics of the systematic review are reasonably defined by Jesson et al. (2011) with different phases such as mapping the field through a scoping review, comprehensive search, quality assessment, data extraction, synthesis and writing up. Xiao & Watson (2019) identified three main stages for a successful systematic literature review which involve planning, conducting and reporting the review with clearly stated steps for each stage. In this study, a systematic literature review design was adopted to investigate the state-of-the-art and find out the relevant research evidence of implications of the HFO ban in Arctic waters for the shipping activities and sustainable development of the Arctic shipping.

Figure 4

Process of Systematic Literature Review



Note. The figure presents the steps of doing a systematic literature review. Adapted from *Guidance on Conducting a Systematic Literature Review,* by Xiao, Y., & Watson, M. (2019). p. 103.

3.2 Research Approach

During the planning stage of this study, an initial search and the screening of relevant literature were conducted according to the scoping study and background of the problem. This is due to the fact that identifying research questions for a systematic literature review can be an iterative process through pre-reviewing of relevant literature in order to recognise the subtopics and research activities so that a more specific research question will be developed (Xiao & Watson, 2019). Therefore, in this study, the major terms "Arctic shipping" and "HFO" were used in the first place for initial screening to identify the related research activities and subtopics of the area. Then, after narrowing it down to a more specific research topic and scope, the main research question and complementary research questions were developed for this study.

Every step of the planning stage of the systematic literature review is a key foundation for conducting the review. According to Kitchenham & Charters (2007), the research questions are the key drivers of the systematic literature review process because data selection, extraction, synthesis and reporting of the study are designed to answer the research questions (Xiao & Watson, 2019). Furthermore, the review protocol also plays a vital role in rigorous systematic reviews (Brereton et al., 2007; Okoli & Schabram, 2010; Xiao & Watson, 2019) because it will describe all the elements of the review including the purpose of the review, search strategy, quality assessment, selection procedures and methodologies for data extraction, synthesis and report (Gates, 2002; Gomersall et al., 2015; Xiao & Watson, 2019).

After the planning stage, a search strategy was developed for the comprehensive literature search. To conduct the systematic review of the proposed research questions, a comprehensive and unbiased search is of importance to capture all relevant sources of evidence which will provide the most efficient and high-quality method for identifying and evaluating extensive literature (Mulrow et al., 1997; Tranfield et al., 2003). Therefore, a specific thorough search strategy was adopted which involved different key databases and sources of grey literature for this particular study. First of all, the most appropriate keywords and search terms were developed for the systematic search to answer the proposed research questions. Then, the major databases were identified to apply for the developed search terms.

The electronic databases were used for this study since these databases constitute the predominant sources of published literature collections (Petticrew & Roberts, 2008). In this study, Scopus (Elsevier, 2022) and Web of Science (Clarivate, 2022) were identified as key databases to apply keywords and search terms for this study because they were mainly used by Theocharis et al. (2018) to conduct a systematic literature review of comparative studies of Arctic shipping routes from both economic and environmental perspectives. Moreover, the searches were also extended to include Google Scholar (Google, 2022) database because it is a powerful resource to find open access journal articles and grey literature. To obtain a complete list of literature, the search strategy also included backwards searching from the reference lists of retrieved papers.

After completing the exhaustive search of the literature, the screening process was conducted based on the inclusion and exclusion criteria for this study. Xiao & Watson (2019) mentioned the two-stage procedure for screening articles which are the coarse process based on reviewing the abstracts of the articles and the refined process based on reviewing the full text of the articles. After the screening procedure, it was followed by the quality assessment of the articles according to the type of the review (Whittemore & Knafl, 2005). The quality assessment process is to assess the full articles of the selected literature and is important for data extraction and synthesis (Xiao & Watson, 2019). Once the quality assessment procedure was complete, the data extraction from the selected literature was conducted followed by analysing and synthesising of data, and finally, reporting of the findings.

3.3 Search Strategy

As the research scope of this study is Arctic shipping and the use and carriage of HFO in Arctic waters, the search term was developed to focus on the geographical area of the Arctic region and the shipping activities. The key three dimensions of the sustainability framework were also an important aspect to adopt the search strategy to answer the research questions. Therefore, the striking environmental impacts of Arctic shipping related to the use and carriage of HFO were identified according to the extant literature. Furthermore, socio-economic impacts such as cost and profit were identified concerning the use and carriage of HFO by ships in Arctic waters.

As stated in Table 2, the three search blocks were developed based on the research questions of this study. The first block is to focus on the geographical and study scope of the research questions which are the Arctic region and shipping activities. The second block of keywords was particularly developed for HFO so that different marine fuel terms of HFO used by ships were included to cover all the relevant literature that investigated the fuel usage of Arctic shipping as a fuel of HFO and alternative fuel of HFO. The third block was mainly focused on the key dimensions of the sustainable framework which are major concerns of the use and carriage of HFO by ships in Arctic waters. The keywords and search terms of each block were extended to include synonyms, alternative and related terms.

Table 2

Developed Search String

Research Scope	HFO and Marine Fuel Terms	Sustainability Dimension Impacts
arctic ship*	"Heavy Fuel Oil"	emission
arctic maritime	"HFO"	pollution
arctic transport*	"Fuel Oil"	"Black Carbon"
arctic marine	"Marine Fuel"	“GHG”
arctic water	"Marine Fuel Oil"	“Particulate Matter”
"Northern Sea Route"	"Residual Fuel"	"Oil Spill"
"Northeast Passage"	"Bunker Oil"	risk
"Northwest Passage"	"Alternative Fuel"	impact
		environment*
		economic*
		cost
		profit
		"Cost-benefit"
		social*
		indigenous
		communities
		society
		"Social-economic"
		sustain*
		analysis

Note: The search terms within each column were connected with the Boolean operator OR, and the three columns were connected with the Boolean operator AND. The asterisk (*) was used as a wildcard to return multiple variations of the search term. Double quotation (“”) was used to find the combination of words inside the quotation mark. Without a double quotation mark, the phrase words were automatically connected with the Boolean operator AND. There was no case sensitive issue to return the results.

When these keywords were applied in the electronic databases, Boolean operators were used as conjunctions between them. Boolean operators are the words such as “AND”, “OR” and “NOT” which are used as conjunctions for the purpose of combining keywords to generate more relevant results. The search terms of each block were connected with the Boolean operator “OR”, which means that one of the search terms will retrieve in the results. Then the three search blocks were connected with the Boolean operator “AND” so that a combination of these search terms will appear in the results.

3.3.1 Database Search

After developing the search strategy and keywords, the databases of Scopus (Elsevier, 2022) and Web of Science (Clarivate, 2022) were used with an advanced search setting to search published literature. Because the default setting of each database is different, using an advanced search setting can produce refined results. The default setting of Scopus (Elsevier, 2022) is set to title, abstract and keywords, whereas the default setting of Web of Science (Clarivate, 2022) is set to all fields which may lead to unexpected results. For this study, the search strategy of these two databases was limited to the topic search instead of searching the whole text to return the most relevant information. As a result, TITLE-ABSTRACT-KEY was added in Scopus (Elsevier, 2022), while the “TOPIC” (TS in the search string) was added in Web of Science (Clarivate, 2022) when applying the search terms.

Moreover, Google Scholar (Google, 2022) database was also used to explore further published articles and grey literature. However, unlike Scopus (Elsevier, 2022) and Web of Science (Clarivate, 2022), the advanced setting of Google Scholar (Google, 2022) offers the limitation of keyword search for either “in the title of the article” or “anywhere in the article”. In order to return all the relevant articles and literature, the search setting was set to “anywhere in the article”. Hence, some of the developed keywords were not put in Google Scholar (Google, 2022) to avoid a huge number of results returning and unmanageable outcomes for the review. Furthermore, the search keywords and search string were modified and adjusted to fit the requirement and compatibility of the search method in Google Scholar (Google, 2022). The final search strategy for Google Scholar (Google, 2022) was using an advanced setting by putting keywords of (Arctic Ship* AND HFO*) AND (emission OR pollution OR environment* OR economic* OR social* OR sustain* "oil spill" "black carbon").

The database search was conducted on the 15th of March, 2022, and all the databases were accessed through the University of Gothenburg Login. The language setting was English, and there was no time span limitation.

3.3.2 Inclusion and Exclusion Criteria

In order to select the relevant articles to be included in the study, the inclusion and exclusion criteria were decided according to the research questions. The geographical scope and the activities of the study scope were key to determining inclusion criteria. As the study scope was to investigate the use and carriage of HFO by ships in Arctic waters and their consequences, the several effects of HFO usage and carriage by ships in Arctic waters were decided as inclusion criteria. Therefore, the inclusion criteria were the geographical area (Arctic), the study focus on the activities in the region (shipping operations associated with HFO) and the study scope (impacts and sustainability dimensions). The other environmental impacts of Arctic shipping such as the issues of invasive species, chemical spills, garbage and noise pollution were excluded. Similarly, the socio-economic implications of Arctic maritime transportation which were not the outcomes of the use and carriage of HFO such as the employment issues were also excluded. The screening process was not affected by the author, publications of journals or books and the year of publishing.

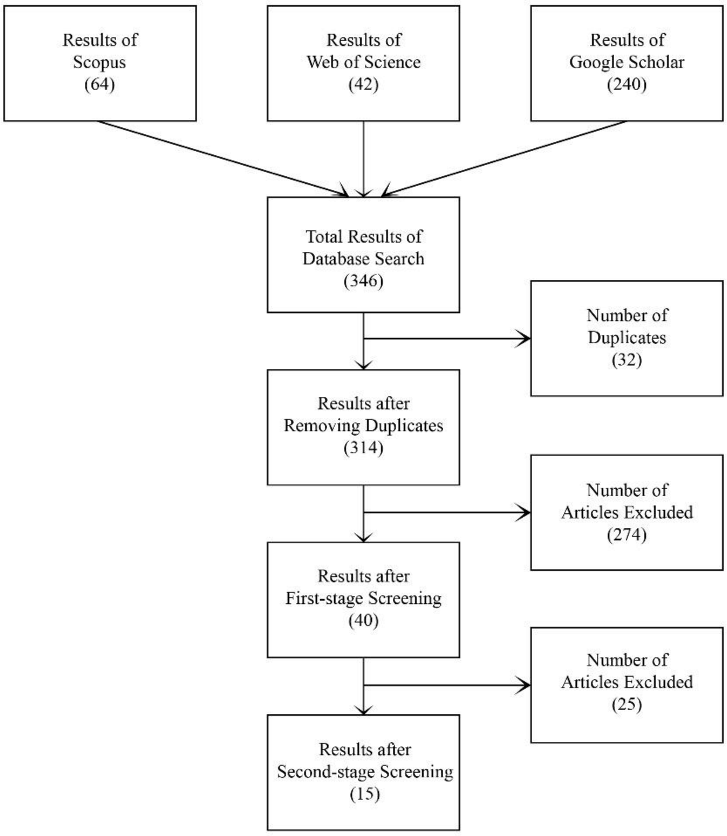
3.4 Database Search Results and Screening Process

During the screening process, the total generated articles from the three different electronic databases were assessed based on the inclusion and exclusion criteria. There were 346 publications in total from the database search, and the first step was to remove the duplicates of these results. The removal of duplicates resulted in 314 publications which were then followed by the two-stage procedure of the screening process mentioned by Xiao & Watson (2019). The first stage of the screening process was to review the abstracts of the articles to include and exclude for the study based on the defined criteria.

After this coarse sieve, the articles which are inapplicable to this review were wed out, and 40 publications were left for the second-stage screening process. During the refined screening process, the full texts of the articles were scanned in order to retrieve articles to answer the research questions of this study. A total of 15 studies were selected from the database search to be included in the literature review as they met all the inclusion criteria. The different phases of the screening and selection process of database search based on the PRISMA model by Moher et al. (2009) was illustrated in Figure 5.

Figure 5

Flow of Screening Process



Note. The figure demonstrates the flow of database search results and the screening process for the systematic literature review based on the PRISMA model by Moher et al. (2009)

3.5 Grey Literature Search

Although Google Scholar (Google, 2022) can generate grey literature papers, Google was specifically used to conduct a further grey literature search. The approach was to explore the websites of existing networks and relevant organisations to find literature including the reports, conference proceedings and publications. The major organisations which are relevant to this study were identified based on the search results and references of the literature. The names of the identified organisations were the IMO, Arctic Council, International Council on Clean Transportation (ICCT), Clean Arctic Alliance and Protection of the Arctic Marine Environment (PAME). As a result, 13 papers including reports, briefings and proceedings were selected for the study as they met inclusion criteria for the study (DNV 2011; DNV, 2013a;

DNV, 2013b; DNV GL, 2019; ICCT, 2018a; ICCT, 2018b; ICCT, 2018c; ICCT, 2018d; ICCT, 2018e; ICCT, 2018f; PAME, 2016; PAME, 2019; Stuer-Lauridsen et al., 2019).

3.6 Backwards Search

The strategy of backwards search is to investigate all the cited references in the selected papers. This search process aimed to fine the related literature which were cited by the retrieved papers in order to achieve a complete list of relevant articles. Therefore, after identifying the retrieved articles from the generated results of the database search, the bibliographies of studies were also examined and screened according to inclusion and exclusion criteria. As a result, 6 publications were found to be included in the study after assessing them with inclusion criteria (Abbasov et al., 2018; Fritt-Rasmussen et al., 2018; Lack, 2016; Nelissen & Tol, 2018; Nelissen, 2019; Winther et al., 2017).

3.7 Limitation

According to Jesson et al. (2011), the process of conducting a systematic literature review is time-consuming as it requires a rigorous and systematic search of all the relevant literature. Therefore, the time spent to work on this study would be one of the limitations because a longer time frame could provide a more extensive literature search by including other relevant databases and using other methods of searching. Another limitation would be the individual attempt of undertaking a systematic literature review. It is mostly recommended to do a systematic literature review by a team in order to spread the effort and avoid possible bias in selecting literature and data extraction. However, Jesson et al. (2011) mentioned that the multi-authored requirement of doing a systematic literature review should not be a deterrence to work on, but it is necessary to recognise the limitation.

4. Results

This section will describe the selected publications for the systematic literature review and presents the results and findings by analysing and synthesising data from the selected literature to answer the research questions.

4.1 The Selected Publications

There are 34 relevant publications selected for the systematic literature review which resulted from the database search, grey literature search and backwards search. The data from these studies covered a wide range of variations depending on the study scope which are related to the use and carriage of HFO and the potential impacts of the HFO ban in Arctic waters. Therefore, the categorisation of literature was conducted according to the presentation and research focus of each literature, and the results of the findings were presented in narrative synthesis. The basic attributes of the reviewed studies comprise the risk implications of HFO usage and carriage by ships and the sustainability implications of the Arctic HFO ban.

The literature is divided into two categories, which are the analysis of the use and carriage of HFO in Arctic waters with the associated environmental risks and the initiative of HFO ban with the potential effects of HFO ban based on the sustainability dimensions as well as energy implications. However, the representation of the papers does not restrict to only one category, and there are a number of papers that are featured in both categories. The categorisation of the selected papers is reported in Table 3.

Table 3

Selected Reviewed Papers

Analysis of the Use and Carriage of HFO by Ships - Category 1		
Reference	Title	Risk Implications
DNV (2011)	Heavy fuel in the Arctic (Phase 1)	Scale and Scope
DNV (2013a)	HFO in the Arctic - Phase 2	Scale and Scope/ Carriage of HFO
DNV (2013b)	HFO in the Arctic - Phase 2B	Scale and Scope/ Carriage of HFO
Comer et al. (2017)	Prevalence of Heavy Fuel Oil and Black Carbon in Arctic Shipping, 2015 to 2025	Scale and Scope/ Use of HFO
ICCT (2018a)	Heavy Fuel Oil use in the IMO Polar Code Arctic Summarized by Flag State, 2015	Scale and Scope
ICCT (2018b)	Heavy Fuel Oil use in the IMO Polar Code Arctic Summarized by Ship Type, 2015	Scale and Scope
ICCT (2018c)	Heavy Fuel Oil use in the IMO Polar Code Arctic Summarized by Ship Owner, 2015	Scale and Scope
ICCT (2018d)	Heavy Fuel Oil use by Cruise Ships in the IMO Polar Code Arctic, 2015	Scale and Scope
ICCT (2018e)	Heavy Fuel Oil use by Fishing Vessels in the IMO Polar Code Arctic, 2015	Scale and Scope
ICCT (2018f)	Heavy Fuel Oil use in the IMO Polar Code Arctic by Russian-flagged Ships, 2015	Scale and Scope
PAME (2019)	Alternative Fuels in the Arctic	Scale and Scope
van Luijk et al. (2020)	Analysis of Heavy Fuel Oil Use by Ships Operating in Canadian Arctic Waters from 2010 to 2018	Scale and Scope
Winther et al. (2017)	Emissions from Shipping in the Arctic from 2012-2016 and Emission Projections for 2020, 2030 and 2050	Use of HFO
Jing et al. (2021)	CO2 Emission Projection for Arctic Shipping: A System Dynamics Approach	Use of HFO
Comer et al. (2020)	The International Maritime Organisation's Proposed Arctic Heavy Fuel Oil Ban: Likely Impacts and Opportunities for Improvement	Use of HFO
Chen et al. (2021a)	Interactions between Arctic Passenger Ship Activities and Emissions	Use of HFO
Chen et al. (2021b)	Implications of Arctic Shipping Emissions for Marine Environment	Use of HFO
Geels et al. (2021)	Projections of Shipping Emissions and the Related Impact on Air Pollution and Human Health in the Nordic Region	Use of HFO
Messner (2020)	Future Arctic Shipping, Black Carbon Emissions, and Climate Change	Use of HFO
PAME (2016)	Heavy Fuel Oil & Other Fuel Releases from Shipping in the Arctic and Near-Arctic - Phase 3 Final Report	Carriage of HFO
Fritt-Rasmussen et al. (2018)	A Review of Fate and Behaviour of HFO Spills in Cold Seawater, including Biodegradation, Environmental Effects and Oil Spill Response	Carriage of HFO

Table 3. (Continued)

Initiative of HFO Ban in Arctic Waters - Category 2		
Reference	Title	Sustainability Implications
DeCola et al. (2018)	Phasing Out the Use and Carriage for Use of Heavy Fuel Oil in the Canadian Arctic: Impacts to Northern Communities	Socio-economic & Environmental
Stuer-Lauridsen et al. (2019)	Impact Assessment on a Ban on Heavy Fuel Oil Use in Greenland	Socio-economic & Environmental
DNV GL (2019)	Impacts of a Ban on Heavy Fuel Oil Use and Carriage as Fuel by Ships in the Norwegian Arctic Waters	Economic & Environmental
Nelissen & Tol (2018)	Residuals Bunker Ban in the IMO Arctic Waters - An Assessment of Costs and Benefits	Socio-economic & Environmental
Nelissen (2019)	Residuals Bunker Ban in the IMO Arctic Waters - Cost Implications for Russian Trade Flows - A Case Study	Economic
Abbasov et al. (2018)	Cost Analysis of Arctic HFO Ban for Cruise Shipping	Economic
Roy & Comer (2017)	Alternatives to Heavy Fuel Oil Use in the Arctic: Economic and Environmental Trade-offs	Economic & Environmental
Comer (2019)	Transitioning away from Heavy Fuel Oil in Arctic Shipping	Economic & Environmental
Lack (2016)	The Impacts of an Arctic Shipping HFO Ban on Emissions of Black Carbon	Environmental
Zhang et al. (2019)	Reducing Black Carbon Emissions from Arctic Shipping: Solutions and Policy Implications	Environmental
Comer et al. (2020) *	The International Maritime Organisation's Proposed Arctic Heavy Fuel Oil Ban: Likely Impacts and Opportunities for Improvement	Environmental
Æsøy & Stenersen (2013)	Low Emission LNG Fuelled Ships for Environmental Friendly Operations in Arctic Areas	Environmental/ Economic
Klimentyev et al. (2017)	Prospects and Opportunities for Using LNG for Bunkering in the Arctic Regions of Russia	Environmental/ Economic
PAME (2019) *	Alternative Fuels in the Arctic	Environmental/ Economic
Savard et al. (2020)	The Electrification of Ships Using the Northern Sea Route: An Approach	Economic

Note. The order of the reviewed papers was arranged according to the narrative synthesis.

* Comer et al. (2020) and PAME (2019) are the two papers that represented both categories.

4.2 Analysis of the Use and Carriage of HFO by Ships (Category 1)

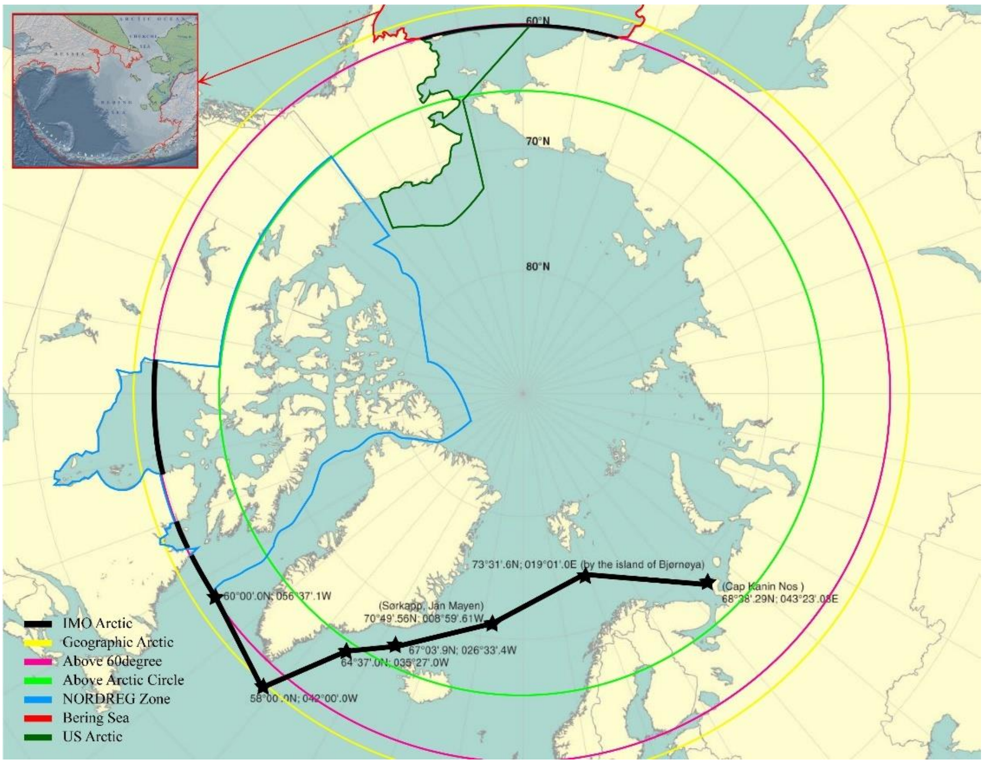
The categorisation of the analysis of the use and carriage of HFO by ships in Arctic waters extended into the scale and scope of HFO usage and carriage by ships and the associated environmental risks of these activities. There are 21 reviewed papers that fall into this category.

4.2.1 Scale and Scope

Among 21 reviewed papers on the analysis of the use and carriage of HFO by ships, 12 studies reported the scale and scope of HFO usage and carriage by ships. Although the study area varied based on the intent and purpose, the majority of them (n=10) mainly focused on the IMO Arctic defined according to the Polar Code.

Figure 6

Illustrations of Study Areas



Note. The figure is developed by the author to just illustrate different study areas of the selected reviewed papers which investigated the scale and scope of the use and carriage of HFO by ships. Adapted from *the Polar Code* by the IMO. p. 3.

However, Comer et al. (2017) further extended Arctic delimitations into the Geographic Arctic (at or above 58.95°N) and the U.S. Arctic (Exclusive Economic Zone (EEZ) of the United States (U.S.) within the IMO Arctic), while PAME (2019) extended into the study areas above 60° and the Polar Circle.The remaining 2 studies by DNV (2013b) and van Luijk et al. (2020) focused on specific areas such as the Bering Sea south of 60 degrees and the Canadian Arctic respectively. The Canadian Arctic area is called the Northern Canada Vessel Traffic Services (NORDREG) Zone that encompasses Canadian Arctic waters including major shipping routes (van Luijk et al., 2020). It is worth noting that the Bering Sea south falls outside of the IMO Arctic, and some parts of the NORDREG Zone are not included in the IMO Arctic.

Regarding the time period of the studies, DNV (2011) was the only study that focused on the four-month period between August 2010 and November 2010, while the other studies were based on either the entire year or a period of particular consecutive years. The justification of the chosen period of DNV (2011) was that most shipping operations usually take place between August and November because the ice coverage is at its minimum during this period. The Automatic Identification System (AIS) database was mainly used for the majority of the studies to identify the shipping traffic in Arctic waters, which were enriched with other ship-specific databases to identify ship characteristics and fuel usage. NORDREG is the only database used by van Luijk et al. (2020) to investigate the use and carriage of HFO in the NORDREG area.

In the IMO Arctic, the vessels operating on HFO in Arctic waters were dominated by larger cargo, tanker and passenger ships, whereas the smaller vessels such as fishing vessels, community support, research and service vessels were more likely to use distillate fuels (DNV, 2011; DNV, 2013a). When it comes to the size of the vessels, the smaller vessels under 1000GT were less likely to use HFO, while the larger vessels above 1000GT were more likely to use HFO. Consequently, DNV (2013a) reported that the onboard bunker mass of HFO vessels accounted for three-quarters of the total mass although the number of vessels that used HFO were just over a quarter of the total vessels in 2012 due to the larger size of HFO-fuelled vessels. This pattern of HFO as a far greater dominating fuel in terms of bunker mass was the same for other studies except for the study by van Luijk et al. (2020) in which the bunker fuel mass was not mentioned.

Table 4 compares the results of the number of HFO vessels out of total vessels in different study areas according to the reviewed papers. In 2015, even though HFO-fuelled ships were less than half of the total numbers, the fuel consumption of HFO was nearly three-fifths of the total consumption in 2015 (Comer et al., 2017). This fuel consumption scale was similar to that of the Geographic Arctic and U.S. Arctic areas which were well over half of the total consumption. (Comer et al., 2017). Similarly, HFO was a dominating fuel of consumption rate in 2017 despite the outnumbering vessels that used distillate fuels (PAME, 2019). The most striking feature of these 12 reviewed studies is that the number of HFO vessels in the Bering Sea accounted for nearly four-fifths of the total number of vessels in 2012.

Table 4

Comparison of HFO-fuelled Vessels out of Unique Total Vessels

Reference	Study Area	Study Period	Total Vessels	HFO Vessels
DNV (2011)	IMO Arctic	August 2010 - November 2010	954	189
DNV (2013a)	IMO Arctic	2012	1347	371
DNV (2013b)	Bering Sea	August 2012 - August 2013	2934	2457
Comer et al. (2017)	IMO Arctic/ Geographic Arctic/ U.S. Arctic	2015	NA	NA
ICCT (2018a, b, c, d, e, f)	IMO Arctic	2015	2089	889
PAME (2019) *	IMO Arctic/ Above Arctic Circle/ Above 60°	2017	1870	614
van Luijk et al. (2020)	Canadian Arctic (NORDREG)	2010-2018	601	220

Note. * PAME (2019) studied the three Arctic areas, however, the study area that the number of HFO vessels was mentioned only in the IMO Arctic.

Furthermore, the number of vessels in the Geographic Arctic was 6 times higher than in the IMO Arctic, and the fuel consumption of HFO in the Geographic Arctic was 10 times higher than in the IMO Arctic in 2015 (Comer et al., 2017). Similarly, the difference in the magnitude of fuel consumption between the three Arctic definitions was reported by PAME

(2019) even though the fuel consumption of HFO was not highlighted between these defined areas.

Although each study analysed the scale and scope of the use and carriage of HFO by ships with different approaches such as based on ship classes and size of vessels, the six papers of ICCT (ICCT, 2018a; ICCT, 2018b; ICCT, 2018c; ICCT, 2018d; ICCT, 2018e; ICCT, 2018f) conducted a detailed analysis of HFO usage and carriage for the year of 2015 based on flag ship, ship type, ship owner and specific classifications of ship types such as cruise ships, fishing vessels and Russian-flagged ships. Similarly, van Luijk et al. (2020) also evaluated three different ship categories of bulk carriers, general cargo and tanker ships as they made up the vast majority of HFO use and carriage in the NORDREG zone.

Among 12 studies that reported the scale and scope of the use and carriage of HFO in the Arctic region, 1 study (Comer et al., 2017) and 2 studies (DNV, 2013a; DNV, 2013b) further investigated the environmental risks of the use of HFO and the carriage of HFO by ships respectively.

4.2.2 Risks of HFO Usage by Ships in Arctic Waters

Air emission is one of the environmental risks posed by the use of HFO by ships in Arctic waters. The lists of emission components from Arctic shipping are the short-lived climate pollutants and their precursors sulphur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compound (VOC), non-methane volatile organic compound (NMVOC), particulate matter (PM), black carbon (BC) and organic carbon (OC) and GHGs such as CO_2, CH_4 and N_2O). (Winther et al., 2017). According to the reviewed studies, the emission results were calculated by multiplying the fuel consumption of ships by the emission factor of each pollutant. 7 studies were selected for this review to analyse air emissions by Arctic shipping due to the defined emission factors for different fuel types, especially for HFO.

There are a number of factors that influence the emission factors of pollutants such as the types of engines (slow, medium, high-speed), the types of machinery (main engine, auxiliary engine, boiler), the design of the engine, engine production year, the sulphur content of the fuel, fuel type and fuel quality. As stated in Winther et al. (2017), the emission factors of NO_X, CO, VOC, NMVOC and CH_4 mainly rely on the engine types (slow, medium, high-speed), the design of the engine and production year, whereas SO_2, PM and OC emission factors rely on the sulphur content of the fuel. Moreover, it was noted that the emission factors of CO_2 and BC are, in particular, to be dependent on the fuel types.

According to the emission factors used in these 7 studies, it is worth noting that the use of HFO with a high sulphur content can have a significant impact on the emission levels of Arctic shipping. The BC emission factors used in Winther et al. (2017) were dependent on fuel sulphur content indicating that HFO with 2.5% of sulphur content is 0.155 g/kg of fuel, IFO with 0.5% of sulphur content is 0.065 g/kg for fuel and MDO with 0.5% of sulphur content is 0.056 g/kg fuel. These significant variations of emission factors based on Sulphur content of different fuel types can be seen in other 5 studies (Chen et al., 2021a; Chen et al., 2021b; Comer et al., 2017; Comer et al., 2020; Geels et al. 2021). On the other hand, CO_2 emission factors used in Winther et al. (2017) were 3190 g/kg fuel for HFO and 3160 g/kg fuel for MDO/ MGO, whereas CO_2 emission factors used in Jing et al. (2021) were 3144 g/kg fuel for HFO and 3206 g/kg fuel for MDO.

4.2.3 Emission Inventory

The results of the emission inventories from these 7 studies were presented differently according to the study area and research focus. Winther et al. (2017) mainly focused on SO_2, NO_x and BC emissions based on the ship activity data from 2012-2016 and estimated the emission projections for 2020, 2030 and 2050 in the Arctic area above 58.95°N. Comer et al. (2017) conducted a BC emission inventory in 2015 for the IMO Arctic, Geographic Arctic and U.S. Arctic. According to this study, the result of BC emissions caused by HFO consumption of ships was well over three-fifths of total BC emissions in the respective Arctic areas. Comer et al. (2020) compared HFO-fuelled ships, HFO carriage, HFO usage and BC emission of HFO for 2015, 2017 and 2019. This study demonstrated that even though the number of HFO-fuelled ships and HFO carriage in 2019 was higher than in 2015 and lower than in 2017, the HFO usage and BC emissions were the highest in 2019 in the IMO Arctic. In 2019, 700 HFO-fuelled ships carried 555 kilotons of HFO and used 437 kilotons of HFO, which resulted in 225 tonnes of BC emissions in the IMO Arctic (Comer et al., 2020).

There is one study that particularly focused on passenger ship activities and their emission inventories in the Arctic. Chen et al. (2021a) quantified passenger ship pollutants in the IMO Arctic with a primary focus on BC and SO_X emissions based on the passenger ship characteristics data assuming all the passenger ships would use HFO between 2012 and 2017. It was found by this study that the average emissions of SO_X and BC from the passenger ships in the IMO Arctic were 3824.01 tons and 39.17 tonnes respectively, and the emission levels for both pollutants reached a maximum in 2014 during the defined period. Another study by Chen et al. (2021b) calculated vessel emissions based on AIS data and used SO_X emissions as a sample to investigate the vessel emissions in the Arctic region between 2012 and 2016. Moreover, this study forecasted SO_X emissions for 2020 with two scenarios of using HFO with sulphur content of 2.7% and MDO with sulphur Content of 0.5% as fuel and compared the results. Due to the considerable difference in emission factors for HFO and MDO, this study demonstrated that the vessels using MDO as fuel scenario in 2020 would achieve an 82.41% reduction of SO_X emissions compared to the scenario of using HFO as fuel.

Another study by Jing et al. (2021) systematically investigated the projection of CO_2 emission along the NSR by setting up a System Dynamics (SD) approach. Because this study aimed to evaluate the potential future CO_2 emissions from Arctic shipping by developing an SD model, the prediction of emission results was based on different scenarios and fuel structures of Arctic shipping. By considering various factors of CO_2 emissions for Arctic shipping, the study recommended a switch to cleaner fuels and an operational solution of slow steaming to be applied by vessels in order to achieve an effective reduction of CO_2 emissions (Jing et al., 2021). Among these 7 studies, there is only one study that further discussed the related impacts on air pollution and human health after projecting shipping emissions based on emission factors of different fuel types. Geels et al. (2021) simulated emission levels of CO_2, NO_X, SO_2 and BC from Arctic shipping in the Nordic and Arctic areas for 2015 and future scenarios of HFO ban and assessed the overall impacts of air pollution on human health.

4.2.4 Impacts of Air Emissions

The focus of Geels et al. (2021) was on the mortality and the number of mature deaths due to the exposure to air pollution, as the pollutants released from Arctic shipping such as NO_X, SO_2 and BC were linked to those impacts. This study used a health assessment model based on the emission results and estimated that shipping emissions might be responsible for roughly (560-1100) premature deaths during the present-day conditions. The figures would be reduced to 440-670 in 2050 based on the HFO ban scenario (Geels et al., (2021).

Other than 7 reviewed studies that conducted emission inventories of Arctic shipping, there is one reviewed paper that discussed the impacts of BC emission. According to Messner (2020), not only does BC emission have an impact on local public health but it also contributes to ice melt in the Arctic. This is because BC is known as a short-lived climate pollutant that can trap heat in the atmosphere and remain in the atmosphere for a shorter period of time. BC emission is caused by the incomplete combustion of fossil fuel, and the combustion of HFO can emit more BC than burning other fuels due to larger emission factors of BC for HFO (Messner, 2020).

4.2.5 Risks of Carriage of HFO by Ships as Bunker Fuel

HFO spill is another significant risk for Arctic shipping, and 2 studies explored the implications of HFO spill as a result of the carriage of HFO by ships. PAME (2016) reported the shipping incidents of HFO and other fuel releases in the Arctic and near-Arctic marine environment which is the area above the 55th parallel north. However, the study scope of PAME (2016) was not restricted to bunker fuel release. As a result, the paper listed shipping incidents involving a release of oil from vessels and identified liability due to these releases between 1970 and 2014. According to the list, there were 44 incidents of HFO spill out of a total of 65 incidents in the designated area from 1970 to 2014. In the event of HFO release from ships, the weathering process is of importance such as evaporation, dissolution, dispersion and water uptake/emulsification (PAME, 2016).

Another study by Fritt-Rasmussen (2018) reviewed studies on the HFO weathering process based on the important physical and chemical parameters of HFO such as viscosity, density, pour point, volatile compounds and content of asphaltenes, resins or wax. However, the primary focus of Fritt-Rasmussen (2018) was not specifically on the Arctic, instead, the study investigated the fate and behaviour of HFO in cold weather and cold temperatures. Moreover, the two studies that fall into the category of analysing the scale and scope of HFO by ships in Arctic waters also conducted a risk assessment of oil spills based on the risk frequencies of oil spills (DNV, 2013a, DNV, 2013b). The properties of HFO and the interaction of HFO with the Arctic marine environment play a vital role to understand the impacts of HFO spill (Fritt-Rasmussen, 2018).

4.2.6 Impacts of HFO Spill

According to PAME (2016), the impacts of HFO spill on the vulnerable Arctic environment and marine biota can be serious and challenging due to remote locations, adverse conditions, safety concerns and possible impacts on the use of marine mammals for subsistence by indigenous people. Based on the experiences of oil spills on the Norwegian coast, Fritt-Rasmussen (2018) presented the environmental impacts of HFO and concluded that although HFO spill may have a small impact on the pelagic organisms due to the low content of water-soluble components and dilution at sea, it can pose significant risks of smothering seabirds and polluting coastline due to the likelihood of remaining on the sea surface.

4.3 Initiative of HFO Ban in Arctic Waters (Category 2)

The categorisation of the initiative to ban HFO in Arctic waters included possible environmental impacts, socio-economic impacts and energy implications of HFO ban. There are 15 papers that fall into this category. The assessment of 15 papers based on the sustainability dimensions is reported in Table 5.

Table 5

Assessment of Reviewed Papers as of Potential Arctic HFO Ban

Reference	Study Scope	Potential Fuel Transition	Society/ Socio-economic	Environmental	Economic
DeCola et al. (2018)	Canadian Arctic	IFO 380 to MGO	Commodity Price on Canadian Arctic communities	Oil Spills	Fuel Costs/ Sealift Prices/ Spill Costs
Stuer-Lauridsen et al. (2019)	Greenland	HFO to MDO/MGO	Socio-economic Impact Assessment	Air Emissions/ Oil Spills	Fuel Costs/ Spill Costs
DNV GL (2019)	Norwegian Arctic	Transition to VLSFO/ULSFO/ MDO	NA	Oil Spills	Fuel Costs/ Spill Costs/ Impacts on Cruise and Mining Industries
Nelissen & Tol (2018)	IMO Arctic	LSFO & HFO with Scrubbers to Distillate	Additional Cost on Greenland and Consumer Price North Canada	Oil Spills	Fuel Costs/ Fuel Expenditures/ Spill Costs
Nelissen (2019)	Case Study of a Russia Terminal	LSFO & HFO with Scrubbers to Distillate	NA	NA	Fuel Costs/ Transportation Costs/ Ban-related Crude Oil Costs
Abbasov et al. (2018)	Case Study of a Cruise Ship	HFO with Scrubber to MGO	NA	NA	Fuel Costs/ Ticket Price
Roy & Comer (2017)	IMO Arctic	HFO & LSFO to Distillate/ LNG	NA	Oil Spills	Fuel Costs/ Fuel Expenditures/ Spill Costs
Comer (2019)	Five Case Studies of Arctic Shipping	Transition to Electricity/ LNG/ Distillate/ Hydrogen	NA	Oil Spills	Fuel Costs/ Spill Costs
Comer et al. (2020)	Regulation of Proposed HFO Ban	NA	NA	BC Emission	NA
Lack (2016)	Future Scenario of HFO Ban	Low to High Quality Fuel (HFO to LSFO/Distillate)	NA	Air Emissions	NA

Table 5. (Continued)

Reference	Study Scope	Potential Fuel Transition	Society/ Socio-economic	Environmental	Economic
Zhang et al. (2019)	Review Study of BC Emissions	Transition to Alternative Fuels (Biodiesel, LNG)/ HFO to Distillate	NA	BC Emission	NA
Æsøy & Stenersen (2013)	Alternative Fuel	Transition to LNG	NA	Air Emissions	Investment Costs
Klimentyev et al. (2017)	Alternative Fuel	Transition to LNG	NA	Air Emissions/ Oil Spills	Investment Costs/ Operating Costs
PAME (2019)	Assessment of Alternative Fuels	Transition to Marine Fuels, Hybrid Fuels, LNG, LPG, Biofuels, Methanol, Hydrogen, Ammonia, Electricity, Electro fuels, Nuclear, Wind, Solar and Wave	NA	Air Emissions/ Oil Spills	Fuel Costs/ Investment Costs/
Savard et al. (2020)	Alternative Fuel	Transition to Electricity	NA	NA	Operating Costs

Note. The order of the reviewed papers was arranged according to the narrative synthesis.

4.3.1 Socio-economic Impacts of the Arctic HFO Ban

Among 15 reviewed papers that explored the potential implications of the HFO ban in Arctic waters, 11 studies focused on the potential impacts of the HFO ban. Although the study scope and research approaches of these 11 studies differed from each other, the majority of them (n=8) mainly focused on the monetary values and additional costs of fuel shifts due to the higher fuel prices of HFO ban-compliant alternatives compared to HFO. There are two studies that focused on the IMO Arctic (Nelissen & Tol, 2018; Roy & Comer, 2017), whereas three studies explored the specific areas in the Arctic (DeCola et al., 2018; DNV GL 2019; Stuer-Lauridsen et al., 2019). Another three papers applied case studies instead of specific areas in the Arctic, but the case studies were different such as oil transportation from a Russian terminal, a cruise ship operation in the Arctic and different vessels sailing through the Arctic routes (Abbasov et al., 2018; Comer, 2019; Nelissen, 2019;).

Regarding the fuel transition, most of the studies assumed distillate fuel as a potential alternative to HFO as only the two studies discussed other alternatives to HFO. Due to the different purposes of the studies, different approaches were used by the studies to assess the impacts of the Arctic HFO ban. In particular, when the studies analysed the specific Arctic areas, DeCola et al. (2018) assessed the community resupply vessel and commercial shipping vessel traffic in the Canadian Arctic, while Stuer-Lauridsen et al. (2019) used the total shipping traffic pattern by analysing the vessels that operated on HFO in Greenland's EEZ and territorial sea. Another study by DNV GL (2019) analysed the vessels in the Norwegian Arctic in 2018.

When the reviewed studies compared the fuel price difference between HFO and alternative fuels, the results were based on different sources depending on the study areas and defined periods accordingly. Although there were fluctuations in fuel price differences, the results of the studies confirmed that HFO fuel price was higher than that of distillate fuels. According to the two studies that discussed alternative fuels other than distillate fuels, the price of LNG was expected to be less than HFO. As a result of the higher fuel price of alternative fuels, the studies further discussed the potential extra cost of the shipping industry including increased transportation costs, cargo costs and fuel expenditures of vessels. DeCola et al. (2018) developed a cost model to evaluate how the increase in fuel cost might influence the sealift prices transported by resupply vessels operating along with the Canadian Arctic community supply, and the model analysis estimated that the incremental cost of using MGO was about one cent per kilogram of cargo transported based on 2017 actual fuel costs.

Alternatively, Stuer-Lauridsen et al. (2019) carried out a comprehensive socio-economic impact assessment of the Arctic HFO ban including the effects on the whole society, citizens of Greenland, the business community, the environment, the climate and the government of Greenland. The analysis showed that the net benefit would be DKK 26.1 million (around 3 million USD) in 2020 because the costs of the total climate and environmental benefit, which was DKK 62.4 million (around 9 million USD), outweighed the total socio-economic costs on the business community, the citizens and the Government of Greenland, which was DKK 36.3 million (around 5 million USD). With regard to the Norwegian Arctic, even though there was no additional cost for Norwegian fleets because of no identified HFO-fuelled Norwegian vessels, there were potential economic impacts on the tourism industry at Svalbard resulting in a 7-12% increase in the weighted average in operating costs for the cruise operators and estimated additional costs of 0-100,000 USD on the mining and coal export sector depending on fuel switch alternatives (DNV GL, 2019).

For the IMO Arctic area, the two studies analysed the ban-related additional costs of transition from HFO to distillate fuels by Arctic vessels. If Arctic ships would choose to comply with the ban by using distillate fuels in 2021, the fuel expenditures of Arctic fleets for the year 2021 would increase by 3%, 9% and 18% for the low, base and high case fuel price scenarios respectively, and the additional cost increase of individual ship, for the base price scenario, would be 2% and 4 to 15% depending on the use of fuel types and methods by ships before an HFO ban (Nelissen & Tol, 2018). According to Roy & Comer (2017), the fleetwide total fuel expenditures of fuel transition from HFO to distillate in 2015 would increase by 30%, while the individual fuel cost in 2015 would increase by 55%. However, the study estimated that the fuel transition cost in 2020 and 2025 would be much less than in 2015 due to the increased number of vessels using Low Sulphur Fuel Oil (LSFO) which is more costly than HFO as an effect of the implementation of the global sulphur cap in 2020. As a result, the fleetwide transition cost from HFO to distillate in 2020 and 2025 would increase by less than 2% (Roy & Comer, 2017).

The three case analyses of the reviewed studies covered different aspects of the impacts of the Arctic HFO ban. For the case study of crude oil transportation, Nelissen (2019) calculated the fuel consumption of three shuttle tankers that transported crude oil from the

Varandey export terminal to Murmansk with three baseline scenarios using different fuel choice methods such as Liquified Natural Gas (LNG) electric, LSFO and HFO in combination with a scrubber to comply with the 2020 sulphur requirement. According to this study, while there was no additional ban-related cost for the first baseline scenario as LNG electric would comply with an HFO ban, the additional ban-related transportation costs for the other two scenarios were estimated to range from 0.3 to 2.4 million USD for the second scenario and 4.6 to 10 million USD for the third scenario in 2021 depending on the bunker fuel price. As a result, there would be a 0.1% to 0.2% of the potential increase in crude oil price depending on the scenarios.

Another analysis of the case study is by Comer (2019) that presented five case studies of the vessels carrying various cargos sailing through different Arctic shipping routes. Because this study compared the fuel prices of different alternative fuels for five vessels, there was no estimation of ban-related fuel costs for Arctic shipping. Instead, Comer (2019) presented a comparison of voyage-level fuel costs relative to HFO, and the results showed that the use of LNG would achieve a 31% of cost reduction, but distillate fuels could be 26% more expensive than HFO and hydrogen would be the most expensive alternative. There is only one case study that focused on a single industry. Abbasov et al. (2018) undertook a case study of a cruise vessel namely MS Rotterdam operating in the Arctic for three summer trips in 2018, and as a result, the potential cost impact of the fuel transition would be an average increase of 6% in 2018 and 3% in 2021. With respect to the ticket price per passenger, the impact would be a €7/day increase in 2018 and a €5/day increase, hence, this study concluded that there would be limited impact on the cruise industry because of the Arctic HFO ban.

With regard to the societal and socio-economic impacts, although there are three studies with particular focuses on the Arctic specific areas, only the two of them assessed the effects on the local communities and indigenous people of designated areas. The study of the Canadian Arctic analysed the relationship between fuel prices and the specified consumer goods in Arctic communities. Interestingly, the results showed that there was no clear correlation between marine fuel prices and the cost of food items in Nunavut based on the historical data (DeCola et al., 2018). Meanwhile, a study by Stuer-Lauridsen et al. (2019) carried out a socio-economic impact assessment of the Arctic HFO ban on the society of Greenland and estimated the cost for citizens of Greenland would be DKK 4.9 million (around 0.7 million USD) in 2020 due to the higher prices of the Arctic HFO ban. Besides, there is one more study that analysed the potential impacts on the additional costs of goods and consumer prices for Greenland and North Canada. According to Nelissen & Tol (2018), there would be a relatively low impact in both areas, estimating the average export and import price would increase by 0.2 to 0.5% in Greenland and the average household expenditure in Iqaluit of North Canada would cost maximally around 30 USD per year.

4.3.2 Impacts of Arctic HFO Ban on Oil Spills

Other than the cost analysis for the communities, 6 studies additionally assessed the impacts of oil spills due to an HFO ban in the Arctic (Comer, 2019; DeCola et al., 2018; DNV GL, 2019; Nelissen & Tol, 2018; Roy & Comer, 2017; Stuer-Lauridsen et al., 2019). DeCola et al. (2018) conducted an assessment of oil spills for different fuel types and estimated the cost impact of an Arctic HFO spill on the communities and Canadian taxpayers. Stuer-Lauridsen et al. (2019) also carried out an oil spill impact assessment based on the four scenarios of oil spills in different areas of Greenland and calculated the monetary consequences of oil spills such as impacts on fishing, tourism, subsistence and clean-up shore. The other two studies by DNV GL (2019) and Nelissen & Tol (2018) presented the same compilation of clean-up costs of the previous studies for different fuel oil types. However, it is worth noting that the potential ecological impact of the oil spills is difficult to quantify because the damage is highly dependent on the actual oil spill circumstances such as the amount of oil spilt and the geographic location of the spill (DNV GL, 2019).

Therefore, these four studies mainly compared the clean-up costs of spills between HFO and distillate fuels. The comparison showed that there would be a significant reduction in potential clean-up costs if the spill was distillate fuels instead of HFO. Meanwhile, another study by Roy & Comer (2017) also explored the environmental and economic trade-offs of switching from HFO and LSFO (less than 05% of sulphur) to LNG and distillate for the years 2015, 2020 and 2025 based on fuel consumption, fuel costs and fuel spill clean-up costs in the IMO Arctic. The study estimated the clean-up costs of the residual fuel would be roughly 7 times higher than that of distillate fuel and concluded that even though a switch from HFO to distillate would increase fuel costs by 32% to 55% depending on the year, the potential cost savings of using residual fuel are outweighed by the benefits of reduction in clean-up costs.

The Etkin model presented in DeCola et al. (2018) demonstrated that the overall estimated costs including clean-up, environmental and socio-economic costs for HFO spill would be between $106,000 and $512,000 per tonne spilt, while the distillate spill would be between $32,000 to $193,000. In addition, Comer (2019) estimated the spill cost by using a conservative model based on worldwide data and not for the Arctic oil spills, evaluating the total cost of HFO spill including clean-up, socio-economic and environmental costs as $150,000 per tonne for the tonnes spilt of 380 to 3850 and $107,00 for the tonnes spilt of more than 3850. It was also noted that these figures were much higher than distillate fuel spills and LNG spills (Comer, 2019).

4.3.3 Impacts of Arctic HFO Ban on Air Emissions

There is only one study that conducted a comprehensive analysis of the effectiveness of the proposed Arctic HFO ban on BC emission. Comer et al. (2020) used AIS data to assess the vessel traffic, ship characteristics and HFO vessels with flagged states operating in Arctic waters in 2019 to identify ships that would be eligible for exemptions and waivers as described in the proposed HFO ban. Then the study compared the results of HFO usage and consumption by ships between 6 alternative approaches and the existing proposal for the Arctic HFO ban. According to the study, the proposed HFO ban would likely phase out only 30% of HFO carriage and 16% of HFO usage if the regulation had been in place in 2019 because of exemptions and waivers, and as a result, BC emission would only be reduced by 5% in 2019. Even if there were no exemption and waiver, the reduction in BC emission would be just 30% (Comer et al., 2020).

The primary focus of the other two papers by Lack (2016) and Zhang et al. (2019) was to assess the potential impacts of the HFO ban on BC emission in general without discussing the exemptions and waivers of the proposed Arctic HFO ban. Lack (2016) discussed the complexity of BC formation because BC emission from HFO can vary depending on many factors such as crude oil quality, the sulphur content of the fuel, ash content, hydrocarbon complexity and heavy metal content. Although there have been many studies of BC emission depending on different fuel types, the evidence suggested that the shift from using high sulphur HFO to very low sulphur distillate fuels (less than 0.1% of sulphur content) may make a 50% reduction in BC emission. Lack (2016) also mentioned that the HFO ban will bring about the reductions of other pollutants such as CO_2, SO_X, PM and OC.

Zhang et al. (2019) conducted a review paper to revisit BC emissions from Arctic shipping and the mitigation efforts to curb BC emissions. As the study made a list of potential solutions, the use of alternative fuels was regarded as a technical solution, and the shift from HFO to distillate fuel as an operational solution to mitigate BC emissions. Because the reduction range of BC emission depends on the chosen alternative fuel and the energy content of distillate fuel, the study reflected that a switch from HFO to distillate fuels should be prioritised for adoption by shipowners based on the potential costs and average robust BC reduction performance. The aspects of technical and financial considerations were also mentioned by Lack (2016) because the fuel switch from HFO to distillate can raise some technical issues and will lead to higher fuel costs.

4.3.4 Energy Implications of the Arctic HFO Ban

The implications of the Arctic HFO ban are more than the socio-economic cost-benefit analysis of fuel transitions because the clean energy applications by the shipping industry also play an important role to become the HFO-free Arctic. According to the 11 studies that analysed the cost impacts of the HFO ban, it can be recognised that 2 studies analysed the potential impacts of fuel switch from HFO to alternative fuels other than distillate. There are 4 studies out of 15 reviewed papers under the category of an initiative of the Arctic HFO ban, that primarily focused on alternative fuels. Among 4 reviewed studies, 2 studies presented LNG as an alternative fuel for Arctic shipping (Klimentyev et al., 2017; Æsøy & Stenersen, 2013), while one study discussed the electrically powered option for ships (Savard et al., 2020). However, there is only one study that assessed different potential alternative fuels based on environmental, economic and scalability (PAME, 2019).

Although the investment costs were mentioned in the two studies for LNG, Klimentyev et al. (2017) pointed out that there was limited data to estimate the price of retrofitting a vessel on LNG. Meanwhile, according to PAME (2019), LNG with a battery-electric hybrid solution ranked the highest for both short-sea and deep-sea shipping in a 5–10-year future perspective. This is due to the fact that the price of LNG is lower than HFO, and it can offer significant environmental benefits such as emission reductions of NO_X, SO_X, PM and BC as well as the relatively low impact of oil spill risk (Klimentyev et al., 2017; PAME 2019; Æsøy & Stenersen, 2013). The only environmental externality of using LNG is that there is a possibility of methane leakage which can be more detrimental to climate than traditional fuel (PAME, 2019). On the other hand, Savard et al. (2020) discusses the feasibility of using electricity for Arctic vessels to sail in the NSR. According to this study, the production cost of electrical energy could be 5 times higher than HFO, and there are still technical obstacles to the production and storage of electricity in the current situation.

5. Discussion

This section will discuss the implications of the use and carriage of HFO by ship and the HFO ban in Arctic waters based on the findings of the systematic literature review. As the study demonstrated the risks of HFO and implications of the potential HFO ban for Arctic shipping, this section will apply the sustainable framework approach to explore the use and carriage of HFO by Arctic shipping and the consequences of the proposed Arctic HFO ban.

5.1 Study Area

When the selected reviewed papers analysed the use and carriage of HFO in Arctic waters, it is reasonable that the majority of the studies emphasised the IMO Arctic as their primary study area because the Arctic HFO ban would only be effective for that area. However, there are 2 reviewed papers that particularly emphasised other specific Arctic regions. There is one paper that focused on the Canadian Arctic where some part of the area is outside the IMO Arctic, while the other one focused on the Bering Sea which is outside the IMO Arctic. Moreover, there are 2 more papers that added the extended Arctic areas other than the IMO Arctic in their studies to investigate the use and carriage of HFO by ships.

According to the studies, it can be seen that there was a disparity in the proportion of HFO-fuelled vessels in the Bering Sea compared to that of IMO Arctic (DNV, 2013b). Moreover, the number of HFO-fuelled vessels and fuel consumption of HFO were significantly higher in the Geographic Arctic (PAME, 2019). As a result, the associated risks and impacts of shipping operations in the near Arctic could be higher than those in the IMO Arctic and would still be an issue for the Arctic region even after the Arctic HFO ban came into force. Due to the similar environmental conditions and the connectivity within and beyond the limits of Arctic waters, the geographical definition of the IMO Arctic defined in the polar code might be one of the existing regulatory gaps because it would be difficult to regulate shipping activities that transit near and through the IMO Arctic limits (Sun, 2019).

5.2 Environmental Sustainability

The environmental risks associated with the use and carriage of HFO by ships in Arctic waters can be categorised into air emissions and oil spills based on the retrieved papers.

Accordingly, the air emissions from Arctic shipping are dependent on the operating hours and HFO fuel consumption of ships, whereas the oil spill risk is subject to the travelling distance of ships with onboard bunker fuel carriage of HFO in Arctic waters. Therefore, the environmental threats to the Arctic Ocean would be greater if the consumption rate of HFO and the carriage of HFO by ships in Arctic waters were high. Although the numbers of HFO-fuelled ships were less than half of the total unique ships in the IMO Arctic, the risks are likely to be on a high level because HFO-fuelled ships were mostly larger vessels that consumed a greater amount of HFO compared to other fuel types.

The risk of air emissions can lead to atmospheric pollution which will have an impact on the Arctic marine environment. There are several pollutants emitted from Arctic shipping as a result of burning HFO and distillate fuels, and the calculation process could be a lot of work with various factors of shipping operations need to be considered. However, the distinct feature of HFO from other fuel types for air emissions is the emission factor of each pollutant. Although there have been many previous studies that conducted the emission inventories of Arctic shipping, some of these studies used coarse emission factors depending on ship classes regardless of fuel types (Corbett et al., 2010; Mjelde et al., 2014; Peters et al., 2011; Winther et al., 2014;). Therefore, this study identified only 7 papers that regarded the emission factors of pollutants for HFO in order to examine Arctic shipping emissions.

Despite variations in defining the emission factors for HFO in the reviewed studies, it can be noted that the emission factors of SO_X, PM and BC for HFO can result in more emissions of these pollutants compared to distillate fuels because their emission factors of them are larger than other fuel types and are functions of fuel sulphur content. Interestingly, there will be no considerable change in CO_2 emission between using HFO and distillate fuels as the CO_2 intensity of both fuel types is nearly the same. Therefore, Arctic shipping can lower the emissions of sulphur content dependent pollutants to a large extent by phasing out using high HFO which is a high sulphur fuel, but CO_2 emissions can still be an issue if the vessels use distillate even after the Arctic HFO ban came into force. In this context, it can be assumed that the global sulphur content limit regulation could be a complementary advantage of reducing SO_X, PM and BC emissions from Arctic shipping (Sun 2019).

Among the several pollutants, BC emission in the Arctic region is regarded as a climate accelerator due to its contribution to ice melt. According to the reviewed studies, BC emission can significantly be reduced by means of switching fuel from HFO to distillate fuels or other cleaner fuels. However, the existing proposal to ban HFO in the Arctic region may provide a relatively small portion of BC emission reduction because of exemptions and waivers (Comer et al. 2020). Moreover, BC emission could still be an issue in the Arctic region if the ships are using distillate fuels instead of HFO.

Regarding the environmental risk of oil spills, despite many previous studies that explored the risks of oil spills in the Arctic region, the majority of these studies did focus on the overall impacts of oil spills instead of HFO spill specifically (Helle et al., 2020; Johannsdottir & Cook, 2019; Marty et al., 2016; Pavlov et al., 2021). This could be due to the reason that the effects of oil spills including HFO and distillate can pose detrimental threats to the marine environment and the ecological integrity of marine ecosystems. The ecological impacts of an oil spill are highly dependent on many factors such as the circumstances of the oil spill areas and the amount of spill released. However, there is a general consensus in the reviewed studies that the consequences of HFO spill may be more harmful to the Arctic marine environment than other oil spills.

To sum up, the environmental risks of the use and carriage of HFO by ships could be reduced by switching using HFO to distillate fuels. However, there is still more to improve in order to achieve the environmental sustainability of the Arctic region. It is undeniable that distillate fuels could be the most preferred option for vessels operating in Arctic waters should the Arctic HFO ban comes into force. However, although distillate fuels can reduce the environmental risks of HFO to a certain extent, Arctic shipping still needs to tackle air emissions and oil spill risks caused by distillate fuels. The fuel alternatives were discussed by some studies, and LNG is regarded as the most promising alternative for the near future in terms of environmental sustainability. Nevertheless, it should also be noted that LNG could have an impact on climate change due to the methane slip.

5.3 Economic Sustainability

HFO is a major fuel source for global shipping due to its lower price compared to other fuel types. Arctic shipping is also no exception to this tendency as HFO was identified as a dominating fuel in terms of use and carriage even though there were fewer numbers of HFO vessels compared to other unique vessels in the IMO Arctic area. This is because the larger vessels were more likely to use and carry HFO as bunker fuel than smaller vessels in the Arctic region. Therefore, the monetary cost of transition from HFO to alternative fuels becomes one of the economic implications for Arctic shipping. This study identified 12 reviewed papers that analysed the use and carriage of HFO by ships in Arctic waters. The like analyses of Arctic shipping based on the scale and scope of HFO usage and carriage depending on different ship categorisations, flag states and ship owners are particularly necessary to provide information not only for an understanding of economic implications but also for policy implementation.

When the reviewed studies analysed the economic impacts of the Arctic HFO ban, the fuel prices between HFO and distillate fuels were compared during a defined period and estimated for future scenarios. Because the fuel prices can be dependent on several conditions, it would be difficult to note a stable fuel price difference between HFO and alternative fuels. However, the results of the reviewed studies demonstrated that most of the alternative fuels are more costly than HFO except LNG. Although the fuel price difference can economically cost the shipping industry, this might be compensated if the clean-up cost in case of potential fuel oil spills is considered. Accordingly, the costs of oil spills for residual fuel and distillate fuels were discussed in the reviewed studies. Even though there was no specific model to estimate the clean-up cost of oil spills in the Arctic region, the retrieved studies agreed upon the fact that the potential clean-up costs of HFO may be expected to be much higher than that of distillate fuels.

Furthermore, some of the reviewed studies presented the cost of oil spills in the Arctic region by adding the monetary values of socio-economic and environmental costs to the clean-up costs. As a result, the combined cost of HFO spills becomes significantly higher than distillate fuels and other alternative fuels. It is inarguably true that the Arctic HFO would be a considerable impact on the economy of the shipping industry because of the fuel price difference. However, there can be some impacts on the economy of other industries because one study is identified by this review which analysed the potential impacts on the cruise industry and mining industry in the Norwegian Arctic area. The potential impacts might be a decrease in cruise traffic and reduced annual income of the cruise industry and an annual cost increase for the mining industry (DNV GL, 2019).

Overall, it would be necessary to look at the complete picture of the possible effects of HFO usage and carriage by ships to understand the economic impacts of the Arctic HFO ban. Although the fuel costs may be an obvious extra cost for the shipping industry, the net benefit would bring up considerable advantages when the monetary values of socio-economic and environmental benefits are included. Fuel transition from HFO to distillate will reduce significant costs of oil spills for the shipping company. When it comes to other alternative fuels, LNG could be the most preferred option in terms of economic benefit because of its lower price than HFO, however, the retrofitting costs of LNG vessels are still uncertain due to the lack of enough data.

5.4 Social Sustainability

The societal impacts of the use and carriage of HFO by ships in Arctic waters are mainly on the local communities and indigenous people of the Arctic region. As humans are inextricably linked to the environment, the impacts on the Arctic communities are closely related to the environmental risks posed by the use and carriage of HFO by ships. Furthermore, the interrelation of the communities with the economy will result in the associated socio-economic consequences due to the Arctic HFO ban. Therefore, the matter of social sustainability will be a result of the environmental and economic impacts.

The reviewed studies covered the emission inventories of different pollutants from Arctic shipping, but there is only one study that focused on the empirical data on the health impacts of the emitted pollutants from shipping (Geels et al., 2021). Because this study covered the entire Nordic region including the Arctic area, it would be difficult to discuss the local health impacts on the Arctic communities as a result of the emissions from Arctic shipping and the Arctic HFO ban. However, it can be noted that the exposure to pollutants produced by shipping operations will lead to adverse health impacts on society.

Another environmental risk of oil spills can also bring about societal impacts, cultural and subsistence issues for the Arctic communities and indigenous people because of potential damages caused by oil spills. As the reviewed studies presented that HFO spill can be more challenging and pose serious damages to the Arctic marine environment and biota, there is no doubt that HFO spill would pose detrimental impacts to the Arctic communities. However, the scale of seriousness of the HFO spill will depend on the abundance of marine species and the resource use by the local Arctic communities. Among the studies, the cost models were presented by the two papers to estimate the socio-economic costs of HFO spill, and the results showed that HFO spill cost would be much higher than other fuel types.

Apart from the environmental risks linked to the societal impacts, there would be possible another socio-economic consequence of the HFO ban in Arctic waters due to the increased fuel cost and shipping cost. Interestingly, one of the reviewed studies showed that there is no correlation between the fuel price and commodity price of the Canadian Arctic area (DeCola et al., 2018). However, the result is only for one specific Arctic area, and it would be premature to assume similar results for the overall Arctic areas. Overall, although there will be potential additional costs for the Arctic communities as a result of the Arctic HFO ban, the net socio-economic benefit would be significant.

6. Conclusion

The aim of this systematic literature review is to investigate the implications of HFO usage and carriage by ships in Arctic waters and to identify the impacts of the proposed Arctic HFO ban under the sustainable development framework. Through the retrieved literature, the amount of fuel consumption and carriage of HFO by ships in Arctic waters is relatively larger than other fuel types. Therefore, the associated environmental risks are significantly high in the Arctic region because air emissions as a result of HFO usage and potential oil spills as a result of HFO carriage by ships are more serious than other fuel types. As a result, these will lead to socio-economic impacts on the Arctic communities by posing health issues and possible damage to the marine environment and resources of subsistence. Nevertheless, although the environmental risks could be reduced due to the Arctic HFO ban, it would still be an issue for the Arctic region if the vessels still use distillate fuels.

In terms of the regulatory measures, the global sulphur cap regulation is likely to lower the air emission levels to a certain extent because most of the pollutant emissions are related to the fuel sulphur content. However, the effectiveness of the existing proposed HFO ban is questionable because of waivers and exemptions. If the Arctic HFO ban would make all the Arctic vessels switch from HFO to alternative fuels, the overall impacts of Arctic shipping would be beneficial based on the sustainable development dimensions. It is undeniable that the fuel price increase would economically cost the shipping industry, but the environmental and socio-economic benefits are significantly positive. However, a switch from HFO to distillate fuels is the most possible option for Arctic shipping as there are challenges to using other alternative fuels in terms of technical knowledge and operating costs. Moreover, an important factor of the potential HFO ban is the limitation of the IMO Arctic area. Even after the Arctic HFO ban came into force, the vessels operating outside the IMO Arctic area could still use and carry HFO. As a result, HFO would still be a threat to the sustainability of the Arctic region.

6.1 Further Considerations

In order to achieve the sustainable development of Arctic shipping, it is important to manage the sustainable performance of maritime transport with respect to the environmental, societal and economic aspects. The initiative of the Arctic HFO ban would be one step closer to achieving the sustainable development of Arctic shipping because it could significantly reduce the environmental and socio-economic risks of using and carrying HFO by ships. Therefore, it is worthwhile to further investigate how the Artic shipping companies intend to tackle the HFO ban. On the other hand, as the existing proposed Arctic HFO ban includes exemptions and waivers, it would also be necessary to conduct the emission inventories of Arctic shipping and related health impacts on the Arctic communities to better understand the effects of the Arctic HFO ban. Furthermore, future research should focus on the development of the potential use of environmental-friendly alternative fuels other than distillate fuels as the switch from HFO to distillate fuels would not completely eliminate the associated environmental and socio-economic issues.

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Appendix

Report To the Marine Environment Protection Committee PPR 7/22/Add.1, 24 April 2020. Annexes 1 to 22 to the report of the Sub-Committee on Pollution Prevention and Response on its seventh session (PPR 7/22).

DRAFT AMENDMENTS TO MARPOL ANNEX I

(Prohibition on the use and carriage for use as fuel of heavy fuel oil by ships in Arctic waters)

Regulation 43A

Special requirements for the use and carriage of oils as fuel in Arctic waters

1 With the exception of ships engaged in securing the safety of ships or in search and rescue operations, and ships dedicated to oil spill preparedness and response, the use and carriage of oils identified in paragraph 1.2 of regulation 43 as fuel by ships shall be prohibited in Arctic waters, as defined in regulation 46.2 of this Annex, on and after 1 July 2024.

2 Notwithstanding the provisions of paragraph 1 of this regulation, for ships to which regulation 12A of this Annex or regulation 1.2.1 of chapter 1 of Part II-A of the Polar Code apply, the use and carriage of oils identified in paragraph 1.2 of regulation43 as fuel by ships shall be prohibited in Arctic waters, on and after 1 July 2029.

3 When prior operations have included the use and carriage of oils listed in paragraph 1.2 of regulation 43 as fuel, the cleaning or flushing of tanks or pipelines is not required.

4 Notwithstanding the provisions of paragraphs 1 and 2 of this regulation, the Administration of a Party to the present Convention, the coastline of which borders on Arctic waters, may temporarily waive the requirements of paragraph 1 of this regulation for ships flying the flag of the Party while operating in waters subject to the sovereignty or jurisdiction of that Party, taking into account the guidelines to be developed by the Organization. No waivers issued under this paragraph shall apply on and after 1 July 2029.

5 The Administration of a Party to the present Convention which allows application of paragraph 4 of this regulation shall communicate to the Organization for circulation to the Parties particulars thereof, for their information and appropriate action, if any.”