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Transitioning away from heavy fuel oil in Arctic shipping

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1. Introduction

In this paper, we present five case studies of Arctic shipping routes serviced by ships that can use heavy fuel oil (HFO). The five cases include (1) a tanker carrying liquified natural gas (LNG) from Norway to South Korea, (2) a cargo ship carrying wind turbine equipment from Shanghai to the Netherlands, (3) a small container ship servicing western Greenland, (4) a bulk carrier transporting nickel ore from Canada to the Netherlands, and (5) a 20-night northern Europe and Arctic cruise originating from Amsterdam. For each case, we compare the costs of using HFO, 0.5% sulfur (S)-compliant fuel, distillate fuel, LNG, electricity, and hydrogen (H_2). We also compare the relative cleanup, socioeconomic, and environmental costs of spilling these fuels. Lastly, we explore the operational consequences of using electricity or H_2 by estimating the number of times each ship would need to be refueled or recharged in order to complete the voyage or voyages in each case.

We find that while in some cases operating on HFO or 0.5% S-compliant fuels results in fuel cost savings, the cleanup, socioeconomic, and environmental costs of spilling even a small amount of fuel outweigh these savings. In the short-term, all ships in this study could cease using HFO and immediately use distillate fuels, and some ships could use LNG. In the longer term, zero-emission vessels (ZEVs) using renewable fuels can provide an alternative to HFO and 0.5% S-compliant fuels. Hydrogen appears to be the most promising solution for zero-carbon long-range Arctic shipping. In most of the cases we analyzed, a ship would need to refuel once or twice along the voyage to operate on liquid H_2. The Arctic may be the natural showcase for ZEVs that use renewable energy because they obviate the spill risk, eliminate black carbon emissions, and avoid GHG emissions.

2. Background

Dwindling Arctic sea ice is opening new Arctic shipping routes, some of which are navigable year-round. Recent years have seen increased interest in both intra-Arctic and trans-Arctic shipping. For example, Russia's Northern Sea Route offers an enticing shortcut for shipping goods between Europe and Asia compared to the Suez Canal route, but the time and cost savings come with detrimental environmental impacts (Yumashev, van Hussen, Gille, & Whiteman, 2017).

Heavy fuel oil is the most commonly used fuel in Arctic shipping, representing 57% of fuel used and 76% of fuel carried on board ships in 2015 (Comer et al., 2017). When spilled, HFO persists in the marine environment. Most of it does not evaporate, unlike lighter petroleum-based fuels, and it can emulsify in the water. This creates a mixture that is much larger than the original volume spilled, and one that is nearly impossible to completely clean up. In his speech to the 7th Symposium on the Impacts of an Ice-Diminishing Arctic on Naval and Maritime Operations in 2017, United States Coast Guard Admiral Paul Zukunft, who coordinated the response to the Deepwater Horizon oil spill, stated that the Coast Guard could not recover all of the oil if a spill happened in the Arctic. In fact, only 15 percent of the crude oil from the Deepwater Horizon spill was removed

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despite favorable weather and sea conditions (Zukunft, 2017). Crude oil is less dense than HFO and should therefore be easier to recover.

Heavy fuel oil is a "residual fuel" and has an average S content of approximately 2.6% by mass. Beginning in 2020, all ships will need to either use fuels with a maximum S content of 0.5% or use cheaper, high-sulfur HFO but employ an exhaust gas cleaning system called a "scrubber." While scrubbers are a popular compliance option, given the time and financial costs of retrofitting and bans on washwater discharges from open-loop scrubbers in some ports, most ships will use 0.5% S-compliant fuels. We expect many different types of 0.5% S-compliant fuels to be available starting in 2020, including desulfurized residual fuels and blends comprised of lighter distillates and heavier residual fuels. Unfortunately, we do not yet know if a spill of 0.5% S-compliant fuel will act more like a distillate fuel and evaporate and break down over time, or more like a residual fuel and sink, emulsify, and persist. Research to answer this question has been proposed by other research organizations.

Ships are currently free to use any fuel in the Arctic provided it meets the minimum global fuel quality standards or by using a scrubber. The International Maritime Organization (IMO) is working to develop a ban on using or carrying HFO for use as a fuel in Arctic waters. It is possible that the ban will apply to both HFO and fuels that may behave like HFO when burned or spilled, which could include 0.5% S-compliant fuels. IMO Member States are aiming to agree to ban HFO by 2021, with enforcement in 2023, although the timing is dependent on the outcome of upcoming IMO meetings. Previously, the IMO agreed to an initial greenhouse gas (GHG) strategy that aims to cut total carbon dioxide (CO_2) emissions from ships by at least 50% from 2008 levels by 2050 and to phase out GHG emissions from international shipping as soon as possible in this century (Resolution MEPC.304 (72), 2018). Therefore, ships will eventually need to be zero-emission if the IMO is to achieve its ambitions.

All ships are capable of using distillate fuels; ships commonly switch from HFO to distillates as they enter and leave Emission Control Areas (ECAs) near the coasts of North America, the Caribbean, and western Europe. Some ships have dual-fuel engines that can use HFO, 0.5% S-compliant fuels, distillates, or LNG. Unfortunately, all of these fuels emit CO_2 and black carbon and, in the case of LNG, methane. These pollutants warm the climate and will eventually need to be eliminated under the IMO's GHG strategy.

Ships could also use energy that results in zero direct emissions and, if produced using low-carbon renewable electricity, could result in near-zero lifecycle emissions. These fuels include electricity from batteries and H_2. The main challenge for batteries is their energy density: powering a ship requires a considerable amount of energy that can be difficult to pack inside the hull of a ship. The highest energy density batteries on the market today are about 250 watt-hours per kilogram (Hall, Pavlenko, & Lutsey, 2018), about one-fiftieth the energy density of HFO. For H_2, the main barriers to widespread use include its high price and limited availability for maritime operations. In addition, while H_2 provides about three times more energy per kilogram than HFO, it is so light, even when liquefied, that one needs about eight times as much space for the same amount of energy. Liquid hydrogen carriers, such as ammonia, are being discussed as potential sources of H_2 because of their higher energy density and ease of handling. However, due to the high toxicity of ammonia, we focus on liquid H_2 but recognize that other H_2 carriers could be used in the future. Despite the barriers there are several ZEVs in operation today, mainly smaller ships such as ferries but also a small number of cargo ships, fishing vessels, and cruise ships (Hall, Pavlenko, & Lutsey, 2018). There is also increasing interest in developing zero-emission fuels and propulsion technologies for longer distances.

3. Methodology

In this paper, we consider five Arctic shipping routes with ships that can use HFO or an alternate fuel. For each case, we compare the costs of using HFO, 0.5% S-compliant fuel, distillate fuel, LNG, electricity in the form of batteries, or liquid H_2 with fuel cells in the year 2023. Additionally, we compare the relative cleanup, socioeconomic, and environmental costs of spilling these fuels. Lastly, we estimate how many times each ship would need to be refueled or recharged in order to complete the voyage when operating on each fuel.

Beginning in 2023, unless a ban on using HFO in Arctic waters is implemented, ships will need to use a scrubber to operate on high-sulfur HFO. The scrubber costs are not considered in this analysis, nor are the costs associated with retrofitting a ship to operate on a different fuel. While we recognize that retrofitting a ship with a new engine, fuel system, or both, can result in significant costs, there are few estimates of what it costs to retrofit a ship to operate on LNG, batteries, or fuel cells. It is especially difficult to estimate retrofit costs for ships because of the heterogeneity of the shipping sector: ships come in many different shapes and sizes,

Table 1. Arctic shipping cases and associated ship and cargo characteristics.

Case	Ship Name	Origin	Destination	Flag	Ship Class	Fuel options without retrofit	Cargo	Cargo Capacity	Fuel capacity (m^3)	Engine power (kW)	Engine volume (m^3)[b]	Significance
1	Christophe de Margerie	Snøhvit LNG platform, Hammerfest, Norway	Boryeong, S. Korea	Cyprus	Liquefied Gas Tanker	HFO, 0.5% S, distillate, LNG	LNG	170,000 cubic meters (m3) gas	6,734	64,350	1,155	First LNG carrier to transport Yamal project LNG to Asia; transited the Northern Sea Route in 2017.
2	Yong Sheng	Dalian, China	Rotterdam, Netherlands	Hong Kong	General Cargo	HFO, 0.5% S, distillate	Wind turbine tower and blades	19,460 deadweight tonnes (dwt)	1,186	7,860	110	First Chinese cargo ship to sail the NSR; transited NSR in 2013, 2015, and 2016.
3	Irena Arctica	Aalborg, Denmark	Greenland	Denmark (DIS)[a]	Container	HFO, 0.5% S, distillate	Containerized cargo	424 twenty-foot equivalent units (TEU)	804	5,880	74	Busiest Arctic container ship.
4	Nunavik	Raglan Mine, Nunavik, Quebec, Canada	Rotterdam, Netherlands	Marshall Islands	Bulk Carrier	HFO, 0.5% S, distillate	Ore from Raglan Mine	31,750 dwt	2,020	21,770	367	Most powerful icebreaking bulk carrier.
5	MS Prinsendam	Amsterdam, Netherlands	Shetland Islands, Iceland, Greenland	Netherlands	Cruise	HFO, 0.5% S, distillate	Passengers	843 passengers	2,061	21,120	355	Popular Arctic cruise ship.

Notes: [a] DIS = Danish international ship registry, which is separate from Denmark's national ship registry; [b] Estimated by the following equation based on Minnehan and Pratt (2017): Engine volume [m^3] = (engine power [kW] – 1906)/54.066 [kW/m^3].

each with their own particular challenges. Retrofitting may also not be worth the investment on an older ship. Additionally, these five routes could be serviced by a replacement vessel that operates on cleaner fuels, requiring no retrofit costs. Therefore, we focus this analysis on the fuel costs, spill costs, and refueling needs.

3.1. CASES

Many different kinds of ships sail the Arctic. Here, we consider five real-word cases, summarized in Table 1 and mapped in Figure 1.

Case 1 considers the 2017 eastbound voyage of the Cyprus-flagged *Christophe de Margerie*, the first of 15 ice-class tankers that will transport LNG from Russia's Yamal Peninsula to Asian markets. In 2017, it made its maiden NSR transit from Norway to South Korea. The *Christophe de Margerie* has dual-fuel main engines that can operate on HFO, 0.5% S-compliant fuel, distillate, or LNG. It is not known which fuel the *Christophe de Margerie* used on this particular voyage and, because the ship was carrying LNG, it may have used LNG as its fuel source. However, because this ship is capable of using HFO in its dual fuel engines, we examine the tradeoffs of using HFO compared to alternative fuels.

Case 2 considers the 2015 voyage of the Hong Kong-flagged *Yong Sheng* general cargo ship on a westbound journey from China to the Netherlands via the NSR carrying wind turbine materials. In 2013, this ship became the first Chinese cargo ship to sail the NSR. The *Yong Sheng* is capable of using HFO, 0.5% S-compliant fuel, or distillate.

Case 3 considers the 2017 voyages of the Denmark DIS[1]-flagged ship the *Irena Arctica* container ship as it sailed from Denmark and then up and down the western Greenland coast transporting containerized cargo. The *Irena Arctica* is the busiest container ship operating in the Arctic, sailing more than 50,000 nautical miles (nm) in 2017, equivalent to about two-and-a-half trips around the world along the equator. The *Irena Arctica* is capable of using HFO, 0.5% S-compliant fuel, or distillate.

Case 4 considers the 2017 voyage of the Marshall Islands-flagged *Nunavik* as it sailed from Glencore's Raglan Mine in Nunavik, Quebec, to Rotterdam

1 DIS is the Danish International Register of Shipping, which includes both Danish and foreign merchant ships, excluding fishing vessels, above 20 gross tonnes. More information can be found here: https://www.dma.dk/SynRegistrering/SkibsregistreringAfgifter/DIS/Sider/default.aspx

carrying a load of nickel ore. With a 22-megawatt engine, *Nunavik is* the world's most powerful icebreaking bulk carrier.

Case 5 considers the 2017 voyage of the Netherlands-flagged *MS Prinsendam* cruise ship as it completed a 20-night round-trip cruise from Amsterdam with stops in the Shetland Islands, Iceland, and Greenland.

3.2. FUEL CONSUMPTION, ENERGY USE, AND FUEL COSTS

This analysis uses Automatic Identification System (AIS) data from exactEarth to track and identify each ship's speed and position. The AIS data includes a ship identification number that can be linked to the IHS Fairplay database to determine ship characteristics. including main engine power, main fuel type, and maximum speed. This information is used to estimate each ship's HFO consumption along each journey using the method described by Olmer et al. (2017).

We then estimate the mass of non-HFO fuels needed to supply the equivalent amount of energy based on each fuel's energy density (Table 2) and the efficiency of converting the fuel to propulsion (Table 3). The equation for determining the amount of fuel use needed for each case is as follows:

$$FC_{i,j} = FC_{i,HFO} \times \frac{ED_{HFO}}{ED_j} \times \frac{\eta_{ICE}}{\eta_{p,j}}$$

$FC_{i,j}$ = fuel consumption of ship *i* when operating on fuel *j*, in kg

$FC_{i,HFO}$ = fuel consumption of ship *i* when operating on HFO, in kg

ED_{HFO} = energy density of HFO in kWh/kg (Table 2)

ED_j = energy density of fuel *j* in kWh/kg (Table 2)

η_{ICE} = the thermal efficiency of an internal combustion marine engine, which we assume is 50%

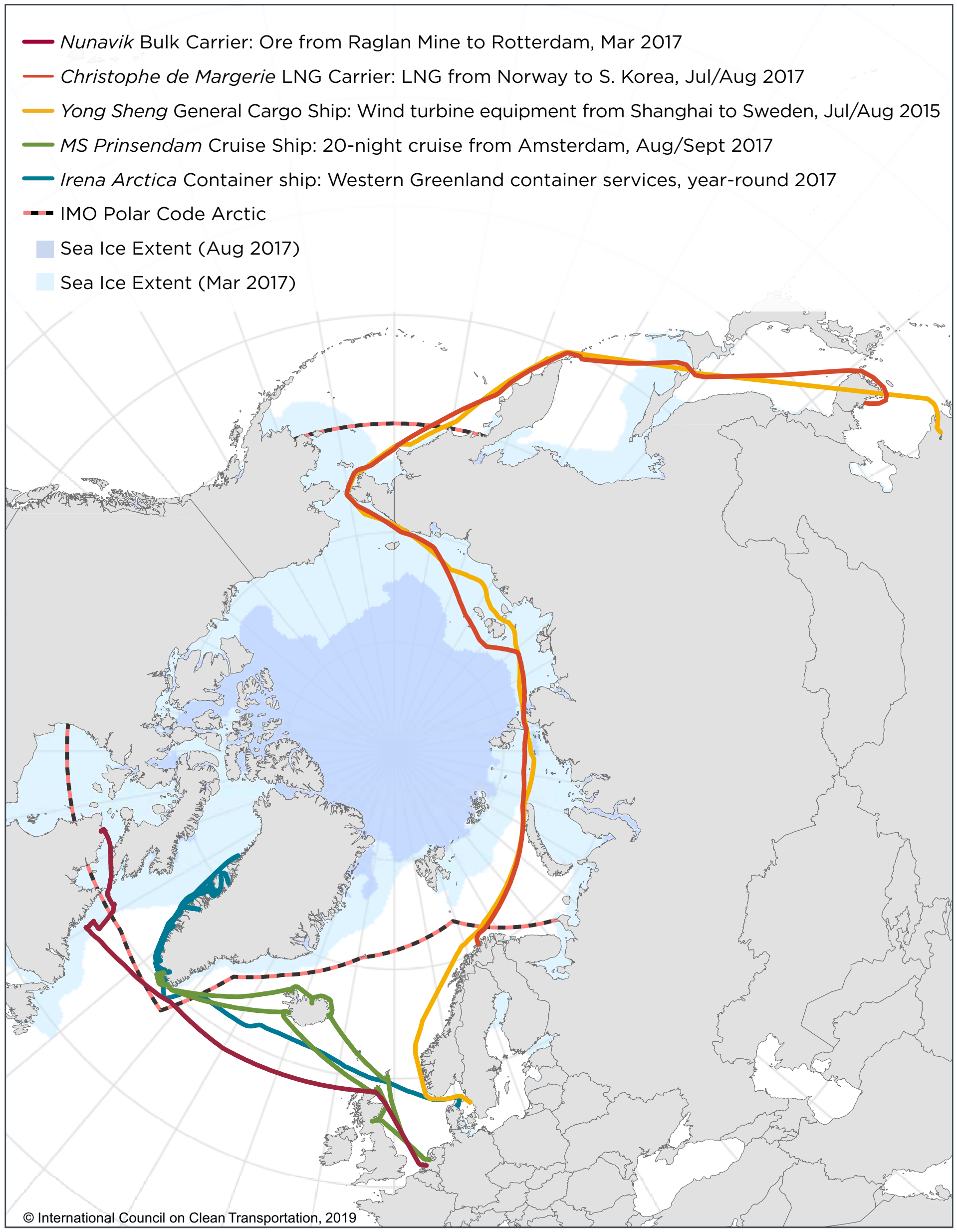

Figure 1. Five Arctic shipping case study routes.

$\eta_{p,j}$ = the efficiency of the propulsion equipment associated with using fuel *j* (Table 3)

In the results, we present energy needed to complete the voyage(s) under each case when using different fuels. To do this, we multiply the fuel consumption calculated using the equation above by the energy density of the fuel (Table 2).

The 2023 fuel costs for each case are calculated using fuel price estimates found in Table 2. Heavy fuel oil, distillate, 0.5% S-compliant fuels, and LNG prices are consistent with Roy and Comer (2017) and Faber et al. (2016). Electricity and H_2 prices are and consistent with Hall, Pavlenko, and Lutsey (2018).

Table 2. Fuel characteristics and fuel price assumptions.

Fuel	Density (kg/m³)	Energy Density (kWh/kg)	2023 Price ($/t)	2023 Price ($/kWh)
HFO	991[a]	11.1[e]	538[g]	0.048
Distillate	890[a]	11.7[e]	712[g]	0.061
0.5% S-compliant	910[a]	11.6[e]	688[g]	0.060
LNG	456[b]	13.9[e]	462[g]	0.033
Electricity (lower)	839[c] (battery)	0.11[c] (battery)	N/A	0.035[f]
Electricity (higher)	839[c] (battery)	0.11[c] (battery)	N/A	0.088[f]
Hydrogen from fossil fuels	40[d]	33.3[f]	4,547[f]	0.137
Hydrogen from renewables	40[d]	33.3[f]	7,828[f]	0.235

Notes: [a] ISO 8217 2017 except 0.5% S-compliant which the author estimated as the weighted average of HFO (20%) and distillate (80%) densities; [b] U.S. Department of Energy (U.S. DOE, 2004). We assume this is the fuel system density for LNG, including insulated fuel tanks, although it may be higher or lower than this in practice. The American Bureau of Shipping (2012) estimates that 1.6 times the storage volume of HFO is needed to provide the same amount of energy with LNG; our assumption equates to 1.74 times the storage space for the equivalent amount of energy; [c] Based on SMAR-11N battery system outlined in Table 2.4 of Minnehan and Pratt (2017); [d] Minnehan and Pratt (2017): While liquid H_2 has a density of 71 kg/m³ at boiling point, we must consider the H_2 fuel system as a whole, which has a density of approximately 40 kg/m³. [e] Author's assumptions based on typical marine fuel energy densities; energy density of 0.5% S-compliant fuel is the weighted average of HFO (20%) and distillate (80%) energy densities; [f] Hall, Pavlenko, and Lutsey (2018); this is the density of liquid H_2; [g] consistent with Roy and Comer (2017) and Faber et al. (2016).

Table 3. Efficiency assumptions.

Fuel	Efficiency of propulsion equipment (η_p)
HFO	50% (ICE)
Distillate	50% (ICE)
0.5% S-compliant	50% (ICE)
LNG	50% (dual fuel engine)
Electricity	90% (95% DC/AC converter[a] x 95% electric motor)
Hydrogen	54% (60% fuel cell x 95% DC/AC converter[a] x 95% electric motor)

Source: Lloyds Register and UMAS (2018) and [a] author's assumption

3.3. COSTS OF FUEL SPILLS

Fuel spills result in cleanup, socioeconomic, and environmental costs. For this analysis, we assume that the HFO and distillate 2023 spill costs are the same as the 2018 costs estimated by DeCola et al. (2018). DeCola and colleagues maintain these spill cost estimates are conservative when applied to Arctic oil spills, as they are based on worldwide data. We have estimated 0.5% S-compliant fuel cleanup costs based on the assumption of a 20% HFO and 80% distillates blend. Fuel spill cost assumptions for this analysis are found in Table 4. Liquefied natural gas spills result in no shoreline cleanup costs because LNG largely evaporates when spilled. Although there may be some environmental impacts, the costs are assumed to be negligible in this analysis. However, spilling LNG, which is mostly composed of methane, a potent GHG, does have socioeconomic costs. Based on the U.S. EPA (2016), we estimate the social cost of methane in 2023 at approximately $1,750 per tonne.[2] We assume that electricity, which cannot be "spilled" per se, and H_2, which is non-toxic, quickly disperses, and is not a GHG, result in zero spill costs.

Fuel spill costs are estimated by multiplying the quantity of fuel spilled by the total costs reported in Table 4.

Table 4. Fuel spill cost assumptions.

Fuel Type	Tonnes spilled[a]	Shoreline cleanup (2023 $/t)	Socioeconomic (2023 $/t)	Environmental (2023 $/t)	Total costs[b] (2023 $/t)
HFO	380 to 3,850	64,000	72,000	14,000	150,000
	>3,850	31,000	63,000	13,000	107,000
0.5% S compliant	380 to 3,850	19,000	40,000	7,000	66,000
	>3,850	8,000	33,000	5,000	46,000
Distillate	380 to 3,850	8,000	32,000	5,000	45,000
	>3,850	3,000	25,000	4,000	32,000
LNG	Any amount	0	1,750	0	1,750
Electricity or H_2	Any amount	0	0	0	0

Notes: [a] Spills <380 tonnes have costs, as presented in DeCola et al. (2018), but the potential spills in this analysis all exceed 380 tonnes; [b] costs are slightly different than DeCola et al. due to rounding.

2 The U.S. EPA estimates the social costs of methane at approximately $1,300 per tonne in constant 2007 U.S. dollars in the year 2023, which is roughly $1,600 per tonne in 2018 U.S. dollars; assuming inflation of 2% per year, we estimate the social costs of methane in 2023 U.S. dollars at approximately $1,750 per tonne.

3.4. NUMBER OF REFUELS OR RECHARGES NEEDED TO COMPLETE EACH CASE

Depending on the specific fuel used, a ship may need to refuel to complete its entire voyage. Based on the volumetric density (kg/m³) and energy density (kWh/kg) of each fuel, we can estimate how much energy could be provided within the space available for the existing fuel and engine systems on board each ship. For each case, we compare the energy needed to the energy that can be provided to estimate how many times the ship would need to refuel or recharge to complete the voyage(s).

For HFO, 0.5% S-compliant, and distillate fuels, we estimate the number of refuels needed to complete the voyage(s) in each case as follows:

$$R_{i,j} = \frac{E_{i,j}}{D_j \times ED_j \times V_f}$$

$R_{i,j}$ = number of times ship *i* needs to be refueled to complete the voyage(s) for each case when using fuel *j*

$E_{i,j}$ = energy input needed for ship *i* to operate on fuel *j* in kWh

D_j = density of fuel *j* in kg/m³ (Table 2)

ED_j = energy density of fuel *j* in kWh/kg (Table 2)

V_f = volume taken up by the existing fuel tanks in m³, equivalent to the ship's fuel capacity (Table 1)

For liquid H_2, we first estimate how much space the fuel cell system would need to occupy to provide an equivalent amount of power as the existing main engine at maximum continuous rating (MCR). Based on Minnehan and Pratt (2017),[3] we estimate the space needed for the fuel cell as follows:

$$V_{FC} = \frac{P_{ME} - 73.331}{55.944}$$

V_{FC} = volume (m³) the fuel cell system would need to occupy to provide an equivalent output power as the existing main engine

P_{ME} = main engine power at MCR

Second, we estimate the remaining space available on board for liquid H_2 fuel storage.[4] We first assume that the combustion engine room is five-times larger than the volume of the engine (J. Pratt, personal communication, December 18, 2018). We then assume that the fuel cell engine room is twice the size of the fuel cell system plus the volume taken up by the existing fuel tanks to allow enough space to operate and maintain the fuel cell systems. Therefore, the volume of liquid H_2 that can be stored on board is calculated as follows:

$$V_{LH_2} = V_e \times 5 - V_{FC} \times 2 + V_f$$

V_{LH_2} = the volume available to store liquid H_2 on board

V_e = volume taken up by the existing engine in m³ (Table 1)

V_{FC} = volume of the fuel cell

V_f = volume taken up by the existing fuel tanks in m³, equivalent to the ship's fuel capacity (Table 1)

Finally, we estimate the number of refuels needed to complete the voyage(s) when using liquid H_2 as follows:

$$R_{i,LH_2} = \frac{E_{i,LH_2}}{D_{LH_2} \times ED_{LH_2} \times V_{LH_2}}$$

R_{i,LH_2} = number of times ship *i* needs to be refueled to complete the voyage(s) for each case when using liquid H_2

E_{i,LH_2} = energy input needed for ship *i* to operate on liquid H_2 in kWh

D_{LH_2} = density of liquid H_2 in kg/m³ (Table 2)

ED_{LH_2} = energy density of liquid H_2 in kWh/kg (Table 2)

V_{LH_2} = the volume available to store liquid H_2 on board

For batteries, we assume that the battery system can take up two-and-a-half times the volume of the engine and all the volume currently taken up by the fuel tanks, consistent with Minnehan and Pratt (2017). We also assume that the battery capacity needs to be greater than the energy the ship will use to avoid damaging the battery. We assume that the ship can use 75% of the energy that the batteries can store. Therefore, the number of recharges needed to complete the voyage(s) when operating on batteries is as follows:

$$R_{i,elec} = \frac{E_{i,elec}}{(D_{batt} \times ED_{batt} \times [V_e \times 2.5 + V_f]) \times 0.75}$$

$R_{i,elec}$ = number of times ship *i* needs to be refueled to complete the voyage(s) for each case when using electricity in batteries

$E_{i,elec}$ = energy input needed for ship *i* to operate on electricity in kWh

D_{batt} = density of batteries in kg/m³ (Table 2)

ED_{batt} = energy density of batteries in kWh/kg (Table 2)

V_e = volume taken up by the existing engine in m³ (Table 1)

V_f = volume taken up by the existing fuel tanks in m³, equivalent to the ship's fuel capacity (Table 1)

3 Minnehan and Pratt (2017) equation 2.8 can be modified to estimate the volume of the fuel cell needed to provide a given amount of installed power.

4 Note that these assumptions are different than those published in Minnehan and Pratt (2017) but are informed by personal communication with J. Pratt. The methodology in this working paper attempts to avoid underestimating both the combustion engine room volume and the volume available to the fuel cell.

4. Results

A summary of each case and the estimated HFO fuel cost to complete each voyage is presented in Table 5. Note that, with the exception of Case 1, these ships spend a portion of the voyage within ECAs where using HFO is prohibited unless the ship can demonstrate equivalent compliance with ECA fuel quality regulations. One means of compliance is using an exhaust gas cleaning system, also called a scrubber. For this analysis, we assume these ships could use HFO along the entire voyage in 2023, which implies the use of scrubbers. In practice, these specific ships may comply by using distillate fuels when operating in ECAs, which would reduce the amount of HFO used along the journey but increase the overall fuel costs along the voyage.

All five ships can operate on cleaner fuels in addition to HFO and 0.5% S-compliant fuels. In the short-term, operators could carry and use distillate fuels and, in the case of the *Christophe de Margerie*, LNG fuel. In the medium-term, the other four ships could be retrofit to operate on LNG, which largely solves the spill problem but ignores climate impacts. Additionally, these ships could be retrofit to use electricity, H_2, or some other low- or zero-carbon fuel.

Table 5. Activity, fuel consumption, and fuel cost for each case.

Case	Ship Name	Voyage Description	Distance sailed (nm)	Voyage days	Maximum petroleum fuel onboard (t)	HFO used (t)	HFO fuel cost (2023 US $)
1	Christophe de Margerie	LNG from Norway to S. Korea	6,300	19	6,734	2,985	1,606,000
2	Yong Sheng	General cargo from Shanghai to Sweden	7,700	28	1,186	578	311,000
3	Irena Arctica	Year-round container service in western Greenland	54,000	Year-round	804	3,212	1,733,000
4	Nunavik	Ore from Canada to Rotterdam	3,100	19	2,020	597	321,000
5	MS Prinsendam	20-night Shetland Islands, Iceland, Greenland cruise	4,500	21	2,061	469	252,000

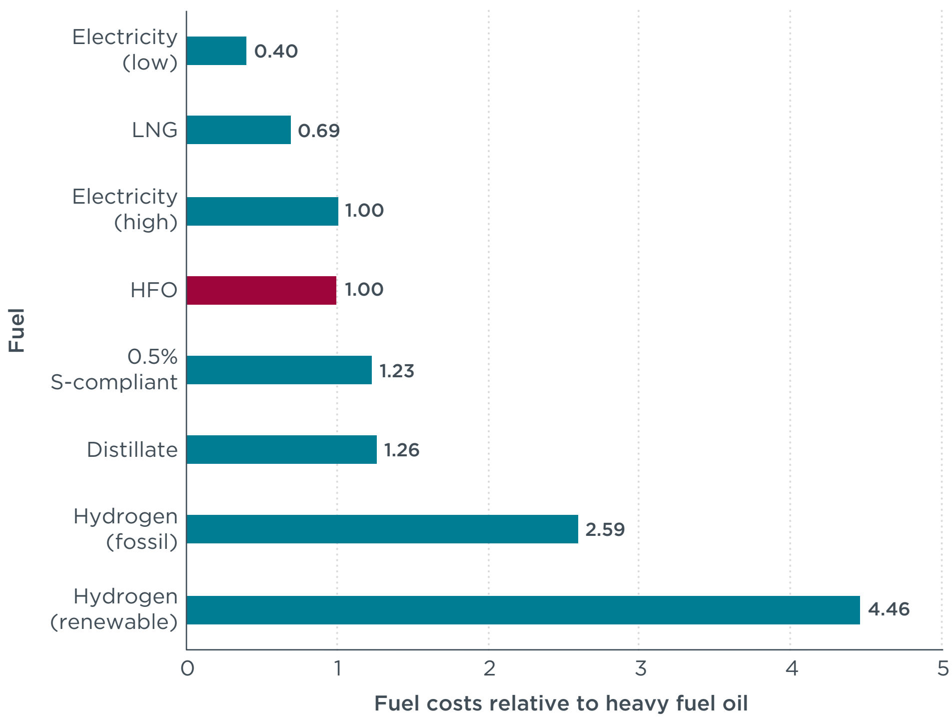

Figure 2. Voyage-level fuel costs relative to heavy fuel oil, accounting for energy density of each fuel and propulsion equipment efficiency.

4.1. FUEL COSTS

Figure 2 shows the voyage-level costs of operating any of the five ships on different fuels in 2023, relative to the cost of operating on HFO, taking into account the energy densities of the fuels (Table 2) and the propulsion equipment efficiencies found in Table 3. Heavy fuel oil is not always the least-cost fuel option for ships that can use other fuels. Operating on LNG is expected to cost 31% less than HFO. Depending on the electricity price, using batteries could be as expensive as HFO or up to 60% less expensive. Using 0.5% S-compliant fuels or distillates is expected to be roughly 23% to 26% more expensive than HFO. Using hydrogen could be two-and-a-half to four-and-a-half times more expensive than using HFO for fossil-fuel derived H_2 and renewable-derived H_2, respectively.

4.2. SPILL COSTS COMPARED TO FUEL COSTS

While using distillate and hydrogen would result in higher voyage-level fuel costs compared to HFO or 0.5% S-compliant fuels, a spill of distillates or hydrogen would result in low or no cleanup, socioeconomic, and environmental costs. Therefore, when considering which fuel to use in Arctic shipping, one should consider not only the fuel costs, but also the costs of a potential spill.

Consider a concrete example: transporting approximately 30,000 tonnes of ore from Canada to Rotterdam (Case 4) requires nearly 600 tonnes of HFO at a cost of approximately $321,000 (Table 5). Using distillate fuel, the most likely replacement fuel for the *Nunavik* bulk carrier, would cost approximately $405,000 to complete the same voyage. Now, consider the costs associated with a spill. The total cleanup, socioeconomic, and environmental costs of an HFO spill of between 380 and 3,850 tonnes are estimated to be $150,000 per tonne (Table 4). The total costs of a distillate spill of the same size are approximately $45,000 per tonne, a difference of $105,000 per tonne. If less than one tonne of HFO is spilled along the route, the extra costs would outweigh the fuel cost savings from HFO, especially given that smaller spills tend to be costlier per tonne than larger spills.[5]

Table 6 indicates how much HFO or 0.5% S-compliant fuel would need to be spilled before the cost savings associated with operating on the less expensive fuel were overcome by the costs of spilling the fuel. Heavy fuel oil and 0.5% S-compliant fuels are compared only to distillate fuel and H_2 because using LNG or electricity would be less expensive. For Cases 1, 2, 4, and 5, because cleaning up residual fuel spills is more expensive than cleaning up distillate spills, spilling more than 0.1% of the HFO or 0.5% S-compliant fuel that could be carried during that particular voyage would result in spill costs that exceed the fuel cost savings of using these fuels. Similarly, because there are no costs associated with spilling H_2, spilling more than ~1% of the HFO or 0.5% S-compliant fuel that could be carried would result in spill costs exceeding fuel cost savings for the voyages in each case.

Case 3 models one full year of activity rather than a one-off journey. In this case, the *Irena Arctica* would need to avoid spilling more than 0.53% of the HFO or 0.32% of the 0.5% S-compliant fuel the ship could carry in its fuel

Table 6. Tonnes of HFO or 0.5% S-compliant fuel that, if spilled, results in spill costs outweighing fuel cost savings of using these fuels.

Case	Ship Name	Voyage	HFO instead of distillate	HFO instead of hydrogen (fossil)	HFO instead of hydrogen (renewable)	0.5% S-compliant instead of distillate	0.5% S-compliant instead of hydrogen (fossil)	0.5% S-compliant instead of hydrogen (renewable)
1	Christophe de Margerie	LNG from Norway to S. Korea	4.0 t (0.06% of fuel capacity [FC])	17 t (0.26% of FC)	37 t (0.55% of FC)	2.4 t (0.03% of FC)	33 t (0.50% of FC)	79 t (1.2% of FC)
2	Yong Sheng	General cargo from Shanghai to Sweden	0.8 t (0.07% of FC)	3.3 t (0.28% of FC)	7.2 t (0.61% of FC)	0.5 t (0.04% of FC)	6 t (0.55% of FC)	15 t (1.3% of FC)
3	Irena Arctica	Year-round container service in western Greenland	4.3 t (0.53% of FC)	19 t (2.3% of FC)	40 t (5.0% of FC)	2.5 t (0.32% of FC)	36 t (4.5% of FC)	85 t (11% of FC)
4	Nunavik	Ore from Canada to Rotterdam	0.8 t (0.04% of FC)	3.4 t (0.17% of FC)	7.5 t (0.37% of FC)	0.5 t (0.02% of FC)	7 t (0.33% of FC)	16 t (0.78% of FC)
5	MS Prinsendam	20-night Shetland Islands, Iceland, Greenland cruise	0.6 t (0.03% of FC)	2.7 t (0.13% of FC)	5.9 t (0.28% of FC)	0.4 t (0.02% of FC)	5.3 t (0.25% of FC)	12 t (0.60% of FC)

5 DeCola et al. (2018) estimate that the total costs of an HFO spill of less than 2 tonnes is $246,000 per tonne compared to $77,000 per tonne for a distillate spill.

tanks in order to ensure that the fuel cost savings would outweigh the costs of spilling them. If operating on HFO or 0.5% S-compliant fuel instead of H_2, the most the *Irena Arctica* could spill would be 85 tonnes (~11% of fuel capacity) over the course of the year to guarantee that the fuel cost savings of using the residual fuels would exceed the spill costs.

In each case, fuel costs savings will continue to accrue for every voyage where the quantity of HFO or 0.5% S-compliant fuel spilled is less than those indicated in Table 6. However, one large spill could erase those accumulated savings. If, for example, we define a "large spill" as one where 65% of the maximum fuel capacity of the ship is spilled, we can estimate how many voyages of fuel cost savings would be erased from a large spill.

As shown in Figure 3, if the *Irena Arctica* (Case 3) managed to sail 122 voyages without a major spill, the savings associated with operating on HFO instead of distillate would be erased if a spill occurred on the 123rd voyage. Because each voyage of the *Irena Arctica* represents one year of activity, this is equivalent to avoiding a large spill for more than a century. In Case 1, the *Christophe de Margerie* would need to avoid a large spill for 775 voyages and, in Case 5, the *MS Prinsendam* would need to make over 2,000 20-night voyages without a large spill. If the *Nunavik* (Case 4) operated on HFO instead of H_2, it would have to complete more than 178 voyages to ensure that the fuel cost savings of operating on HFO instead of renewable H_2 were realized, or more than 388 voyages if HFO was used instead of fossil H_2. If not, a large HFO spill would cost more than operating on H_2.

Figure 4 shows that a similar pattern is observed if a ship operates on 0.5% S-compliant fuel instead of distillate or H_2.

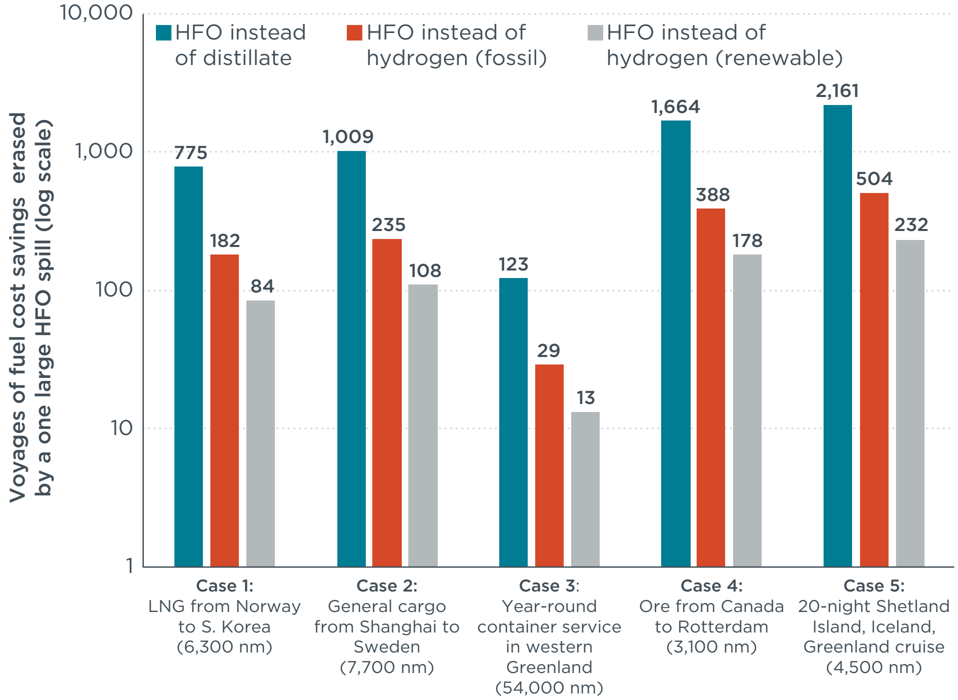

Figure 3. Number of voyages that must be completed before using heavy fuel oil is guaranteed to result in net cost savings assuming that, in the event of a "large spill", 65% of the maximum fuel capacity is lost.

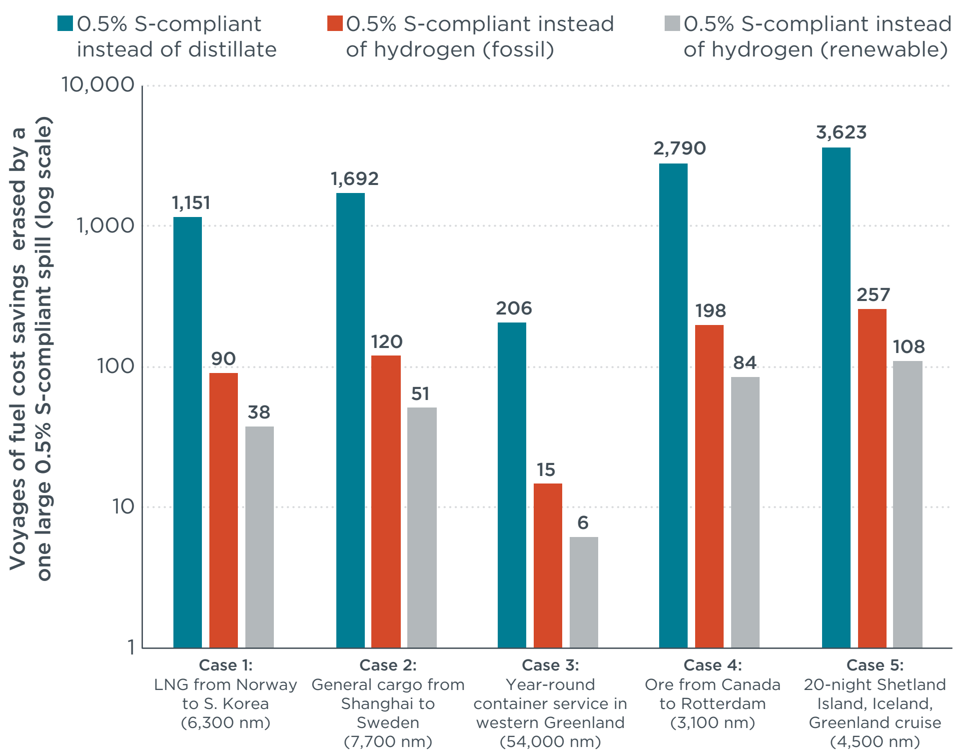

Figure 4. Number of voyages that must be completed before using 0.5% S-compliant fuel is guaranteed to result in net cost savings assuming that, in the event of a "large spill", 65% of the maximum fuel capacity is lost.

4.3. REFUELING OR RECHARGING REQUIREMENTS

For all five cases, the routes could be serviced by ships that operate on any of the fuels analyzed. In some cases, the ship will need to refuel to complete the voyage(s) that make up each case. Table 7 indicates the number of times the ship will need to refuel or recharge (for batteries) to complete the voyage within each case. This assumes that the ship does not sacrifice cargo space to operate on the alternative fuel.

In Cases 1, 2, 4, and 5, no ships require refueling when operating on petroleum-based fuels (HFO, 0.5% S-compliant, or distillates) or LNG.

To complete voyages using H_2, Cases 4 and 5 would need to refuel once and Cases 1 and 2 would need to refuel twice. Again, this assumes that no cargo or passenger space is sacrificed to carry more fuel. Case 5 provides a reasonable opportunity to use H_2 given that the *MS Prinsendam* and similar cruise ships make frequent port calls. Case 1 and Case 2 could also be good candidates if the *Christophe de Margerie* and the *Yong Sheng* or similar ships were able to bunker H_2 in Europe, along the Northern Sea Route, and in Asia. Case 4 could also use H_2 if the *Nunavik* or a similar ship sacrificed ore capacity to carry more fuel. Using batteries to provide all the energy needed to complete the voyages in all cases is out of reach with current technology, but batteries could provide supplemental propulsion energy and auxiliary energy.

In Case 3, we find that with HFO, 0.5% S-compliant, or distillate fuels, the *Irena Arctica* would need to refuel at least 3 times to complete a season of year-round container service to western Greenland. Using LNG would require 6 refuels. If the ship used H_2, it would need 27 refuels. Using fully battery electric propulsion would mean 288 recharges, essentially requiring daily recharging. The *Irena Arctica* completes many short journeys along the Greenland coast each year and some may be short enough to use battery power for most or all of the trip, although additional detailed analysis would be required to confirm this. Batteries could also be used to supplement main engine power and smooth out variations in main engine load when the ship is operating at variable speeds, such as near port.

Table 7. Number of refuels or recharges required to operate on each fuel in each case.

Case	Fuel	Energy that can be provided within the existing space for fuel and engine systems (GWh)	Energy needed for the case (GWh)	Refuels or recharges needed over the course of the voyage(s) in each case
Case 1: LNG from Norway to S. Korea	HFO	74.1	33.2	0
	0.5% S-compliant	77.1	33.2	0
	Distillate	77.9	33.2	0
	LNG	42.6	33.2	0
	Electricity	0.67	18.3	27
	Hydrogen	13.6	30.5	2
Case 2: General cargo from Shanghai to Sweden	HFO	13.1	6.4	0
	0.5% S-compliant	13.6	6.4	0
	Distillate	13.7	6.4	0
	LNG	7.5	6.4	0
	Electricity	0.10	3.5	34
	Hydrogen	1.9	5.9	2
Case 3: Year-round container service in western Greenland	HFO	8.9	35.8	3
	0.5% S-compliant	9.2	35.8	3
	Distillate	9.3	35.8	3
	LNG	5.1	35.8	6
	Electricity	0.07	19.7	288
	Hydrogen	1.3	32.9	25
Case 4: Ore from Canada to Rotterdam	HFO	22.2	6.6	0
	0.5% S-compliant	23.1	6.6	0
	Distillate	23.4	6.6	0
	LNG	12.8	6.6	0
	Electricity	0.20	3.7	17
	Hydrogen	4.1	6.1	1
Case 5: 20-night Shetland Islands, Iceland, Greenland cruise	HFO	22.7	5.2	0
	0.5% S-compliant	23.6	5.2	0
	Distillate	23.8	5.2	0
	LNG	13.1	5.2	0
	Electricity	0.20	2.9	13
	Hydrogen	4.1	4.8	1

5. Conclusions

Given IMO's efforts to ban HFO use and carriage as fuel in Arctic waters and to phase out GHGs from international shipping, we presented five case studies of Arctic shipping routes serviced by ships that can use HFO or 0.5% S-compliant fuels. We explored the costs and benefits of using fossil fuels that have less severe consequences when spilled (distillates and LNG) and alternative fuels that eliminate spill risk and emit zero emissions from the ship (electricity [batteries] and H_2) for the year 2023. We also examined what it would take, logistically, to use alternatives to HFO and 0.5% S-compliant fuels on these routes.

In each of the five scenarios, all the ships can stop using HFO and avoid the use of 0.5% S-compliant fuels by 2020. All ships can immediately use distillate fuels and the *Christophe de Margerie* tanker can use LNG. In the long term, these ships can be modified to use fuels that emit zero emissions from the ship, including electricity and H_2. These alternatives emit fewer and potentially zero lifecycle air and climate pollutants compared to HFO or 0.5% S-compliant fuels and they reduce or eliminate the costs associated with fuel spills.

Using distillate fuels is the simplest way for all ships to immediately stop using HFO in the Arctic. Using distillates requires only minor mechanical modifications, and ships routinely switch from HFO to distillates as they enter and depart ECAs. Distillate fuels are expected to be slightly more expensive than 0.5% S-compliant fuels and 26% more expensive than HFO in 2023. However, distillate spills are estimated to be 30% less costly than 0.5% S-compliant spills and 70% less costly than HFO spills when the cleanup, socioeconomic, and environmental costs are considered. Additionally, distillate fuels would result in fewer air pollutants (e.g., sulfur oxides) and climate pollutants, including black carbon.

Liquefied natural gas, a major export commodity in the Arctic, is another viable alternative that is predicted to be less expensive to use than any other fossil fuel in the Arctic in 2023. The *Christophe de Margerie* is the only ship in our five cases that can use LNG immediately due to its dual fuel engine. The other ships would need to be retrofitted, which would mean completely overhauling the fuel and engine systems, or an LNG-powered ship would need to be substituted along this route. While there are socioeconomic costs associated with LNG spills, there are zero spill-related cleanup costs because it evaporates. It also releases few harmful air pollutants and nearly zero black carbon. The downside of using LNG is that it is a fossil fuel, so combusting it releases CO_2 that contributes to climate change; more importantly, LNG is mainly methane, a potent climate warming pollutant. Methane leakage throughout the fuel's lifecycle and methane slip from the marine engine can result in LNG being more damaging to the climate than petroleum-based fuels. Therefore, while LNG avoids many of the negative consequences of a bunker fuel spill, we do not consider LNG a long-term solution to decarbonize the shipping sector.

The use of batteries avoids the costs of fuel spills, but the source of electricity will determine the overall health and climate impacts compared to other fuels. It is possible to produce electricity from low- or zero-carbon sources today, including in and near the Arctic. Additionally, electricity is often less expensive on a per-unit-energy basis than fossil fuels and H_2. However, because of the low energy density of batteries relative to other fuels, there are limited applications for their use. There simply is not enough space on most ships to make long fully electric journeys possible at this time. Batteries could be used for short routes in the Arctic, perhaps on voyages that take less than one day to complete, and as part of a hybrid system where the battery provides power when the ship is operating at variable engine loads, such as when the ship is maneuvering in and near port.

Hydrogen appears to be the most promising solution for zero-carbon, long-range Arctic shipping. In most of the cases we analyzed, a ship would need to refuel once or twice along the voyage to operate on liquid H_2. The *MS Prinsendam* cruise ship could be a prime candidate for using H_2 because it requires only one refueling for a 20-night journey and makes frequent port calls. If the *Christophe de Margerie* tanker and the *Yong Sheng* general cargo ship or similar ships were able to bunker H_2 in Europe, along the Northern Sea Route, and in Asia, these ships and routes could also be good candidates for using H_2. In the case of the *Irena Arctica*, it would have to refuel only 25 times per year to provide year-round H_2-powered container service to western Greenland if it were retrofitted with a fuel cell. While there is growing interest in using H_2 for maritime shipping applications, current barriers include a limited supply, especially from sustainable sources, limited fueling infrastructure, and higher costs relative to other fuels. For now, H_2 is mainly limited to ferry operations and other domestic shipping applications, but that could change depending on the relative costs of using H_2 compared to other fuels. There is interest in using ammonia as an H_2 carrier but there are serious health and safety risks that must be overcome given that it is highly toxic at low concentrations.

As Arctic shipping increases, pressure will mount to take actions to protect the environment and its peoples from the consequences of using and carrying fuels that are harmful when burned and spilled. If the use and carriage of HFO is banned in Arctic waters, there are alternatives that may be less expensive to use (e.g., LNG or electricity) or less costly when spilled (e.g., distillates, LNG, electricity, or H_2). In the short-term all ships are capable of operating on distillate fuels, which are less damaging when spilled, and some ships can operate on LNG, which avoids spill cleanup costs. Both of these fuels are fossil fuels and do not offer a long-term climate solution for shipping. In the longer term, ships can use renewable energy stored in batteries or used in fuel cells. The main barriers to using these technologies are the relatively low energy density of batteries and the relatively high price of H_2, barriers that should lower over time. Eventually, ships will need to be zero-emission if the IMO is to achieve its goal of eliminating GHG emissions from the international shipping sector. The Arctic may be the natural showcase for ZEVs that use renewable energy because they obviate the spill risk, eliminate black carbon emissions, and avoid GHG emissions.

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