A Techno-Economic Study of Shipping LNG to the Asia-Pacific from Western Canada by LNG Carrier

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Abstract

There is a high demand for natural gas in the Asia-Pacific region. Most of this gas is exported from the Middle East, Australia, Indonesia, and Malaysia. There is interest in the Asia-Pacific to diversify its import portfolio. From a Canadian perspective, there are abundant resources of natural gas in Western Canada, and countries in the Asia-Pacific are potential customers. This paper develops the cost of shipping a unit of natural gas (in liquefied form) from proposed liquefaction facilities in Western Canada to liquefied natural gas (LNG) re-gasification terminals

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in Asia-Pacific countries (Japan, China, and India). Fundamental engineering principles-based models were developed to estimate costs. A comparative analysis of delivery costs to Japan, China, and India is presented. To account for various propulsion systems available for LNG carriers, five scenarios were developed. Calm water resistance for the two different categories of LNG carriers was estimated. These estimates were used to determine the required propulsion power needed for an LNG carrier at a given speed and to select the appropriate main engine. The results of this study show that shipping costs to Japan range from 51-95 U.S. cents/GJ depending on the type of propulsion system selected and for an average transport distance of 7793 km. The shipping costs to China and India range from 59-113 U.S. cents/GJ and 98-197 U.S. cents/GJ for an average transport distance of 9475 km and 17035 km, respectively. The results show that a propulsion system burning only natural gas as primary fuel is the most economical scenario, while a propulsion system based on pure marine diesel oil is the least economical. In addition to a sensitivity analysis, a risk analysis was conducted to identify the range of shipping costs in each scenario with their occurrence probability measure.

Keywords: LNG; LNG carriers; natural gas; LNG shipping; LNG carrier propulsion systems

Nomenclature

Bcm	Billion cubic meters
GJ	Gigajoules
LNG	Liquefied natural gas
CNG	Compressed natural gas
NGH	Natural gas hydrates
GTL	Gas to liquids
FOB	Free on board
CIF	Cost, insurance, and freight
SFC	Specific fuel consumption
USD	United States dollar
HFO	Heavy fuel oil
MDO	Marine diesel oil
BOR	Boil-off rate
BOG	Boil-off gas
N-BOG	Natural boil-off gas
F-BOG	Forced boil-off gas
DFDE	Dual fuel diesel electric
MW	Megawatt
GCV	Gross calorific value
LHV	Lower heating value
LFO	Low fuel oil

C_v	Cargo volume
Δ	Displacement of the LNG carrier, tonnes
dwt	Deadweight tonnage, tonnes
L_{OA}	Overall length, meters
L_{PP}	Length between perpendiculars, meters
L_{wl}	Length on waterline, meters
B	Breadth, meters
D_{design}	Design draught, meters
S	Sailing speed, m/s
T	Depth, meters
A	Air draft, meters
$D_{ballast}$	Ballast draft, meters
lcb	Longitudinal center of buoyancy, meters
A_M	Midship section area, meter square
A_{wl}	Waterline section area, meter square
C_b	Block coefficient
C_m	Midship section coefficient
C_w	Waterplane coefficient
SFO_m	Main engine specific fuel consumption, g/kWh
SFO_{aux}	Auxiliary engine specific fuel consumption, g/kWh
SPR	Liquefaction plant specific power requirement, kW/(kg/sec)
P_E	Towing power
P_B	Brake power

Greek letters

η_H	Hull efficiency
η_o	Open water propeller efficiency
η_R	Relative rotative efficiency
η_s	Shaft efficiency

1. Introduction

1.1. Motivation

Canada has a large conventional and unconventional natural gas resource base. With declining net pipeline exports (see Figure 1, below) of natural gas to the United States (Canada's sole natural gas export client) and limited domestic demand growth, there is a need to diversify the export market. During the last ten years, Canada's net pipeline exports of natural gas to the United States have declined significantly, from around 100 billion cubic meter (bcm) in 2004 to 50 bcm in 2014 [1]. The natural gas import and export data as illustrated in Figure 1 were taken from the U.S. Energy Information Administration [1]. It is expected that the decrease in exports will continue till 2035 [1]. According to the National Energy Board's forecast, between 2015 and 2035, Canada's domestic natural gas demand will grow on average at a lower rate than gas production, and the net gas available for export, which is the difference between Canadian production and demand, will be around 0.13 bcm/d in 2035 [2]. This clearly illustrates that there would be surplus natural gas available in Canada to export to potential markets. Advanced fracturing and well drilling technologies, Canada's attractive fiscal regime, and relative proximity of the west coast to Asia-Pacific countries could contribute to extensive natural gas trade with these countries.

Figure 1: Natural gas trade between the U.S. and Canada [1]

Asia-Pacific markets are lucrative for Canadian LNG producers for many reasons. First, these markets are predominantly based on LNG, unlike North American and European markets, which are gas-based [3]. Second, there is a rapid energy demand growth in these markets presently and it is forecasted that by 2030, energy consumption (per capita) will grow to approximately 85 GJ/y [4, 5]. Also, it is envisaged that natural gas has the potential to play a huge role in satisfying growing demands of the Asia-Pacific region and transitioning it to a lower carbon economy [6]. This is because of the potential environmental benefits of using natural gas as a primary fuel in the energy mix. Natural gas demand in the Asia-Pacific region would be sufficiently large enough to accommodate the domestic and external sources of natural gas [5].

1.2. LNG Supply Chain

There are various processes involved in producing and transporting natural gas to a potential market. An LNG supply chain typically consists of four processes: gas production, gas processing, liquefaction, and shipping. A techno-economic model to quantify the cost of the first three processes in the LNG supply chain has been developed earlier by the authors [7]. In the earlier paper, the authors discussed the total cost of producing and liquefying a unit of shale gas in Western Canada and the sensitivity of the cost to various economic parameters. A detailed estimate of shipping cost is crucial in any LNG supply chain as it has a critical role in decisions related to diverting cargo to a high-priced market with the highest payback and to influencing LNG trade flow between markets and pricing dynamics of LNG as well. This paper aims to address this gap, that is, to estimate the costs of the fourth process in the supply chain, shipping of natural gas. It is a well-known fact that pipelines provide the most economical and reliable means of transporting large quantities of natural gas [8]. However, gas pipelines are usually more economical for short transport distances [9, 10]. For long-distance routes, particularly those crossing long stretches of water or oceans, transporting natural gas in the form of LNG is more cost competitive, as constructing pipelines under the sea is highly expensive and technically challenging [8]. Although natural gas can be transported and stored in different forms such as LNG, CNG (compressed natural gas), GTL (gas-to-liquid), and NGH (natural gas hydrate) depending on factors such as proximity of the gas resource to the market or the scale of development [11], transporting natural gas in the form of LNG provides flexibility advantages over gas pipelines and other technology alternatives [10]. The LNG industry has successfully brought many stranded and huge gas resources to gas markets unreachable by pipeline, such as

Japan, South Korea, and Taiwan [12]. In 2013, Japan consumed about 37% of the world's total LNG imports, followed by South Korea (17%), China (7.9%), and India (5.5%) [13].

LNG is transported by ships called LNG carriers that are designed to contain the cargo slightly above atmospheric pressure at a cryogenic temperature of approximately -169 ^{o}C [12]. An LNG carrier's capacity ranges from 19,000 to 265,000 m^3 [14]. However, the typical dimensions of LNG carriers are summarized in Table 1 [12].

Table 1: Typical dimensions of different LNG carriers

Characteristics	**Conventional**	**Q-flex**	**Q-max**	**Units**
Cargo capacity	13800-17300	210,000	263,000	m^3
Length overall	277-290	315	345	m
Depth	26-26.5	27	27	m
Breadth	43.3-45.8	50	55	m
Number of tanks	4	5	5	
Number of propellers	1 or 2	2	2	

Source: [12]

Over the past few decades, the steam turbine propulsion system has dominated the LNG shipping industry with around 40 % of the LNG carrier fleet [2]. This is because of the simplicity of using the boil-off gas in steam boilers to produce steam for steam turbines. However, with the increase in cargo capacities of LNG carriers in LNG shipping, the steam turbine propulsion system has been losing its market share due to its low efficiency and many other factors such as fuel flexibility, reliability, availability, and safety [15]. As a result, several advanced propulsion systems for LNG carriers have emerged in the market [16]. The emerging propulsion systems can be broadly categorised in the following ways [17]:

- Dual-fuel flexibility-based - These propulsion systems are powered by either natural boil-off gas (or forced boil-off gas) or heavy fuel oil.
- Pure fuel oil burning systems - These are slow-speed diesel-based propulsion systems fuelled by heavy fuel oil or marine gas oil and have an on-board re-liquefaction plant to return the boil-off gas to the cargo tanks.
- Pure gas burning systems - These are gas turbine-based propulsion systems using natural boil-off gas (or forced boil-off gas) and marine gas oil as a pilot fuel. The combustion of natural gas as a fuel is characterized by low levels of CO_2, SO_X, NO_X and particulate matter production compared to conventional fuels like HFO and MDO. [18, 19].

1.3. Knowledge gaps and objectives

The delivery cost of a unit of LNG is critical information for decision makers in the Asia Pacific, North America, Australia, and the Middle East. For those in Asia-Pacific countries, this information provides an opportunity to diversify their import portfolio and explore the option of importing LNG from a politically stable region. Most of the LNG imports to Asia-Pacific countries are to the Middle East, Australia, Indonesia, and Malaysia. The import of LNG from North America is limited and information related to it is scarce. There is a need to understand LNG export to these countries and the impact it could have on the market share of various suppliers.

There are no studies in the academic literature that comprehensibly address the LNG shipping costs from Canada to Asia-Pacific countries. Some studies provide partial estimates [20-23] with limited focus on the bottom-up approach using fundamental engineering principles to estimate overall shipping costs. With the exception of one study [21], the studies do not consider any parameters such as cargo volume, LNG carrier speed, boil-off rate, etc. in shipping cost estimates. In addition, these few studies do not account for the various propulsion systems available for LNG carriers today [16, 24]. The selection of a propulsion system for a particular voyage is critical in determining shipping cost and hence is critical for assessment. Moreover, as most of the Canadian LNG projects are still in the development phase, the decision makers of those projects have the choice of selecting a propulsion system best suited to their situations. Fuel consumption cost makes up a significant portion of the total shipping cost in LNG shipping [24]. Therefore, it is important to estimate fuel consumption comprehensibly. There are a few studies on ship bunker fuel consumption. Ronen [25] and Vernimmen et al. [26] estimated fuel consumption by assuming that motor ship bunker fuel consumption is proportional to the third power of its sailing speed. Along similar lines, Alvarez [27] used the cube law to calculate fuel consumption at sailing speeds below the design speed. Fagerholt et al. [28] stated that fuel consumption is a convex function of the ship speed. However, none of these studies account for a ship's cargo carrying capacity in their empirical relationships. Yao et al. [29] developed an empirical relationship based on data from a shipping liner that gives the correlation between fuel consumption rate and ship sailing speeds for different sizes of container ships. However, their model does not estimate fuel consumption according to the power requirements of the engines installed in LNG carriers. A multi-objective genetic algorithm was used by Larsen et al. [30] to investigate the trade-off between fuel consumption and NO_X emissions for five different configurations of two-stroke diesel-based machinery systems for large ships. Jafarzadeh et al. [31] employed a bond graph to estimate the fuel consumption of fishing vessels under different operational conditions such as steaming, trawling, and hauling fishing gear.

In this paper, we estimate bunker fuel consumption (in a given time frame) of an LNG carrier according to the power requirements of the main and auxiliary engines installed for propulsion.

This paper contributes to the academic literature by addressing the above-mentioned gaps. The specific objectives of this paper are as follows:

- To estimate the shipping cost of natural gas in the form of LNG to Asia-Pacific countries using a bottom-up fundamental engineering approach
- To estimate the cost to ship LNG from Canada to Asia-Pacific in different LNG propulsion carriers in five different scenarios
- To develop models to estimate LNG carrier bunker fuel consumption based on the power requirements of the main and auxiliary engines installed for propulsion
- To conduct a sensitivity analysis to determine the impact of input variables on shipping cost
- To conduct a risk analysis of the shipping cost using a Monte Carlo simulation

2. Methodology

2.1. Model description

For this paper, we developed a model that estimates the cost of shipping one gigajoule of LNG on a per-voyage basis. The estimates are based on the perspective of an LNG trader, who charters the LNG carrier for shipping. The LNG trader in this paper is defined as a buyer of the liquefied natural gas at a free on board (FOB) price, ships it on a charted LNG carrier, and sells it at cost, insurance, and freight (CIF) prices at Asia-Pacific re-gasification terminals. The detailed model, with all the unit operations and associated parameters developed for the assessment, is presented in Figure 2. This model describes the relationship among various technical and economic variables used in this paper. The LNG carrier's speed and its geometrical particulars (overall length, draught, dead weight tonnage, etc.) are independent variables in this model. These variables are used to estimate the total calm water resistance (which includes frictional, appendage, wave, model-ship correlation, and pressure resistances) using Holtrop and Mennen's approximate power prediction approach [32] and the statistical power prediction method [33] (see supplementary information for details). The calm water resistance estimate helps determine the required propulsion power needed at a given speed and hence plays a key role in selecting the correct main engine. At a given LNG carrier speed, the product of the total calm water resistance and LNG carrier speed gives rise to the towing power required by propellers. In this paper, an engine margin of 10% and a sea margin of 15% and have been considered [34]. While sea margin is added to account for various environmental factors such as waves, winds, shallow water, steering effects, and the effects of aging and fouling on the hull and the roughness of the hull and the propeller surface, engine margin is added to serve as a power reserve (mechanical and thermodynamic) for economic engine operation with respect to low maintenance and fuel expenses. These margins, along with propeller efficiency and towing power, as discussed above, determine the power required by the main engines installed in the ship. The details of various main and auxiliary engines used in this paper are given in Table 2. Using the specific fuel consumption (SFC) data for the engine and its power requirement, we calculate the total fuel consumption values and total fuel cost. The other major cost-contributing factors are the hiring rate of LNG carriers and the port and passage fees. The port and passage fees are estimated on the basis of gross register tonnes of the LNG carriers for a particular port. The output of the model is the shipping cost in U.S. dollars (USD) per gigajoule for a specific LNG-importing regasification port in a particular scenario. All the costs mentioned in the paper are in U.S. dollars with 2014 as the base year unless specified otherwise. The various scenarios developed in this paper are discussed in the next section.

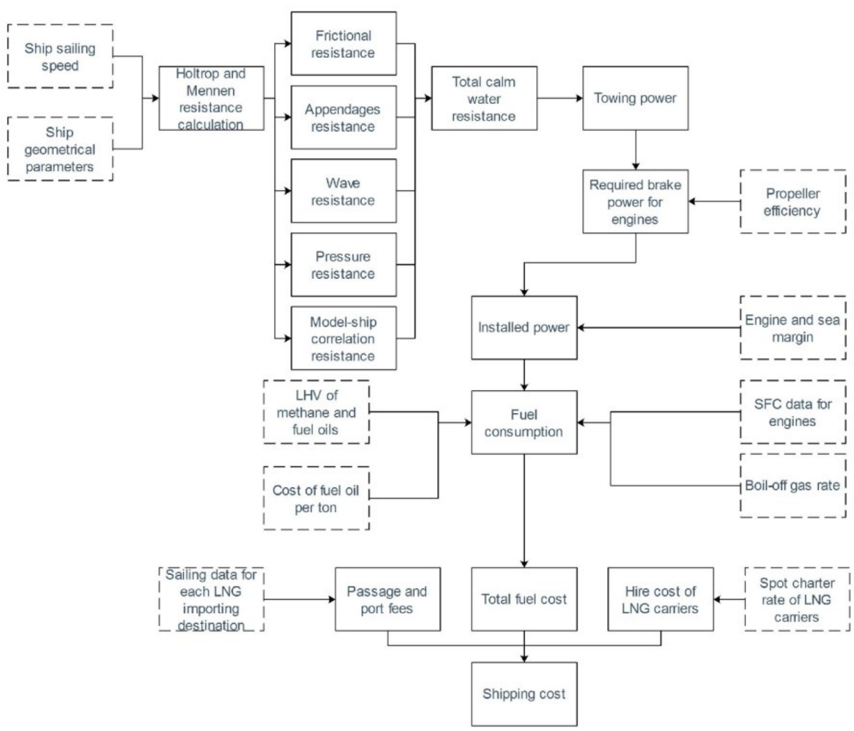

Figure 2: Model to estimate shipping costs

2.2. Scenario description

To account for the various propulsion options available for LNG carriers in LNG shipping cost estimates, five scenarios are considered in this paper (see Table 3). The distinctions in each shipping scenario relate to the use of the boil-off gas as a fuel and the different types of bunker fuel used. For all the scenarios considered, the natural gas liquefaction terminal is in Port Kitimat, British Columbia, as this is an industrial heartland in the province suitable for plants of this nature. Scenarios 1 and 2 represent the dual-fuel flexibility propulsion system of LNG carriers. In scenario 1, heavy fuel oil (HFO) is considered as the primary fuel, whereas in scenario 2, marine diesel oil (MDO) is the primary fuel. MDO is used as a pilot fuel. Dual fuel engines run either on gas or on liquid fuel. In both modes, a tiny quantity of liquid pilot fuel, typically around one percent of total fuel consumption, is injected. Boil-off gas (BOG) is used as the secondary fuel in both scenarios. LNG carrier 1 (see Table 9) is used in both scenarios. This LNG carrier represents the conventional cargo capacity of 155,000 m^3 with an installed power of 36 megawatts. A boil-off rate of 0.12 percent of LNG carrier capacity per day during the laden voyage (loaded condition) and 0.06% during the ballast voyage (unloaded condition) has been used in the base case paper [35] in all five scenarios The case of the pure HFO- (or MDO-) burning LNG propulsion system has been given due attention in scenarios 3 and 4. In these scenarios, the boil-off gas is not used as a fuel but is liquefied instead in an on-board BOG re-liquefaction plant and sent to cargo tanks [36]. LNG carrier 2 (see Table 9) is used for scenarios 3 and 4. LNG carrier 2 is a Q-flex type LNG carrier [36] with four on-board liquefaction plants. Scenario 5 is the case in which LNG cargo is used as a primary fuel. Fuel consumption of gensets during loading and unloading are out of the scope of the current study.

Table 2: Scenarios based on different propulsion system for shipping LNG

Propulsion name	**Installed engines**	**Installed power[e] (MW)**	**Fuel used**	**Representative LNG carrier[f]**
Dual-fuel diesel electric (DFDE)	● Main engine: MAN 9L51/60DF[a] ● Auxiliary engine: MAN 8L32/40[b]	36	N-BOG (or F-BOG), HFO	LNG carrier 1
Dual-fuel diesel electric (DFDE)	● Main engine: MAN 9L51/60DF[a] ● Auxiliary engine: MAN 8L32/40[b]	36	N-BOG (or F-BOG), MDO	LNG carrier 1
Medium speed diesel with on-board re-liquefaction plant	● Main engine: MAN 6S70ME-C8[c] ● Auxiliary engine: MAN 8L32/40[b]	42.7	HFO	LNG carrier 2
Medium speed diesel with on-board re-liquefaction plant	● Main engine: MAN 6S70ME-C8[c] ● Auxiliary engine: MAN 8L32/40[b]	42.7	MDO	LNG carrier 2
Gas turbine simple cycle electric	● Main engine: MAN 7S60ME-GI[d]	33.3	N-BOG and F-BOG	LNG carrier 3

- Auxiliary engine: MAN 8L32/40[b] | (MGO as pilot fuel)

l-fuel marine engine from MAN Diesel & Turbo. The engine project guide is available from [37]

medium speed engine from MAN Diesel & Turbo. The engine project guide is available from [38]

oke marine engine from MAN Diesel & Turbo. The engine project guide is available from [39]

oke engine from MAN Diesel & Turbo. The engine project brochure is available from [40]

cenarios is calculated for a 100% maximum continuous rating (MCR) from respective engine project guides.

LNG carriers can be found in Table 3.

Table 3: Particulars of representative LNG carriers

	Nomenclature	LNG carrier 1	LNG carrier 2	LNG carrier 3	Unit
Principal geometrical dimensions[1]					
Cargo volume	C_V	150000	210000	150000	m^3
Displacement	Δ	98039	136685	98039	tonne
Deadweight tonnage	Dwt	83794	116825	83794	tonnes
Overall length	L_{OA}	288	315	288	m
Length between perpendiculars	L_{PP}	275	303	275	m
Breadth	B	44	50	44	m

Design draught	D_{design}	11.6	12	11.6	m
Average design ship speed	V	10 (19.4)	10 (19.4)	10 (19.4)	m/s (knots)
Depth	T	26.25	27	26.25	m
Air draft	A	41.15	44	41.15	m
Ballast draft	$D_{ballast}$	11	11	11	m
Longitudinal Center of Buoyancy	Lcb	2.75	3.03	2.75	m
Coefficients[2]					
Block coefficient	C_b	0.67	0.73	0.67	
Midship section coefficient	C_m	0.98	0.98	0.98	
Water plane coefficient	C_w	0.77	0.83	0.77	
Average design ship[3] speed	S	10 (19.4)	10 (19.4)	10 (19.4)	m/s (knots)

[1,3]Particulars and average design speed of LNG carriers available from [24]

[2]Coefficients calculated using [41] and the relevant equations used are presented in the supplementary information.

2.3. Resistance and powering estimates

Using the methodology described in section 2.1, we estimated the calm water resistance of LNG carriers 1 and 2 for different sailing speeds; these estimates are presented in Figures 3 and 4, respectively. The various parameters, geometrical dimensions, and coefficients used for LNG carrier resistance estimates are presented in Tables 2 and 3. From Figure 3, one can observe that the calm water resistance for LNG carrier 1, which is a conventional LNG carrier, is around 160 metric tonnes at a sailing speed of 10.3 m/s (20 knots). This value increases by 33% for LNG carrier 2, as can be observed from Figure 4.

Figure 3: LNG carrier 1 power requirements and calm water resistance at different speeds (m/s and knots)

As shown in Figures 3 and 4, towing power at a particular sailing speed is the product of an LNG carrier's calm water resistance and its sailing speed. This power is the effective power required by the propellers to move the LNG carrier at a particular sailing speed. However, there are energy transmission losses between the propellers and the engines and, due to these losses, the brake power (the power provided by the installed engines) is greater than the required towing power. The relationship between total brake power and towing power is expressed in Equation 1 (see supplementary information). A sea margin and an engine margin are added to the total brake power of the engine to estimate the total installed power, as discussed in Section 2.1. From Figures 3 and 4, it can be observed that at a sailing speed of 10.3 m/s (20 knots), LNG carrier 1 requires an installed engine power of around 32 MW and LNG carrier 2 requires around 42 MW.

Figure 4: LNG carrier 2 power requirements and calm water resistance at different speeds (in m/s and knots)

The specification of the engines installed on this LNG carrier were based on the specifications of the engines manufactured by MAN B&W [24]. The engine configuration and specific fuel consumptions for engines are summarized in Table 4.

Table 4: Engine configurations and specific fuel oil consumption (SFOC) for engines

	Nomenclature	**LNG carrier 1**	**LNG carrier 2**	**LNG carrier 3**	**Unit**
Engine configurations					
Main engine configuration		4 x MAN 9L51/60DF [42]	2 x MAN 6S70ME-C8 [24]	2 x 7S60ME-GI [43]	
Auxiliary engine configuration		4 x Aux. Diesel Gen - MAN 8L32/40	4 x Aux. Diesel Gen - MAN 8L32/40	4 x Aux. Diesel Gen - MAN 8L32/40	
SFOC data[a]					
Main engine SFOC	SFO_m	183.5	171	171	g/kWh
Auxiliary engine SFOC	SFO_{aux}	181	181	181	g/kWh
Re-liquefaction plant					
Re-liquefaction unit		No	Yes (4 units)	No	

availability					
Liquefaction plant specific power requirement	SPR	Not applicable	2719[b]	Not applicable	kW/kg/sec

[a]Specific fuel oil consumption (SFOC) data available from respective engine project guides (references provided in Table 2)

[b] Liquefaction plant specific power requirement data from [35]

3. Case Study Model Parameters

In this section, the parameters (sailing distance, LNG carrier chartering, boil-off gas and weathering, fuel consumption) related to the cost analysis of a voyage are described. For the purposes of this paper, it is assumed that during a specific voyage the LNG carrier sails to only one of the regasification ports from Port Kitimat and then sails back. Note the developed model for cost estimations is generic and could be used for other locations with appropriate adjustment of the input parameters.

3.1. Sailing distances

According to GIIGNL [13], at the end of 2013 there were 30, 11, and 4 operating re-gasification terminals in Japan, China, and India, respectively. The regasification capacities of those terminals along with the number of sailing days from Port Kitimat are presented in the supplementary information. The terminals' regasification capacity values have been obtained from [13] and the number of sailing days is estimated by using inter-port sea distances given in [44]. The Sodegaura LNG terminal, 7989 km from Port Kitimat, has, at 2.6 million cubic meters, the highest re-gasification capacity of all the terminals in Japan. In China, the LNG terminal with the highest LNG re-gasification capacity is Shanghai LNG (4.95 million cubic meters), whereas in India, Dahej terminal, with a capacity of 5.92 million cubic meters, is the highest. It is estimated to take an average of around 8-9 days to sail from Port of Kitimat, Canada to Japanese re-gasification terminals and 11 and 20 days to those in China and India, respectively.

3.2. LNG carrier chartering

The transportation of LNG by sea is contracted between two parties: ship owners and charterers. The charting of LNG carriers is generally conducted in one of two basic ways: term/time charter and spot charter [45]. For a charting contract, the charterer pays the fuel consumption cost, port and passage fees, and a daily hire cost to the ship owner. The hire cost is generally quoted in dollars per day. For a spot charter, the charterer pays the ship owner on a per-tonne basis, while the ship owner pays for the passage and port fees, fuel consumption cost, and crew costs. Most LNG carriers operate under the term/time charting contract [46]. In this paper, we consider a short-term charting contract for an LNG carrier hire cost estimate. The average hire rate for a modern steam turbine is $54,000 per day, while an LNG carrier equipped with dual-fuel propulsion costs around $64,000 per day [47].

3.3. Boil-off gas and LNG weathering

During an LNG carrier voyage, heat ingress from surroundings to the low-temperature cargo tanks generates the boil-off gas [48]. The boil-off gas rate depends on the heat transfer rate, which largely depends on heat transfer area, heat transfer coefficient, and the temperature difference. To determine the exact boil-off rate, one needs detailed information such as LNG carrier hull dimension, initial gas composition, cargo tank insulation material, and environmental and sailing conditions. Moreover, the boil-off rate is dynamic and involves multiple variables. The dynamic nature of boil-off gas during marine transportation has been studied by Dimopoulus et al. [49] and is beyond the scope of current paper. In this paper, the boil-off rate is taken to be constant throughout the voyage and is assumed to be 100% CH_4. BOG is used as the secondary fuel in scenarios 1 and 2. A boil-off rate of 0.12 percent of carrier LNG capacity per day during the laden voyage and 0.06% during the ballast voyage has been used in the base case paper [35]. Figure 5 illustrates the amount of boil-off gas for different LNG carriers in laden and in ballast conditions at certain sailing hours. LNG carrier 1, which has a cargo capacity of 150,000 m^3, boils off a total of around 1600 m^3 of natural gas in 215 sailing hours (9 days) when sailing to Japan in laden conditions.

Figure 5: Cumulative boil-off gas amount for LNG carriers in laden and ballast conditions

In ballast conditions, the boil-off amount drops to 800 m^3. For LNG carrier 2, which has a cargo capacity of 210,000 m^3, the boil-off gas amount in laden and ballast conditions is around 2245 m^3 and 1125 m^3, respectively. Note that in this paper the time discretization scheme considered for the boil-off gas amount estimate is a one-hour time interval. Time intervals of one day can be used as well. However, there is a small difference in the results produced with the two-time discretization schemes discussed above. During ship transportation, the composition of LNG changes over time because of the heterogeneous nature of LNG vaporization [50]. This phenomenon is called LNG ageing or weathering and it is not observed in pipeline transport of natural gas. The main effect of this phenomenon is the gradual change in LNG specifications from the loading terminal to the receiving terminal. The specification of most concern in this study is the change in the gross calorific value (GCV) of the LNG being shipped. This is because the change in GCV value affects the estimated amount of energy transferred from the ship to ground tanks in the receiving terminals. In this paper, a GCV value of 23 GJ/m^3 [51] is taken in the base case study. We consider the effect of weathering in the sensitivity analysis section by varying the LNG GCV values. The parameters of the base case study are given in Table 5.

3.4. Fuel consumption

In this paper, we estimate bunker fuel consumption (in a given time frame) of an LNG carrier according to the power requirements of the main and auxiliary engines installed for propulsion. This estimation methodology is illustrated in Figure 6.

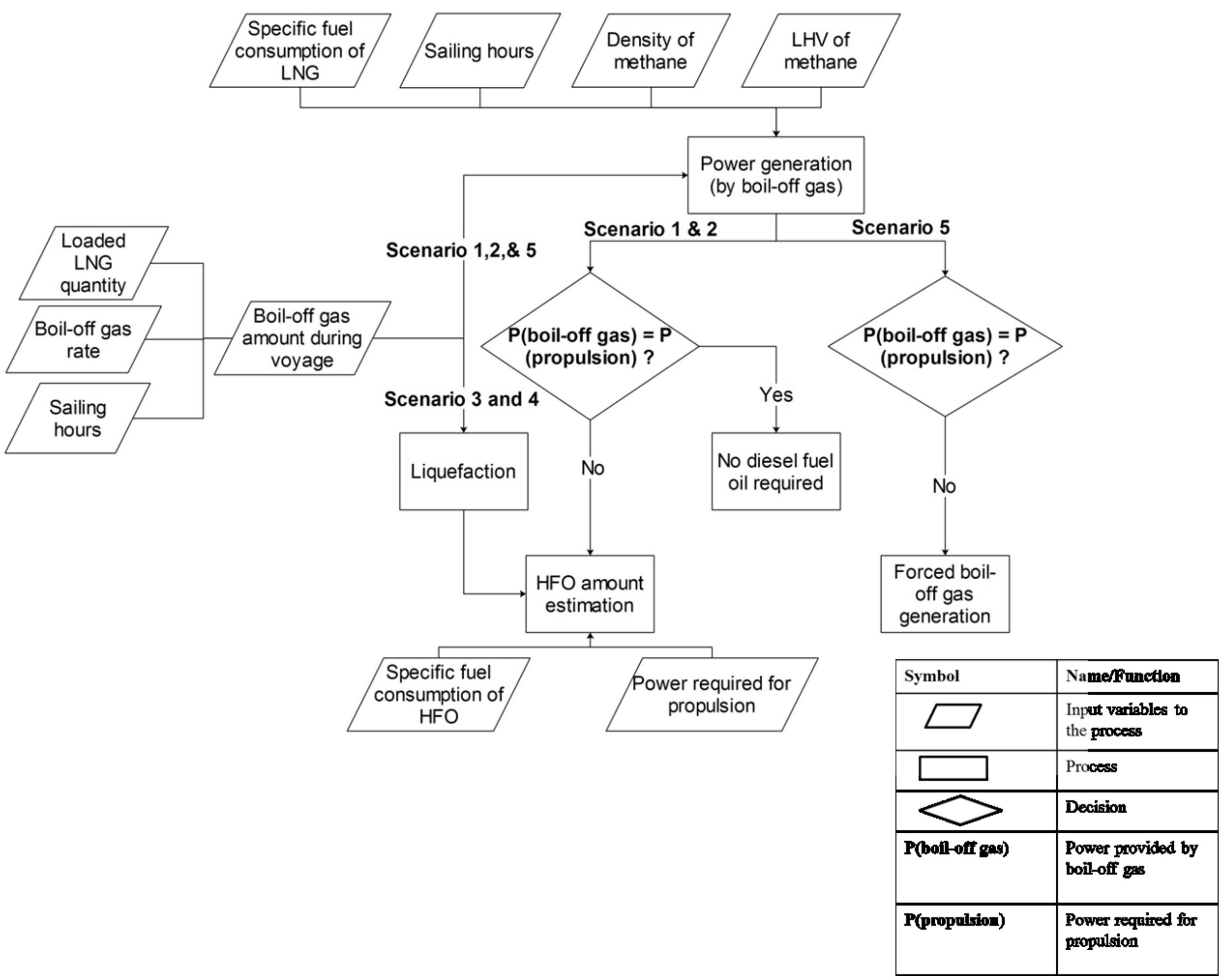

Figure 6: Logical structures to estimate fuel consumption in scenarios 1 to 5

For scenarios 1 and 2, the engines consume all the available natural boil-off gas power for propulsion and the rest of the power is provided by diesel fuel oils (HFO or MDO). If the power provided by boil-off gas [P (boil-off gas)] is equal to the power required for propulsion [P (propulsion)], then no diesel fuel is required. In scenarios 3 and 4, HFO-fuelled engines provide the propulsion power required by the LNG carrier and the boil-off natural gas is liquefied in an on-board liquefaction power plant. In scenario 5, only natural gas is used as a fuel with marine gas oil (MGO) as a backup fuel. In this scenario, if the power required for propulsion is not met by the power generated by boil-off gas then forced boil-off gas is used.

Table 5: Parameters for the base case cost model

Sailing parameters	Base case	Low	High	Units	References
Distance from Port Kitimat					
Japanese ports	7793	7157	8274	km	[44]
Chinese ports	9474	8765	10136	km	[44]
Indian ports	17034	15962	17531	km	[44]
Speed of LNG carrier	10.3 (20)	9.5 (18.5)	11 (21.3)	m/s (knots)	Average design speed of LNG carriers [52]
Boil-off rate, laden	0.12%	0.10%	0.15%	% of total cargo, per	[35]

				day	
Boil-off rate, ballast	0.06%	0.01%	0.08%	% of total cargo, per day	[35]
Energy content of LNG at loading terminal[1]	40	38	44	MJ/Nm^3	[53]
LNG loading and unloading rate	12000	10000	15000	m^3/hr	[12, 53]
LNG properties					
Density of methane liquid at 1.06 bar a	470	425	485	kg/m^3	[53]
LHV of methane	50000			kJ/kg	[53]
Fuel oil cost (dollars per tonne)					
HFO	625	375	875	$/tonne	[54]
MDO	810	486	1134	$/tonne	[54]
LNG carrier (spot charter rates) hire cost	64000	38400	89600	$/day	[47]

[1] This is the energy of combustion of gas (vaporized LNG) and not liquid LNG

4. Results and Discussion

4.1. Fuel consumption

Fuel consumption is estimated using the logical structure described in section 3.4 and presented in Figure 7 below. In the case of dual-fuel flexibility, it is worth noticing the difference in fuel consumption between laden and ballast voyages. The quantity of HFO consumed per day for propulsion is lower in laden conditions and higher in ballast conditions than the quantity of natural gas consumed. This is attributed to the fact that the boil-off gas amount is significantly higher in laden conditions than in ballast conditions. Hence when the importing country is Japan, in laden conditions, the boil-off gas meets around 60% of the power requirements of the LNG carrier and around 30% in the return or ballast voyage. For the pure fuel-oil based system, no boil-off gas is consumed for power. In this case, since all the boil-off gas is liquefied, the per day consumption of HFO is, in laden conditions, four times, and in ballast conditions, two times the HFO consumption of the dual-fuel flexibility case. In the pure gas-based propulsion system, HFO is only used as a pilot fuel and the propulsion power requirements are largely met by the natural boil-off gas or the forced boil-off gas (if required). The fuel consumption trends (for different propulsion categories) when MDO is used as a fuel instead of HFO are similar to fuel consumption results as shown in Figure 7. Figure 8 shows the total voyage fuel consumption for all three importing countries considered. From all three propulsion scenarios, it is evident that the fuel consumption is highest in the case of shipping LNG to India due to the greater number of sailing days compared to China or Japan.

Figure 7: Fuel consumption per day with different propulsion systems

Figure 8: Total fuel consumption for different countries in various scenarios

4.2. Shipping cost

The cost to ship one gigajoule of liquefied natural gas from Port Kitimat to Japan is given in Figure 9. Shipping costs range from 51 cents to 95 cents per gigajoule depending on the type of propulsion system.

Figure 9: Cost to ship LNG to Japan in propulsion scenarios 1 to 5

Scenario 4 has the highest propulsion cost because of the relatively higher cost per tonne of marine diesel oil than heavy fuel oil. Moreover, scenario 5 has the lowest shipping cost owing to the low cost of natural gas compared to any marine fuel oil. The results of the present study have been compared with other existing shipping cost estimates (these estimates have been adjusted for inflation and are presented in 2014 USD using the most recent U.S. government CPI data [55]) . This comparison is presented in Figure 10. NERA's 2012 shipping cost estimates are based on a 149,000 m^3 LNG carrier with a per-day hire cost of $65,000 and a sailing speed of 9.97 km/h [21]. NERA assumes a cargo volume boil-off rate of 0.15% per day. Other studies do not mention the cargo capacity or other parameters in their shipping cost estimates.

Figure 10: Comparison of the results of the current study with existing studies

The total shipping costs and cost components for China and India are summarized in Table 6. For China, costs range from 60 cents/GJ in scenario 5 to 113 cents/GJ in scenario 4 and for India the range is from 98 cents/GJ to 197 cents/GJ. It is clear that for all the importing countries, the lowest shipping cost is in scenario 5 and the highest is in scenario 4. Scenario 5 tends to have the lowest costs because of significantly low cost of natural gas compared to other fuel oils, whereas the high cost of marine diesel oil, which is the main fuel in scenario 4, make this scenario the most expensive means of transporting natural gas in the form of LNG. Also, in scenarios 1, 2, and 5, the LNG carrier hire cost is the same because in all these scenarios LNG shipping is done with the 150,000 m^3 LNG carrying capacity LNG carrier.

Table 6: Shipping cost (cents/GJ) for China and India in different scenarios

Scenario	Name	Fuel oil cost	LNG carrier hire cost	Port and passage fees	Total cost	Fuel oil cost	LNG carrier hire cost	Por pas fees
1	GAS/HFO fuel flexibility	32	45	9	86	58	79	10
2	GAS/MDO fuel flexibility	41	45	9	95	75	79	10
3	Pure HFO burning system	58	33	5	96	104	57	5
4	Pure MDO burning system	75	33	5	113	135	57	5
5	Pure gas burning system	5	45	10	60	8	80	10

4.3. Sensitivity and risk analysis

We conducted a sensitivity analysis to determine the sensitivity of the shipping cost to the input variables (see Figure 11). The input variables with their respective range of values are summarized in Table 5. It can be observed from Figure 11 that the hire cost of the LNG carrier is the most influential parameter, followed by the per tonne cost of heavy fuel oil. The third most influential parameter is the boil-off gas rate, which lowers shipping costs when it increases. This is because a higher boil-off gas rate decreases the consumption of expensive heavy fuel oil and simultaneously increases consumption of the relatively cheaper natural gas, leading to a reduction in the total cost of shipping.

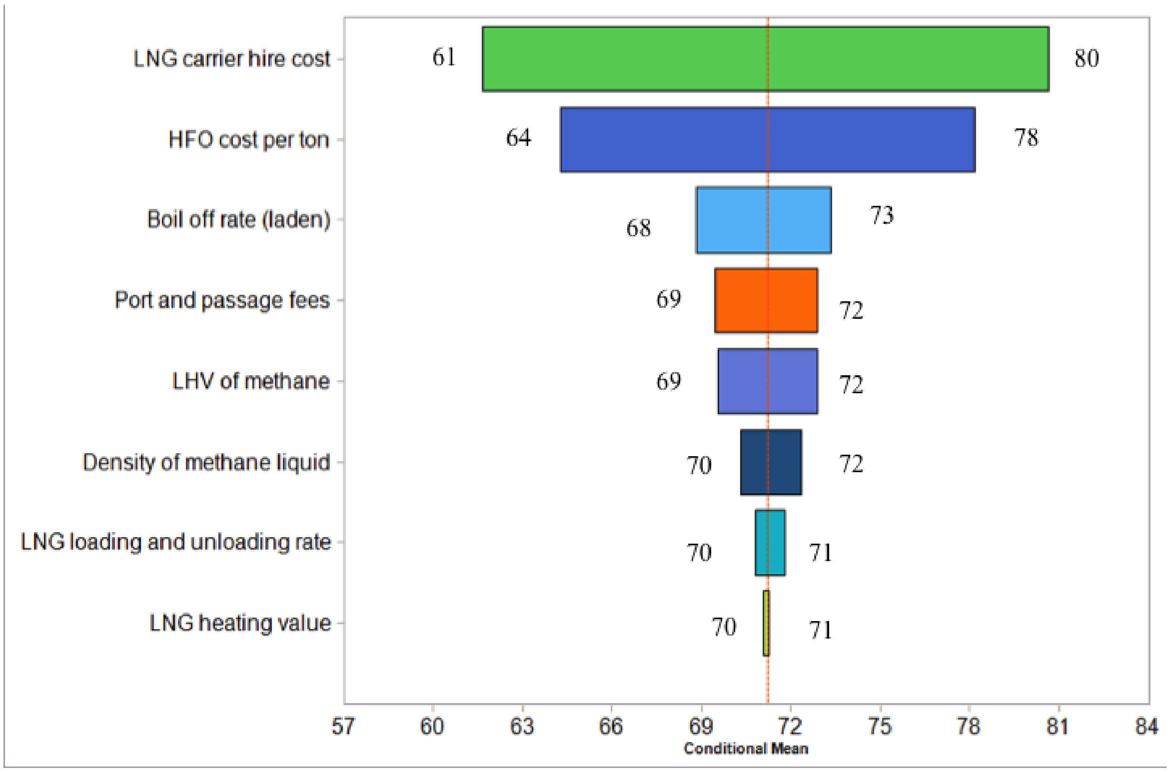

Figure 11: Sensitivity analysis for shipping costs (Japan) in scenario 1

The sensitivity of shipping cost to port and passage fees is almost equal in magnitude to the boil-off rate but opposite in nature. The density and lower heating value of methane do not influence the shipping cost as much as the other parameters do. However, an increase in their values definitely reduces shipping costs. The shipping cost is least sensitive to the loading and unloading rate at the LNG terminals. Increasing these rates decreases the hiring time of the LNG carriers and hence reduces shipping costs.

In this section, to identify the range of shipping costs in each of the five scenarios and for each of the LNG importing countries considered in this study, a Monte Carlo simulation is performed. First, all the key uncertain input variables are identified and then, for each of these variables, the maximum and minimum values are defined. The uncertain input variables with their expected ranges are presented in Table 5. After this, a random sampling is performed by using uncertain input variables to generate a range of outcomes with their occurrence probability measure.

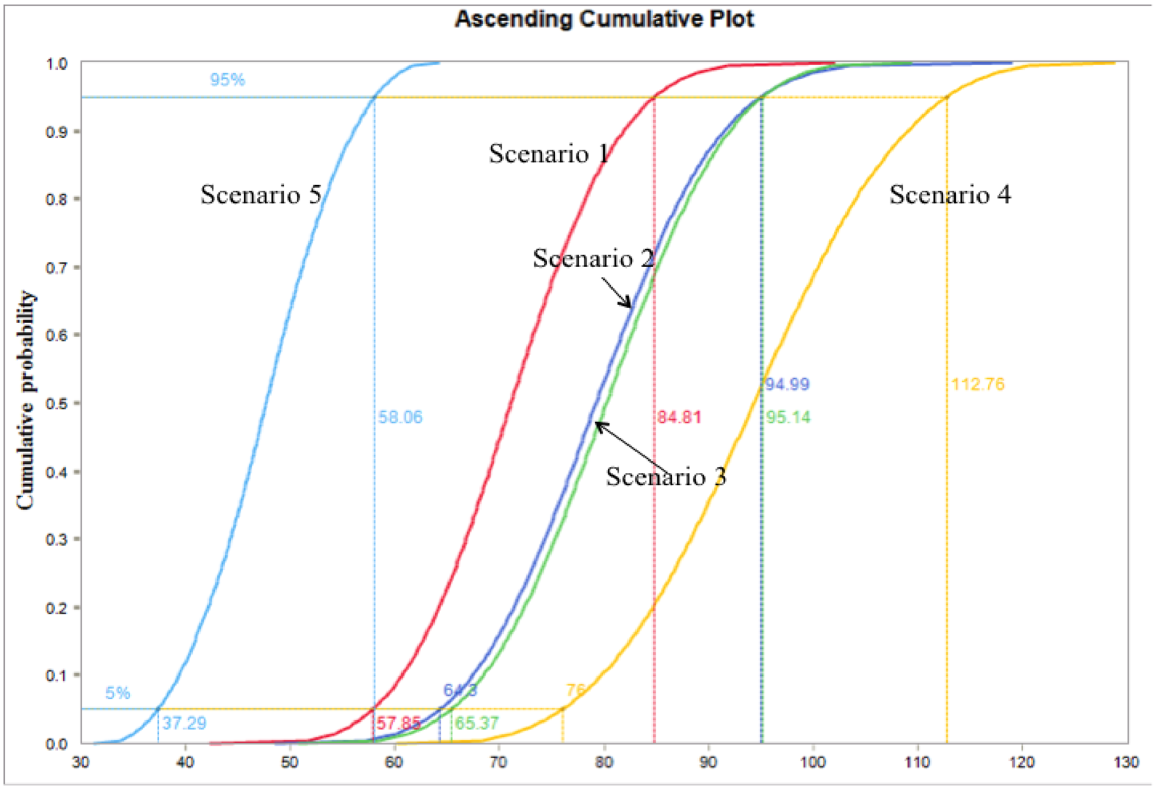

Figure 12: Ascending cumulative probability plot for shipping costs (cents/GJ) to Japan

Figure 12 presents the ascending cumulative probability plot for the shipping costs in each of the five scenarios for Japan. From the figure, it can be observed that there is a 90% probability that the shipping cost in scenario 1 will lie between 57 cents/GJ and 84 cents/GJ. For scenario 2, the range is from 64 cents/GJ to 95 cents/GJ. For scenarios 2 and 3, the ranges are almost identical. Similar inferences can be drawn for the remaining scenarios. From Figure 12, it can be observed that the 90% probability range is highest for scenario 4. This is mainly due to the broad range of marine diesel oil cost considered in this paper. For China and India, these ranges in different scenarios are given in Table 7.

Table 7: Range of shipping costs for China and India with 90% confidence in cents per gigajoule

Scenarios	China	India
Scenario 1	68-100	117-175
Scenario 2	76-113	131-198
Scenario 3	77-113	134-198
Scenario 4	90-135	157-236
Scenario 5	43-68	72-116

5. Conclusions

This paper discusses the cost of shipping one gigajoule of natural gas in liquefied form from proposed liquefaction facilities situated on the west coast of Canada to LNG re-gasification terminals in three Asia-Pacific countries (Japan, China, and India). Five scenarios encompassing various available propulsion systems for LNG carriers were developed and shipping cost estimates from the scenarios were compared. Calm water resistance for two different categories of LNG carriers was calculated and used to determine the propulsion power needed to the ship at a given speed and hence to select the most appropriate main engine. The techo-economic model developed in this paper estimated the shipping costs for Japan, which range from 51-95 U.S. cents/GJ depending on the type of propulsion system for an average transport distance of 7793 km. For China and India, the shipping costs range from 59-113 U.S. cents/GJ and 98-197 U.S. cents/GJ for an average transport distance of 9475 km and 17035 km, respectively. From the sensitivity analysis, it was found that the shipping costs are most sensitive to fluctuations in the cost of marine fuel oils and the per-day hiring cost of LNG carriers and least sensitive to loading and unloading rates at LNG terminals.

As discussed in the introduction, an LNG supply chain typically consists of four processes: gas production, gas processing, liquefaction, and shipping. A techno-economic model to quantify the cost of the first three processes in the LNG supply chain was developed earlier by the authors [7]. In the earlier paper, the authors discussed the total cost of producing and liquefying a unit of shale gas in Western Canada and the sensitivity of the cost to various economic parameters. The total product cost estimated by the authors was $7.8/GJ, if the gas supply source was Montney, and $9.1/GJ, if the gas supply source was Horn River. This cost includes the gas wellhead cost, the pipeline tariff, and the liquefaction cost. If the shipping costs, estimated in this study, are added, we get the total delivery cost of Canadian LNG to Asian countries. For Japan, the delivered cost of Canadian LNG ranges from $8.2/GJ to $10/GJ with a mean estimate of $9.15/GJ. Therefore, Canadian LNG projects require a minimum of $62/barrel in the central case assumptions, if an average 14.5% slope for Japanese contracts indexed on the Japanese Crude Cocktail Price (JCC) is assumed. Hence it is clear that LNG projects in Canada are very much susceptible to the oil prices in Japan. We can also compare the price of Canadian LNG in Japan to the price of LNG from other places like Indonesia and Malaysia. Indonesian LNG prices have changed dramatically over the past 5 years. average Indonesian LNG price was around $17/GJ in

2014 [56] and has since dropped to around $8.5/GJ [56]. Malaysian LNG prices have also fallen considerably.

In China there is a wide gap in the city gate prices of natural gas from different sources. Natural gas city gas prices in Shanghai range from $8/GJ for the domestics gas transported through China's West-Eeast pipeline to $13/GJ for Turkmenistan gas imports [57]. The delivered cost of Canadian LNG is in the middle of this range and hence imported LNG from Canada may offer a cheap alternative source of LNG for China at a time when Chinese policy makers are trying to diversify their LNG import mix.

Future work stemming from this research can include the study of more advanced LNG propulsion systems and the development of techno-economic models to determine optimal LNG carrier speed in the scenarios presented here.

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