

Manouchehrinia, Babak; Dong, Zuomin; Gulliver, T. Aaron

## Article

# Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada

Energy Reports

## Provided in Cooperation with:

Elsevier

*Suggested Citation:* Manouchehrinia, Babak; Dong, Zuomin; Gulliver, T. Aaron (2020) : Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 802-812, <https://doi.org/10.1016/j.egy.2020.03.016>

This Version is available at:

<https://hdl.handle.net/10419/244078>

### Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

### Terms of use:

*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*



<https://creativecommons.org/licenses/by-nc-nd/4.0/>



## Research paper

## Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada



Babak Manouchehrinia\*, Zuomin Dong, T. Aaron Gulliver

University of Victoria, BC, Canada

## ARTICLE INFO

## Article history:

Received 14 November 2019

Received in revised form 18 March 2020

Accepted 18 March 2020

Available online xxxx

## ABSTRACT

This paper examines the environmental impact of Natural Gas (NG) as a transportation fuel, particularly for marine transportation use. The aim is to provide a systematic evaluation of Greenhouse Gas (GHG) emissions in the upstream fuel supply chain of NG fuel in British Columbia (BC), Canada. The recent introduction of Liquefied Natural Gas (LNG) fuel for ferry operations in western Canada presents a major step towards the large-scale adoption of NG as a cleaner and lower-cost fuel. This makes a systematic approach for accurate Lifecycle Assessment (LCA) of GHG emissions for the NG/LNG fuel more important and urgent. An analysis using operation and fuel consumption data from vessels with different engine technologies and types of fuel shows that the diesel cycle NG engine will produce 2% less CO<sub>2e</sub> emissions in comparison to the low sulphur petroleum diesel engine, while other NG engine technologies, such as the lean-burn Otto cycle engine or dual-fuel gas engine, will result in 4% higher CO<sub>2e</sub> emissions. This study clears doubts on well-to-pump (WTP) NG emissions, supports the wide adoption of NG fuel and promotes further pump-to-propeller (PTP) emission improvements in marine propulsion.

© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

## 1. Introduction

Natural gas (NG) is a potential transition fuel towards green energy systems. It has a lower carbon emission per unit of energy compared to other fossil fuels such as oil or coal (Manne and Richels, 1990; Karion et al., 2013; Anon, 1999). In British Columbia (BC), Canada, NG is playing an increasingly significant role as a cleaner and more economical transportation fuel. Canada has abundant NG resources as the fourth-largest NG producer in the world. The marketable NG production in Canada was over 450 million cubic metres per day (M m<sup>3</sup>/d) in 2017, with BC and Alberta contributing 25% and 72% of the total production, respectively (Natural Resources Canada, 2018). The recently announced major investment in Liquefied Natural Gas (LNG) production facilities in BC by the provincial government will boost NG production in the province. In addition, improvements in drilling technology in recent years have resulted in more cost-effective techniques for the production of unconventional NG (BC Oil and Gas Commission, 2016), leading to increased Canadian production and lower fuel costs, likely with an improved NG fuel adoption rate that is above the global average.

Stricter environmental regulations imposed by the International Marine Organization (IMO) and increased world energy

demand (U.S. Energy Information Administration (EIA), 2019) have created an opportunity for increased NG use in the transportation sector, including marine applications (Balcombe et al., 2019; Feng et al., 2017). Most deep-sea shipping and a high percentage of coastal shipping operate on Heavy Fuel Oil (HFO). HFO is a residual product of crude oil and contains a wide range of contaminants such as sulphur, sodium, and ash that are particularly harmful to the environment and human health. Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) are traditional marine fuels known as marine distillates. These fuels have a lower concentration of sulphur compared to HFO. Table 1 shows the properties of different marine fuels (Thomson et al., 2015; Winnes and Fridell, 2009). Low Sulphur light Diesel Fuel (LSDF/DF) and MGO have less than 0.1% Sulphur in comparison to HFO and High Sulphur Light Diesel Fuel (HSDF).

In comparison to HFO and distillate fuels, NG is known as a cleaner fossil fuel to reduce SO<sub>x</sub>, NO<sub>x</sub>, and Particulate Matter (PM) (Sharafian et al., 2019). However, methane (CH<sub>4</sub>) is the primary component of NG and is a significant GHG. The radiative force of methane is 30 times greater than CO<sub>2</sub> over 100 years (Intergovernmental Panel on Climate Change (IPCC), 2014). Thus, the potential benefits of NG have been challenged considering upstream methane leakage (Karion et al., 2013; Brandt et al., 2014; Pétron et al., 2012; Howarth et al., 2011; Atherton et al., 2017; Alvarez et al., 2012; Johnson et al., 2017), as well as during low speed and low load operation of NG compression engines. High

\* Corresponding author.

E-mail address: [bmn14@uvic.ca](mailto:bmn14@uvic.ca) (B. Manouchehrinia).

**Table 1**  
Properties of different marine fuels.

Property	LSDF/DF	HSDF	HFO 180 (0.5% Sulphur)	HFO (1.6% Sulphur)	MGO	NG
Density (20 °C, kg/m <sup>3</sup> )	845	875	932	989 (@15 °C)	849 (@15 °C)	–
Sulphur content (%wt)	<0.1	3.09	0.5	1.6	0.03	0
Carbon content (%wt)	86.49	83.95	87.6	87.7	86.7	0
Hydrogen content (%wt)	13.44	12.48	12.5	10.4	13.4	0
Methane (CH <sub>4</sub> ) (%)	0	0	0	0	0	93.49
Ethane (C <sub>2</sub> H <sub>6</sub> ) (%)	0	0	0	0	0	4.71
Carbon Dioxide (CO <sub>2</sub> ) (%)	0	0	0	0	0	0.5
Nitrogen (N <sub>2</sub> ) (%)	–	–	–	0.46	<0.05	0.95

vent and leakage rates to the atmosphere between production wells and the point of combustion can significantly reduce the environmental benefits of NG.

The evolving and increasingly stricter environmental regulations enforced by IMO have led to changes in marine fuels and engine technologies globally (Tyrovala et al., 2017; Hyvättinen and Hildén, 2004). Recent IMO emission regulations limit the sulphur content of fuel to 0.10 percent by weight in the North America Emission Control Area (ECA) and below 0.5% globally (International Maritime Organization, 2010; International Maritime Organization (IMO), 2018). For small and medium-sized marine vessels, Ultra Low Sulphur Diesel (ULSD) fuel has been mandatory as of June 2012.

Assessment of the environmental impact of NG is a complex task, and there is a lack of reliable data to estimate the associated emissions due to uncertainties (Bouman et al., 2017). One uncertainty is the amount of fugitive gas emitted into the atmosphere during operation, leading to adjustments in the methane emissions reported by the U.S. Environmental Protection Agency (EPA). The estimated national average production leak rate in EPA reports has increased from 0.16% of production in 2010 to 1.36% in 2011 and 1.25% in 2012. This rate was increased to 1.36% in 2013 and then reduced to 1.33% in 2014 (U.S. Environmental Protection Agency (EPA), 2018; Cai et al., 2017). It is estimated that if more than 3.2% of the NG transported from wells to gas-fired power plants in the US leaks into the atmosphere, the environmental impact would be greater than the equivalent coal-fired plants (Alvarez et al., 2012).

This paper presents the first effort to systematically estimate GHG emissions in the upstream supply chain of NG in BC, Canada. BC is the second-largest producer of NG in Canada, and an accurate estimation of these emissions can improve the understanding of the NG upstream supply chain emissions in Canada. Similar technologies are used in Alberta, the largest NG producing province in Canada. The assessment covers all areas of the NG supply chain where there are GHG emissions, including fugitive, vented, flared and combustion emissions. Several scenarios are examined to estimate the emission rates. At present, the lifecycle GHG emissions of various transportation fuels are estimated using standard LCA models to assess the environmental impact of alternative fuel paths, including GREET (Greenhouse gas, Regulated Emissions, and Energy use in Transportation) developed and maintained by the Argonne National Laboratory (ANL) of the US Department of Energy (Argonne National Laboratory, 2017), and GHGenius (GHGenius, 2018) developed and maintained by Natural Resources of Canada (NRCan) with a primary focus on transportation fuels in Canada. Many transportation studies have employed these LCAs (Kasumu et al., 2018; Thomson et al., 2015; Johnson et al., 2017). However, neither incorporate detailed GHG emission data and operations from BC NG producers, and they do not include marine transportation specific considerations. For example, well completion emissions are flared in Canadian shale gas facilities and venting of unloaded liquids is not permitted in

conventional gas production operations in Canada, whereas it is common practice in the US. The LCA of marine transportation fuels in this work is called Well-to-Propeller (WTP) assessment and covers all stages of fuel production and usage from feedstock recovery (wells) to vessel propellers. To date, the WTP GHG emissions of LNG fuel for marine vessels based on actual fuel consumption has not yet been systematically evaluated, and this study fills this gap. In this work, units of grams of carbon dioxide released per megajoule of energy (gCO<sub>2e</sub>/MJ) are considered based on the IPCC Fifth Assessment Report (AR5). Further, we use the 100-year Global Warming Potential (GWP) of methane and nitrous oxide, which are 30 and 265 times greater than CO<sub>2</sub>, respectively.

## 2. Natural gas system analysis

The upstream GHG emissions depend on the geologic reserve formations and the extraction, transportation, and fuel processing methods employed. Identifying the fuel path is essential for an accurate assessment of GHG emissions in the upstream supply chain. In BC, there are five main NG production areas located mainly in the northeast of the province. Unconventional gas production accounts for 85% of the production in BC. The largest NG production operations in BC are in the Montney area, covering 130,000 km<sup>2</sup> between BC and Alberta. This super condensate area contributed 73% of the total BC NG production in 2016 (BC Oil and Gas Commission, 2016). With current drilling in Montney, this percentage is expected to increase. Horizontal drilling and multi-stage hydraulic fracturing are common extraction practices in this area. Six main pipeline companies transport the extracted NG. Enbridge, formerly known as Spectra, has the largest share of the pipeline system in BC and transports NG from the northeast to the lower mainland as shown in Fig. 1. FortisBC is the second largest transporter and distributes NG to the lower mainland and Vancouver Island (BC Oil and Gas Commission, 2016). The pipeline length from the Montney area to Vancouver Island is approximately 1,300 km.

### 2.1. Vessel description

An accurate evaluation of energy efficiency and GHG emissions of marine vessels must be based on the actual fuel consumption during vessel operation. For this purpose, the fuel consumption of two vessels on the same route is used. One of these vessels operates on diesel fuel while the other operates on LNG fuel. The approximate route is shown in Fig. 2. The vessels travel several times per day between Vancouver Island and Vancouver terminals to transfer goods and passengers.

### 2.2. LNG upstream CO<sub>2e</sub>

The upstream NG supply chain is divided into extraction and processing, transportation, conversion and storage, and distribution/bunkering, as shown in Fig. 3. With this division, the

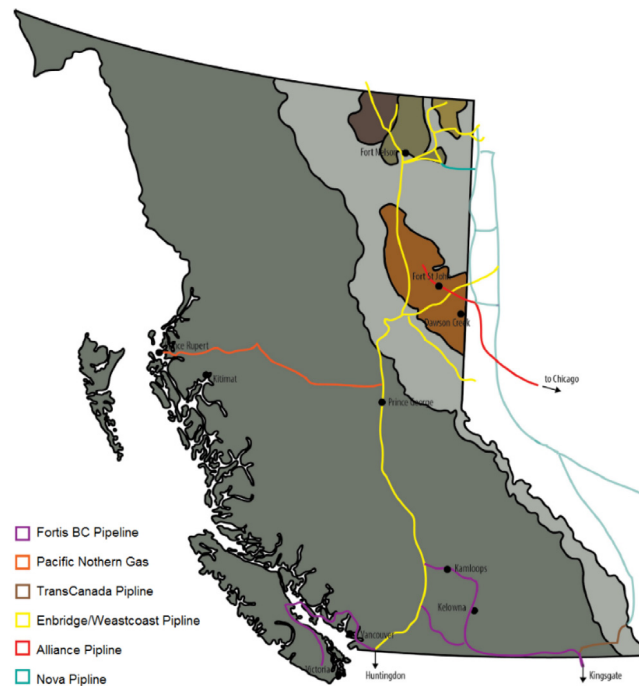


Fig. 1. The natural gas pipeline system in BC (BC Oil and Gas Commission, 2016).

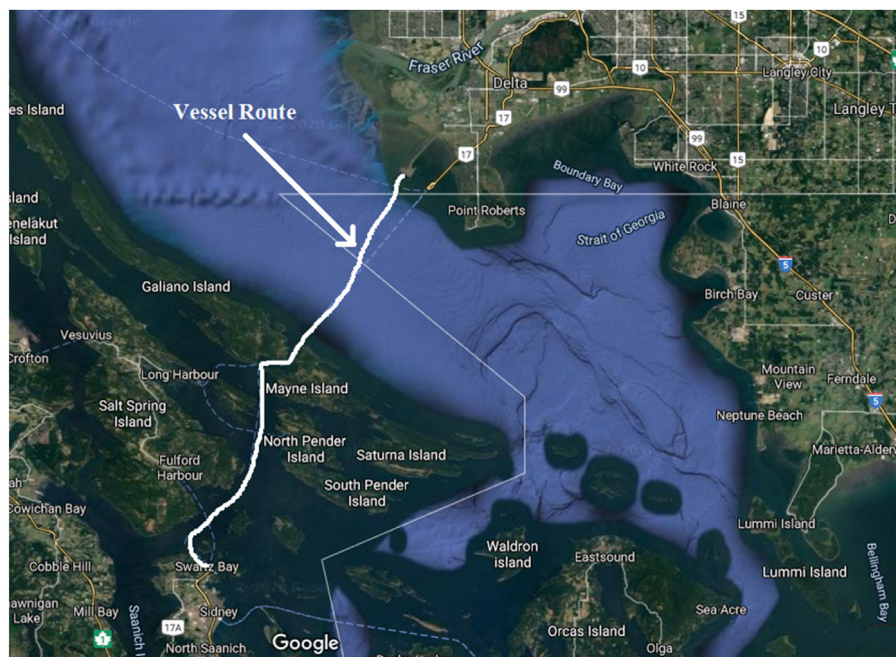


Fig. 2. The approximate vessel route.

bunkering stage is included in the upstream chain rather than in the downstream chain, as in the related literature, to better characterize downstream consumption emission sources.

A comprehensive analysis of GHG emissions needs to consider all emissions produced during the fuel production stages and use lifecycle, including fuel consumption, flaring, venting and fugitive gases. In addition to the BC GHG emission data published in BC Oil and Gas Commission (2016), British Columbia (2015), forty-seven oil and gas companies in BC were interviewed for this study to have more accurate GHG emission estimates for these com-

panies. The total upstream NG GHG emissions were calculated by adding the carbon dioxide equivalent ( $\text{CO}_2\text{e}$ ) emissions from each of the four segments shown in Fig. 3, resulting in estimated total GHG emissions between 9.8 to 10.4  $\text{gCO}_2\text{e}/\text{MJ}$ . Details of this analysis for each segment are given below. Note that the BC emission inventory includes only facilities over the provincial reporting threshold of 10,000 tonnes of  $\text{CO}_2\text{e}$  per year, so smaller facilities are not considered in this study. This will not have a significant effect on the results obtained given the low number of facilities with emission levels below this threshold.

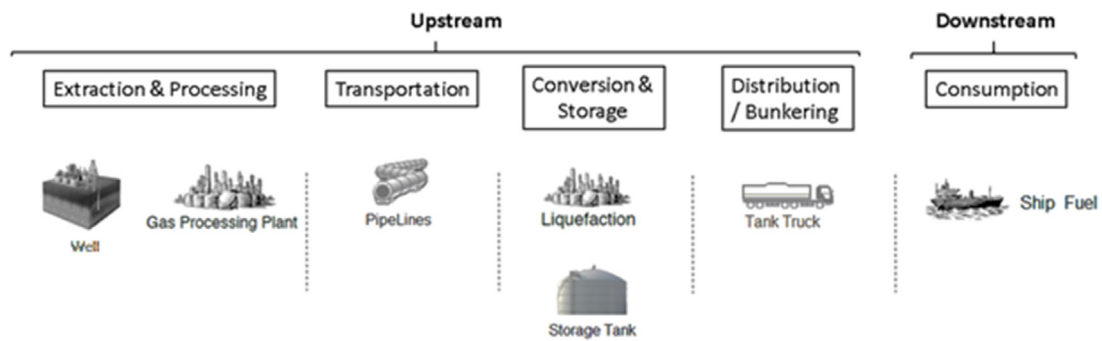


Fig. 3. The natural gas supply chain.

### 2.2.1. Extraction and processing

Horizontal drilling and multi-stage hydraulic fracturing are common methods of gas extraction in Montney. Recent LCA studies have suggested that unconventional gas extraction methods result in higher emissions than conventional methods due to the emissions released during well completion (Hultman et al., 2011; Stephenson et al., 2011; Jiang et al., 2011). A study found that shale gas has 1.8% to 2.4% higher lifecycle GHG emissions than conventional gas, mainly due to higher methane release during well completion (Stephenson et al., 2011; El-Houjeiri et al., 2019). Fig. 4 illustrates the CO<sub>2e</sub> emissions during extraction and processing for each segment in BC, showing that fuel combustion during operation contributes about 56% of the total emissions. The second and third highest emissions are related to venting CO<sub>2e</sub> from fossil fuels and methane venting, accounting for about 16% and 12% of the total emissions, respectively.

The BC GHG emission repository (BC Oil and Gas Commission, 2016) was used to determine company emissions during NG extraction and processing and the results are shown in Table 2. The total emissions for each company were calculated by adding the emissions during each stage. For example, the emissions for the Alliance Pipeline Company are calculated by summing the following sources:

$$\text{Stationary Combustion} + \text{Industrial Process} + \text{Flaring} + \text{Venting} + \text{Fugitive} = \text{Total}$$

$$9,098 + 0 + 0 + 1,632 + 1,214 = 12,508 \text{ tonnes CO}_2\text{e}$$

The total extraction and processing emissions from all companies are then 8,972,566 tonnes of CO<sub>2e</sub>. The total BC NG production in 2015 was 37,873,364 thousand cubic metres (Government of British Columbia, 2015). Based on this information and the conversion factors given in Appendix, the total emissions for extraction and processing is estimated to be between 5.53 and 6.10 gCO<sub>2e</sub>/MJ. A recent study using mobile collection of methane emissions data from oil and gas infrastructure estimated that the Montney area contributes 111,800 tonnes of methane per year to the atmosphere, about 43% higher than the value given in the BC emission inventory used in this analysis (Atherton et al., 2017). This increases the estimated extraction and processing emissions to between 6.40 and 6.82 gCO<sub>2e</sub>/MJ. In another study using airborne measurements of oil and gas infrastructure in the Red Deer region of Alberta, Canada, methane emissions were estimated to be between 25% and 50% greater than government estimates (Johnson et al., 2017).

### 2.2.2. Pipeline transportation

The emissions from pipelines are mainly due to the burning of fossil fuels at the compressor stations and methane leaks. Compressor methane losses account for about 46% of the total methane emissions in the stations, while compressor-packing vents contribute about 17% of the total compressor methane

losses (International Maritime Organization (IMO), 2018). The remaining emissions are due to pneumatic actuators and controllers, engine crankcases, wet seal vents, and slop tanks. Stricter maintenance practices and more energy-efficient compressors can reduce pipeline emissions. The emissions of the five main pipeline companies in BC, including FortisBC, Pacific Northern, TransCanada, Enbridge, and Alliance, are considered in this study, and the total emissions were calculated by adding the pipeline emissions from these companies given in Table 2. The emission contribution of each company is shown in Fig. 5. The total emissions related to NG management, pipelines, and transportation are estimated to be 1.31 gCO<sub>2e</sub>/MJ. NOVA Gas Transmission Ltd. has a short pipeline with limited activity in BC and so is not included. The total pipeline emissions are 13% lower than that obtained for Canadian NG pipeline emissions (1.512 gCO<sub>2e</sub>/MJ) using GHGenius (GHGenius, 2018), partially due to stricter environmental regulation in BC and newer facilities (Anon, 2018).

### 2.2.3. Conversion and storage

The energy density of NG is less than that of diesel fuel, so a larger fuel tank is required for vessels with NG engines. Natural gas is stored in liquid form at a temperature of approximately –160 °C which reduces the volume by a factor of 600 (Usama et al., 2011). Any impurities and contaminants are removed from the gas before liquefaction, which is performed using coolant chilled by a large refrigerator. LNG is a clear, colourless, and safe liquid that is easy to store and transport. It is kept in insulated tanks during transportation and storage until it is ready for loading onto a ship or vehicle. There are five NG liquefaction processes in use today, propane pre-cooled mixed refrigerant (C3MR), AP-X large train cycle, optimized cascade, Shell double-mixed refrigerant (DMR), and mixed fluid cascade (Usama et al., 2011), and each of these processes have different efficiencies and production capabilities.

Emissions and energy use at NG liquefaction facilities are a function of the leakage rate, type of prime mover (electric motor or combustion engine), and facility efficiency. Unfortunately, little data is available on the emissions and energy requirements of the liquefaction processes and facilities, so further study is needed to obtain more accurate estimates of these emissions. LCAs such as GREET and GHGenius combine liquefaction with pipeline transportation emissions giving 3.38 gCO<sub>2e</sub>/MJ. Different emission factors for different paths are given in Table 3. In our study, an average emission factor of 5.35 to 8.2 gCO<sub>2e</sub>/MJ is used for the liquefaction process.

### 2.2.4. Bunkering

Four different types of LNG bunkering systems are used, fixed shore facilities, portable tank transfer, tanker trucks, and LNG barge carriers, as shown in Fig. 6. LNG bunkering systems depend on many factors such as berth characteristics (turns, depth,

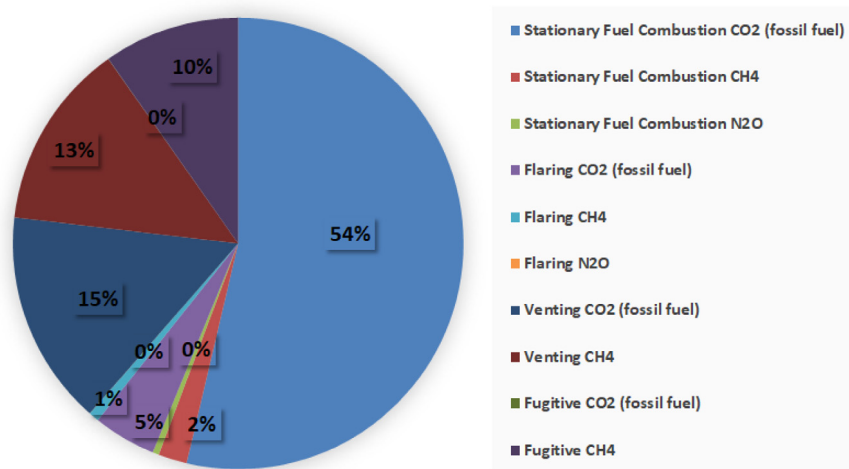


Fig. 4. Extraction and processing of CO<sub>2e</sub> per segment.

Table 2

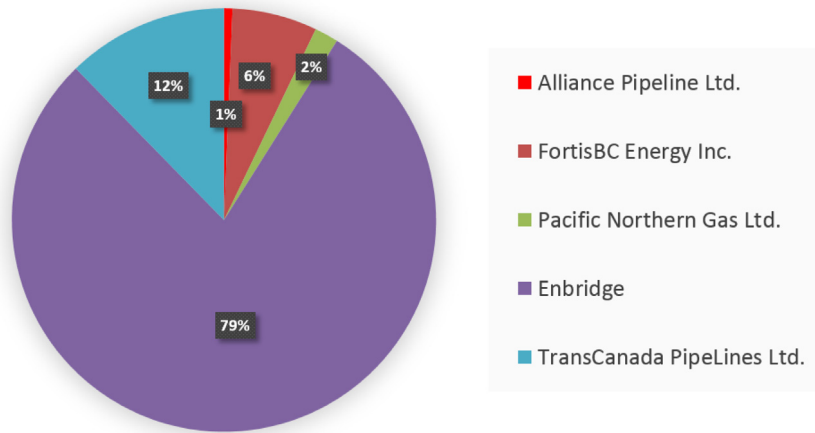
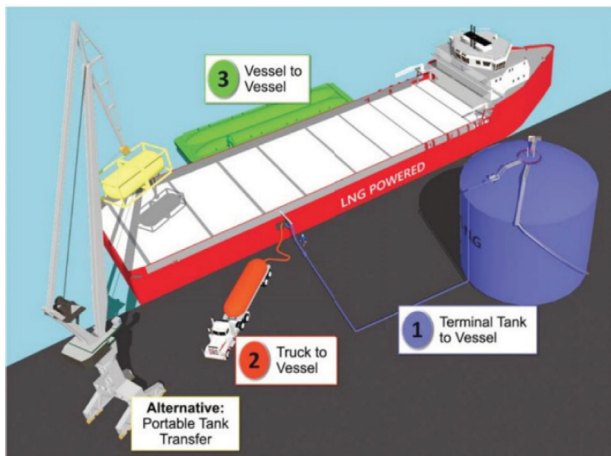
BC company GHG emissions in 2015.

Company	Type of company	Pipeline GHG (tonnes CO <sub>2e</sub> )	Emissions (tonnes CO <sub>2e</sub> )
Aitken Creek Gas Storage ULC	NG	0	47,070
Alliance Pipeline Ltd.	NG	12,508	0
AltaGas Ltd.	NG	0	85,157
ARC Resources	Oil	0	0
Black Swan Energy	NG	0	47,416
Bonavista Energy Corporation	NG	0	67,919
British Columbia Hydro and Power Authority	N/A	0	0
Canadian Natural Resources Limited	NG	0	1,264,479
Canbriam Energy Inc.	NG	0	111,213
Cequence Energy Ltd.	NG	0	11,325
Chevron Canada Resources	NG	0	39,596
Chinook Energy Inc.	NG/Oil	0	53,379
ConocoPhillips Canada Resources Corp.	NG	0	331,118
Crew Energy Inc.	NG	0	92,850
Devon Canada Corporation	NG	0	5,539
Direct Energy Marketing Ltd.	Unknown	0	111,827
Encana Corporation	NG	0	900,761
Endurance Energy Ltd.	Unknown	0	602,952
Enerplus Corporation	Unknown	0	43,295
EOG Canada Oil & Gas Inc.	Unknown	0	34,253
FortisBC Energy Inc.	Transportation	136,382	0
Harvest Operations Corp.	Oil	0	0
Husky Oil Operations Limited	NG	0	114,045
Imperial Oil Resources Ltd.	Unknown	0	0
Kelt Exploration	Unknown	0	0
Keyera Corporation	NG	0	40,091
Lightstream Resources Ltd.	Unknown	0	9,953
Lone Pine Resources Canada Ltd.	NG	0	6,748
Murphy Oil Company Ltd.	NG	0	177,411
Nexen Energy ULC.	NG	0	92,089
Pacific Northern Gas Ltd.	Transportation	39,019	0
Painted Pony Petroleum Ltd.	NG	0	46,566
Pengrowth Energy Corporation	NG	0	34,732
Penn West Petroleum Ltd.	NG/Oil	0	76,047
Polar Star Canadian Oil and Gas Inc.	Unknown	0	23,815
Progress Energy Canada Ltd.	NG	0	979,105
Quicksilver Resources Canada Inc.	Unknown	0	15,151
Ramshorn Canada	NG	0	23,157
Shell Canada Limited	NG	0	362,850
Spectra Energy Midstream Corporation	NG	0	250,873
Spectra Energy Transmission	Transportation	1,500,642	2,800,790
Suncor Energy Inc.	NG	0	20,937
Taqa North Ltd.	NG/Oil	0	48,058
Tourmaline Oil Corp.	Unknown	0	0
TransCanada PipeLines Ltd.	Transportation	234,513	0
Veresen Midstream General Partner Inc.	Oil	0	0
Whitecap Resources Inc.	Oil	0	0
<b>Total</b>		<b>1,923,063</b>	<b>8,972,566</b>

**Table 3**

NG liquefaction emission factors for different paths (Taglia and Rossi, 2009; Roman-White et al., 2019).

	Egypt–Italy	Qatar–Italy	Trinidad–Spain	US–Netherlands	Algeria–Netherlands	US–China	Australia–Japan
NG liquefaction (gCO <sub>2e</sub> /MJ)	5.141	4.980	5.944	8.20	8.11	8.34	8.15

**Fig. 5.** BC Pipeline company emission contributions.**Fig. 6.** The four different bunkering methods (Canadian Natural Gas Vehicle Alliance, 2017).

and hazards), vessel design, fuel demands, and availability. LNG bunkering using tanker trucks is the most favourable method in terms of flexibility and capital investment. Tanker truck bunkering is the current bunkering method employed by BC Ferries. The main reason for not using other methods is high tidal deviations on the west coast of Canada and limited berthing space.

The emissions from tanker trucks used in transporting LNG to vessels are relatively small in comparison to the overall upstream emissions and are thus ignored. However, methane leakage during bunkering is significant and so must be included. There is a lack of methane emission data for marine vessel bunkering, so the available LNG station leakage data for LNG powered ground transportation obtained from Cai et al. (2017), Clark et al. (2017) and given in Table 4 are used in this work for marine vessels. LNG delivery, continuous station, fuel tank, and fuel nozzle leakage will occur during truck bunkering, so the total bunkering emissions are estimated to be 0.89 gCO<sub>2e</sub>/MJ.

### 2.3. LNG downstream CO<sub>2e</sub>

NG engines are the main emission contributors in downstream. Therefore, accurate estimation of engine emissions is essential for precise lifecycle assessment. An NG engine emits less CO<sub>2</sub> than a diesel engine (Thomson et al., 2015), mainly due to the gas composition with lower hydrocarbons. Although this implies a lower environmental impact, the potential benefit can be compromised by methane leakage or the release of unburned methane from the engine. The level of emissions and methane leakage depend on the age and technology of the engine.

NG engines can be classified into three basic types: spark-ignited, dual-fuel, and direct-injection. A spark-ignited engine uses a spark plug to ignite a mixture of NG and air. This type of engine has high thermal efficiency due to the high specific heats for lean fuel-air mixtures (Manivannan et al., 2003). These engines have an average efficiency of about 42% (Stenersen and Thonstad, 2017) and meet IMO Tier III standards, but are sensitive to gas quality and methane slip. Dual-fuel engines operate on NG and/or a secondary fuel such as a distillate fuel. These engines use a pilot fuel to start the combustion process, and this fuel is less than 5% of the total consumed with modern technology. A dual-fuel engine is an attractive option for shipowners as it provides flexibility in fuel type, cost, and availability. Dual-fuel engines also meet IMO Tier III but are sensitive to gas quality and methane slip. A direct-injection engine operates on a diesel cycle with high pressure. Natural gas is injected at the top of the compression stroke. The modifications required to convert a regular diesel engine to a direct-injection NG engine are minimal, thus providing great potential for retrofitting existing diesel engines to NG direct-injection. However, direct-injection engines do not meet the IMO Tier III standard. Recently produced direct-injection engines use advanced combustion control technologies which have resulted in a 10% performance improvement over traditional direct-injection engines (Iwamoto et al., 1997). A comprehensive study of marine NG engines is given in Žaglinskis et al. (2018).

The emissions and fuel consumption of diesel engines depend on the way these engines are used in a hybrid-electric propulsion system. The architecture of the powertrain system is one of the key factors determining the power demand from the engine. Four types of powertrain architectures for marine vessels are shown in Fig. 7. Fig. 7A illustrates a conventional powertrain

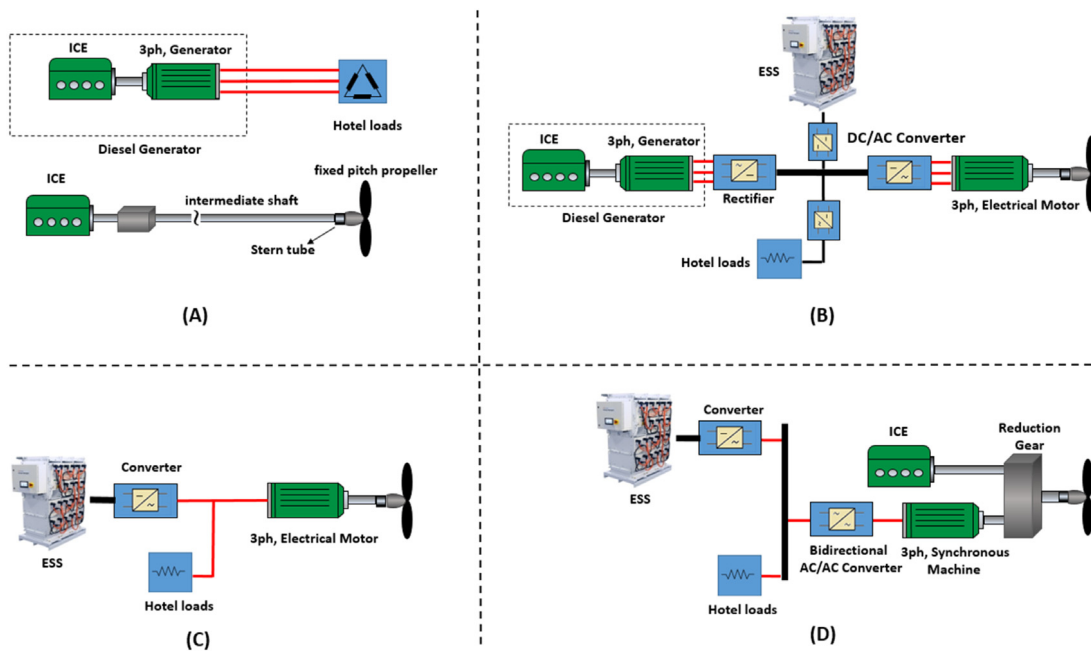


Fig. 7. Four common powertrain architectures.

**Table 4**  
LNG station methane leakage ( $\text{CH}_4$  g/MJ).

	LNG delivery	Manual vent	Boil off gas from the tank	Continuous station	Fuel tank	Fuel nozzle
LNG station ( $\text{CH}_4$ g/MJ)	0.015	0.013	0.011	0.002	0.011	0.002

system in which the diesel engine is directly connected to the propeller via a speed reduction gearbox. The engine provides all the propulsion power required by the vessel. In the series hybrid-electric powertrain shown in Fig. 7B, the engine is coupled to a generator that generates electricity, and an electric motor is coupled to the propeller with speed adjusted using a variable frequency drive. Multiple generators and motors can be used to provide sufficient propulsion power. An electric Energy Storage System (ESS) provides additional power for propulsion when needed and absorbs excess engine power at low propulsion loads (Manouchehrinia et al., 2018). This approach allows the engine to operate in its most efficient speed and torque output zones, and a series hybrid-electric powertrain that disconnects the engines from the propellers can better serve vessels with dynamically varying power loads such as tugboats. In the parallel hybrid-electric powertrain architecture shown in Fig. 7C, the engine and electric motor are both connected to the propeller through mechanical links, and the electric motor can operate either as a motor or a generator. A bidirectional converter provides power from the bus-bar to the motor/generator, and an electric ESS provides or stores energy. This powertrain system allows the engine size to be reduced to an optimal value. A parallel hybrid-electric powertrain architecture is suitable for vessels dominated by static propulsion loads, such as ferries sailing on calm water, to avoid mechanical-electric-mechanical energy conversion losses.

In a battery-electric or pure electric powertrain option, as shown in Fig. 7D, the battery ESS is the only source of energy to meet the propulsion needs of the vessel, similar to in Battery Electric Vehicles (BEV). In this system, the battery ESS is coupled to a DC/DC converter to provide power for the electric motor(s). For small and short-haul vessels, this design offers high energy efficiency, low noise, and good reliability, but clean electric power and long battery life are essential for this architecture to be beneficial. Factors such as limited travelling range, high battery cost, bulky and expensive fast-charging stations, and the cost of

expanding existing electrical grids have restricted the adoption of pure electric vehicles and vessels.

In this work, engine emission factors are obtained using the Total Energy and Environmental Analysis for Marine Systems (TEAMS) model (The Total Energy and Emissions Analysis in Marine Systems (TEAMS) model, 2018) and from Corbett et al. (2014), Sharafian et al. (2019), Thomson et al. (2015), and are given in Table 5. The fuel consumption of a new LNG powered vessel and a diesel fuel vessel of similar size operating on the same route was obtained using vessel fuel logs. These values were used to calculate the emissions of different engine technologies and the results are given in Table 6.

### 3. Results and discussion

#### 3.1. Total fuel-cycle emissions results

The total well-to-propeller  $\text{CO}_2\text{e}$  emissions per vessel crossing for three scenarios and four different types of engines for the NG pathway in BC were calculated, and the results are given in Table 7.

Scenario 1 represents the GHG analysis without any changes in the emission values obtained in the previous sections. Scenario 2 includes an additional 43% in methane leakage during extraction and processing of NG according to the approach recommended in Winnes and Fridell (2009), and Scenario 3 represents the worst case which is the 43% increase in methane leakage during extraction and processing and  $6.9 \text{ gCH}_4/\text{kWh}$  of leakage during engine combustion (Sharafian et al., 2019). The total  $\text{CO}_2\text{e}$  was obtained using the emissions produced at each stage of the fuel pathway based on the energy consumed in each crossing. The upstream  $\text{CO}_2\text{e}$  represents the emissions from the extraction, processing, transportation, conversion, and distribution of the NG fuel, and the downstream  $\text{CO}_2\text{e}$  includes emissions from the main and auxiliary engines of the marine vessel.



**Table 5**

Engine emission factors in grams per Megajoule of fuel burned (Corbett et al., 2014; Sharafian et al., 2019; Thomson et al., 2015).

	Lean-burn Otto cycle engine	Dual-fuel gas engine (gas mode)	Diesel cycle gas engine	Low sulphur petroleum diesel engine
NO <sub>x</sub>	264	264	1583	1846
PM <sub>10</sub>	5	13	13	58
SO <sub>x</sub>	0.269	0.269	0.269	9.862
CH <sub>4</sub>	660	660	91.4	4.5
N <sub>2</sub> O	2	2	2	2
CO <sub>2</sub>	58,532	58,532	58,532	77,219

**Table 6**

Vessel emissions per round trip (kg).

Fuel type	NO <sub>x</sub>	PM <sub>10</sub>	SO <sub>x</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CO <sub>2e</sub> <sup>a</sup>
Lean-burn Otto cycle engine	21.39	0.41	0.02	53.49	0.16	4743	6413
Dual-fuel gas engine (gas mode)	21	1.05	0.02	53.49	0.16	4743	6413
Diesel cycle gas engine	128	1.05	0.80	7.41	0.16	6258	6653
Low sulphur petroleum diesel engine	150	4.70	0.80	0.36	0.16	6258	6467

<sup>a</sup>CO<sub>2e</sub> is based on three main gasses: CH<sub>4</sub>, N<sub>2</sub>O, CO<sub>2</sub>.**Table 7**Total well to propeller CO<sub>2e</sub> per crossing for three scenarios.

	Fuel type	Downstream CO <sub>2e</sub> (kg/crossing)	Upstream CO <sub>2e</sub> (kg/crossing)		Total CO <sub>2e</sub> (kg/crossing)	
			Lower bound	Higher bound	Lower bound	Higher bound
Scenario 1	Lean-burn Otto cycle engine	6391	1109	1401	7500	7792
	Dual-fuel gas engine (gas mode)	6391	1109	1401	7500	7792
	Diesel cycle gas engine	6523	1109	1401	7632	7924
	Low sulphur petroleum diesel engine	6312	1882	1882	8193	8193
Scenario 2	Lean-burn Otto cycle engine	6391	1185	1463	7575	7854
	Dual-fuel gas engine (gas mode)	6391	1185	1463	7575	7854
	Diesel cycle gas engine	6523	1185	1463	7707	7986
	Low sulphur petroleum diesel engine	6312	1882	1882	8193	8193
Scenario 3	Lean-burn Otto cycle engine	7023	1185	1463	8207	8486
	Dual-fuel gas engine (gas mode)	7023	1185	1463	8207	8486
	Diesel cycle gas engine	6586	1185	1463	7770	8049
	Low sulphur petroleum diesel engine	6312	1882	1882	8193	8193

The upstream fuel emissions for the low sulphur petroleum diesel engine were obtained using the default setup for marine diesel fuel in GHGenius 5.0 (GHGenius, 2018). The total upstream CO<sub>2e</sub> of NG in BC is calculated to be between 9.8 and 10.38 gCO<sub>2e</sub>/MJ. There is broad agreement between these results and those in Taglia and Rossi (2009) for European gas import GHG emissions.

For all three scenarios, the largest contributor to emissions is the marine engine. Improvements in NG engine and propulsion system design and efficiency will thus have a major effect on total emissions. In the first scenario with a low sulphur petroleum diesel engine, downstream emissions account for 77% of the total emissions, and for LNG fuel engines account for 82% of the total emissions. The Lean-burn Otto cycle engine and Dual-fuel gas engine (gas mode) result in a 5% and diesel cycle gas engine in a 3% reduction in total CO<sub>2e</sub> per round trip of the vessel. In the second scenario, 43% methane leakage during extraction and processing resulted in a 4% increase in upstream emission. The LNG fuel engines still have lower overall CO<sub>2e</sub> (3% less) than the low sulphur petroleum diesel engine. In the third scenario, downstream and upstream emissions increased by 10% and 4%, respectively. The lean-burn Otto cycle engine and the dual-fuel gas engine (gas mode) have 4% higher total CO<sub>2e</sub> and the diesel cycle gas engine still has 2% lower emissions in comparison to the low sulphur petroleum diesel engine. This is mainly due to the lower methane slip of the diesel cycle gas engine.

### 3.2. Air quality comparison

The upstream and downstream emissions for the three main gases are now examined.

Table 8 presents the upstream and downstream emissions per vessel crossing based on the actual fuel consumption of the vessel. The downstream emissions data is given based on the value calculated for scenario one. The CH<sub>4</sub> and CO<sub>2</sub> emissions mainly come from the downstream and engine operation. The methane emissions depend on the engine technology employed. For instance, the CH<sub>4</sub> emissions for a lean-burn Otto cycle engine and dual-fuel gas engine in the downstream are significantly higher than in the upstream, while for a diesel cycle gas engine, the upstream emissions are slightly higher than the downstream emissions. A significant portion of the emitted NO<sub>x</sub> comes from the downstream engine combustion, and this depends on the operating temperature of the engine. Higher cylinder temperatures produce greater NO<sub>x</sub> emissions. For this reason, a diesel engine with a high operating temperature produces more NO<sub>x</sub> emissions than an equivalent Otto cycle engine. The use of NG fuel can also reduce sulphur oxide (SO<sub>x</sub>) emissions by 99% due to the very low NG sulphur content.

### 3.3. Discussion

The results in this study demonstrate the advantages of LNG as a marine fuel compared to diesel fuel. The use of other fuel pathways and bunkering methods may lead to different results. For example, the upstream CO<sub>2e</sub> or GHG emissions with LNG fuel in the first scenario can vary by about 6% depending on the pathways and bunkering methods, ranging from a low of 9.81 gCO<sub>2e</sub>/MJ to a high of 10.38 gCO<sub>2e</sub>/MJ. The total LNG fuel upstream emissions in BC is about 55% lower than the default value given by the GHGenius software (22.01 gCO<sub>2e</sub>/MJ) for marine diesel fuel. For the second scenario with 43% additional methane leakage,

**Table 8**  
Total fuel cycle emissions in kg per round trip.

	Gases	Lean-burn Otto cycle engine	Dual-fuel gas engine (gas mode)	Diesel cycle gas engine	Low sulphur petroleum diesel engine
Downstream	CH <sub>4</sub>	53.49	53.5	7	0.36
	N <sub>2</sub> O	0.16	0.16	0.16	0.16
	CO <sub>2</sub>	4743	4743	6258	6258
	CO <sub>2e</sub>	6391	6391	6523	6312
Upstream	CH <sub>4</sub>		5.2		15.39
	N <sub>2</sub> O		0.010		0.019
	CO <sub>2</sub>		396		910
	CO <sub>2e</sub>		556		1376
Total	CH <sub>4</sub>	59	53	7	16
	N <sub>2</sub>	0.17	0.16	0.16	0.16
	CO <sub>2</sub>	5139	4743	6258	7167
	CO <sub>2e</sub>	6946	6391	6523	7688

LNG is still a better option with 50% lower total upstream emissions compared to marine diesel. For the third scenario, the high methane slip from downstream engine operations can offset the environmental benefits of NG as a marine fuel for the lean-burn Otto cycle engine and dual-fuel gas engine. It is thus important to develop advanced technology to minimize methane slip. Several engine manufacturers have recently reported improvements that lower methane slip during combustion (Rolls-Royce Marine, 2012). Further, recent studies (Stenersen and Thonstad, 2017; Sommer et al., 2019) indicate 2.3% to 5.0% higher methane slip from NG engine propulsion operations, indicating that the third scenario may be more realistic despite the improvements made by engine manufacturers to reduce methane slip. The research recently completed by our Clean Transportation Research team has introduced an effective way to reduce methane slip during propulsion operation by integrating an NG-diesel dual-fuel engine with hybrid-electric propulsion and globally optimal control, considering both fuel efficiency and HC/CO/NO<sub>x</sub> emissions (Feng and Dong, 2019). This provides a new direction for developing cleaner NG propulsion technology.

In the upstream, the majority of emissions (87%) come from NG extraction and processing and liquefaction stages. The results in Atherton et al. (2017) indicate that old NG extraction and processing infrastructure are more prone to leaks in comparison to younger wells. Using low-bleed devices to reduce fugitive methane from pneumatic valve operation can reduce emissions in extraction and processing. The NG emission lifecycle can also be improved by controlling direct methane leaks from fuel unloading operations during LNG delivery and bunkering.

Another important environmental impact of NG fuel besides methane leakage and emission is water consumption during the process of hydraulic fracturing, also known as fracking, in which a large quantity of pressured fluid is used to create fractures in rocks. More than 90% of the fluid is water and the rest are proppants and chemical additives (U.S. Energy Information Administration, 2016). An analysis of water consumption and wastewater treatment for NG extraction is needed to accurately evaluate the impact and sustainability of NG as a marine fuel.

#### 4. Conclusion

This paper presented an assessment of the lifecycle environmental impact of NG as a marine fuel for BC, Canada, using data from NG producers and suppliers in the province. Several scenarios were considered in evaluating the resulting emissions for different engine technologies. The results obtained indicate that NG is a desirable marine fuel in BC only if a diesel cycle gas engine or advanced clean propulsion technology is used, and methane slip from the engine is limited to 0.111 gCH<sub>4</sub>/MJ. The diesel cycle gas engine generates 2% and 6% less CO<sub>2e</sub> emission

in comparison to the low sulphur petroleum diesel engine and lean-burn Otto cycle engine or dual-fuel gas engine (gas mode), respectively. NG fuel can reduce NO<sub>x</sub> and SO<sub>x</sub> emissions from vessels by 86% and 97% for a lean-burn Otto cycle engine and a dual-fuel gas engine (gas mode), respectively, which makes them suitable candidates for vessel retrofit to meet IMO Tier III restrictions.

In general, the results obtained suggest that LNG fuel for diesel cycle gas engines can reduce overall emissions in BC. This is because BC has strict environmental regulations, relatively new NG infrastructures and the majority (more than 97%) of the electricity used in the NG pathway comes from renewable energy sources such as hydro. A careful investigation of other paths is required to evaluate the suitability of NG as a fuel. The calculated equivalent GHG in this paper contains some uncertainties which show the necessity of further investigation in this area. If NG fuel is considered as a bridge to future all-electric powered vessels, then it must be used carefully.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgements

The authors would like to thank members of the University of Victoria Green Transportation Team, Seaspans and BC Ferries for valuable discussions and assistance, particularly Greg Peterson and Harly Penner, for useful advice. Special thanks to Don D'Souza from the Ministry of Environment and Cathy Mou from the Ministry of Natural Gas Development of British Columbia for their assistance in obtaining GHG emissions and facilities data. Financial support from the Dennis and Phyllis Washington Foundation, Canada and Seaspans and the Natural Science and Engineering Research Council of Canada are gratefully acknowledged.

#### Appendix. Units and conversion factors

See Table A.1

#### References

- Alvarez, R.A., Pacala, S.W., Winebrake, J.J., Chameides, W.L., Hamburg, S.P., 2012. Greater focus needed on methane leakage from natural gas infrastructure.. Proc. Natl. Acad. Sci. 109 (17), 6435–6440. <http://dx.doi.org/10.1073/pnas.1202407109>.
- Anon, 1999. Natural gas 1998: Issues and trends, United States.
- Anon, 2018. Personal Communication. Victoria, BC.

**Table A.1**  
Units and conversion factors.

Unit	Equivalent to
1.0 Cubic metres (m <sup>3</sup> )	6.2898 Barrels (bbl)
1.0 Cubic metres (m <sup>3</sup> )	1,000 Litres (l)
1.0 Cubic metres (m <sup>3</sup> )	35.3147 Cubic feet (cf) natural gas
1.0 Cubic feet (cf) natural gas	0.028317 Cubic metres (m <sup>3</sup> )
1.0 US Gallons	3.7854 Litres (l)
1.0 US Gallons	3.7854 × 10 <sup>-3</sup> Cubic metres (m <sup>3</sup> )
1.0 Litres (l)	1 × 10 <sup>-3</sup> Cubic metres (m <sup>3</sup> )
1.0 Gigajoules (GJ)	0.9478 Million British thermal units (MMBtu)
1.0 Gigajoules (GJ)	947.8171 Cubic feet (cf) natural gas
1.0 Gigajoules (GJ)	26.853 Cubic metres (m <sup>3</sup> ) natural gas
1.0 Million British thermal units (MMBtu)	1.0551 × 10 <sup>9</sup> Joules (J)
1.0 Million British thermal units (MMBtu)	1.0551 Gigajoules (GJ)
1.0 Million British thermal units (MMBtu)	1,000 Cubic feet (cf) natural gas
1.0 Gigawatt-hours (GW.h)	3.6 × 10 <sup>12</sup> Joules (J)
1.0 Cubic feet (cf) natural gas	0.0388 Gigajoules (GJ)
1.0 Cubic feet (cf) natural gas	1 × 10 <sup>-3</sup> Million British thermal units (MMBtu)
Diesel fuel energy	0.0358745 Gigajoules per litre (GJ/L)
FortisBC natural gas energy	0.055058 Gigajoules per kilogramme (GJ/kg)
1.0 Cubic metres (m <sup>3</sup> ) LNG	0.4049 Tonnes (t) LNG
1.0 Tonnes (t) LNG	1,379.549 Cubic metres (m <sup>3</sup> ) natural gas
1.0 Billion cubic feet (Bcf) natural gas	4.8471 × 10 <sup>4</sup> Cubic metres (m <sup>3</sup> ) LNG

- Argonne National Laboratory, 2017. The Greenhouse Gases Regulated Emissions and Energy Use in Transportation Model. (Online). Available: <https://greet.es.anl.gov/>.
- Atherton, E., et al., 2017. Mobile measurement of methane emissions from natural gas developments in Northeastern British Columbia, Canada. *Atmos. Chem. Phys.* 17 (20), 12405–12420. <http://dx.doi.org/10.5194/acp-17-12405-2017>.
- Balcombe, P., et al., 2019. How to decarbonise international shipping: options for fuels, technologies and policies. *Energy Convers. Manage.* 182, 72–88. <http://dx.doi.org/10.1016/j.enconman.2018.12.080>.
- BC Oil and Gas Commission, 2016. British Columbia's Oil and Gas Reserves and Production Report, BC Oil and Gas Commission, Victoria, BC.
- Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. *Transp. Res. Part D Transp. Environ.* 52, 408–421. <http://dx.doi.org/10.1016/j.trd.2017.03.022>.
- Brandt, A.R., et al., 2014. Methane leaks from North American natural gas systems. *Science* 343 (6172), 733–735.
- British Columbia 2015 GHG emission report summary. (Online). Available: <https://www2.gov.bc.ca/gov/content/environment/climate-change/data/provincial-inventory>. (Accessed 30 July 2018).
- Cai, H., Burnham, A., Chen, R., Wang, M., 2017. Wells to wheels: environmental implications of natural gas as a transportation fuel. *Energy Policy* 109, 565–578. <http://dx.doi.org/10.1016/j.enpol.2017.07.041>.
- Canadian Natural Gas Vehicle Alliance, 2017. Liquefied Natural Gas: A Marine Fuel for Canada's Great Lakes and East Coast, Ottawa.
- Clark, N.N., et al., 2017. Pump-to-wheels methane emissions from the heavy-duty transportation sector. *Environ. Sci. Technol.* 51 (2), 968–976. <http://dx.doi.org/10.1021/acs.est.5b06059>.
- Corbett, J., et al., 2014. Methane emissions from natural gas bunkering operations in the marine sector: A total fuel cycle approach, University of Delaware, US.
- El-Houjeiri, H., Monfort, J., Bouchard, J., Przesmitzki, S., 2019. Life cycle assessment of greenhouse gas emissions from marine fuels: a case study of Saudi crude oil versus natural gas in different global regions. *J. Ind. Ecol.* 23 (2), 374–388. <http://dx.doi.org/10.1111/jiec.12751>.
- Feng, Y., Dong, Z., 2019. Optimal control of natural gas compression engine hybrid electric mining trucks for balanced fuel efficiency and overall emission improvement. *Energy* 189, <http://dx.doi.org/10.1016/j.energy.2019.116276>, art. 116276.
- Feng, L., Zhai, J., Chen, L., Long, W., Tian, J., Tang, B., 2017. Increasing the application of gas engines to decrease China's GHG emissions. *Mitig. Adapt. Strateg. Glob. Chang.* 22 (6), 839–861. <http://dx.doi.org/10.1007/s11027-016-9700-5>.
- GHGenius, Lifecycle Analysis (LCA) Model. (Online). Available: <http://www.ghgenius.ca/>. (Accessed 01 October 2018).
- Government of British Columbia, 2015. Natural Gas and Oil Statistics – Province of British Columbia. (Online). Available: <https://www2.gov.bc.ca/gov/content/industry/natural-gas-oil/statistics>. (Accessed 01 October 2018).
- Howarth, R.W., Santoro, R., Ingraffea, A., 2011. Methane and the greenhouse gas footprint of natural gas from shale formations. *Clim. Change* 106 (4), 679–690. <http://dx.doi.org/10.1007/s10584-011-0061-5>.
- Hultman, N., Rebois, D., Scholten, M., Ramig, C., 2011. The greenhouse impact of unconventional gas for electricity generation. *Environ. Res. Lett.* 6 (4), <http://dx.doi.org/10.1088/1748-9326/6/4/044008>, art. 044008.
- Hyvättinen, H., Hildén, M., 2004. Environmental policies and marine engines—effects on the development and adoption of innovations. *Mar. Policy* 28 (6), 491–502. <http://dx.doi.org/10.1016/j.marpol.2004.01.001>.
- Intergovernmental Panel on Climate Change (IPCC), 2014. Fifth Assessment Report, Geneva.
- International Maritime Organization, 2010. Revised MARPOL Annex III adopted at IMO environment meeting, Marine Environment Protection Committee, Sep.–Oct. 2010. (Online). Available: <http://www.imo.org/en/MediaCentre/PressBriefings/Pages/Revised-MARPOL-Annex-III-adopted-at-IMO-environment-meeting.aspx#.XksrDShKiUk>. (Accessed 17 February 2020).
- International Maritime Organization (IMO), Sulphur 2020 – cutting sulphur oxide emissions. (Online). Available: <http://www.imo.org/en/mediacentre/hottopics/pages/sulphur-2020.aspx>. (Accessed 21 September 2018).
- Iwamoto, Y., Noma, K., Nakayama, O., Yamauchi, T., Ando, H., 1997. Development of gasoline direct injection engine. *J. Engines* 19, <http://dx.doi.org/10.4271/970541>.
- Jiang, M., Michael Griffin, W., Hendrickson, C., Jaramillo, P., VanBriesen, J., Venkatesh, A., 2011. Life cycle greenhouse gas emissions of marcellus shale gas. *Environ. Res. Lett.* 6 (3), <http://dx.doi.org/10.1088/1748-9326/6/3/034014>, art. 034014.
- Johnson, M.R., Tyner, D.R., Conley, S., Schwietzke, S., Zavala-Araiza, D., 2017. Comparisons of airborne measurements and inventory estimates of methane emissions in the Alberta upstream oil and gas sector. *Environ. Sci. Technol.* 51 (21), 13008–13017. <http://dx.doi.org/10.1021/acs.est.7b03525>.
- Karion, A., et al., 2013. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophys. Res. Lett.* 40 (16), 4393–4397. <http://dx.doi.org/10.1002/grl.50811>.
- Kasumu, A.S., Li, V., Coleman, J.W., Liendo, J., Jordaan, S.M., 2018. Country-level life cycle assessment of greenhouse gas emissions from liquefied natural gas trade for electricity generation. *Environ. Sci. Technol.* 52 (4), 1735–1746. <http://dx.doi.org/10.1021/acs.est.7b05298>.
- Manivannan, A., Porai, P.T., Chandrasekaran, S., Ramprabhu, R., Tamil, P., Chandrasekaran, S., 2003. Lean burn natural gas spark ignition engine – an overview. *SAE Int.* (724), <http://dx.doi.org/10.4271/2003-01-0638>.
- Manne, A.S., Richels, R.G., 1990. CO2 emission limits: an economic cost analysis for the USA. *Energy J.* 11 (2), <http://dx.doi.org/10.5547/issn0195-6574-ej-vol11-no2-3>.
- Manouchehrinia, B., Molloy, S., Dong, Z., Gulliver, T.A., Gough, C., 2018. Emission and life-cycle cost analysis of hybrid and pure electric propulsion systems for fishing boats. *J. Ocean Technol.* 13, 64–87.
- Natural Resources Canada, Marketable Natural Gas Production in Canada. (Online). Available: <https://www.nrcan.gc.ca/energy/facts/natural-gas/20067#L6>. (Accessed 30 July 2018).
- Pétron, G., et al., 2012. Hydrocarbon emissions characterization in the Colorado front range: a pilot study. *J. Geophys. Res. Atmos.* 117 (D4), 170–182. <http://dx.doi.org/10.1029/2011JD016360>.
- Rolls-Royce Marine, 2012. Overcoming Methane Slip, Rolls Royce Marine Builds Spark-Ignited LNG-Powered Engines – gCaptain. (Online). Available: <http://gcaptain.com/overcoming-methane-slip-rolls/>. (Accessed 27 July 2018).
- Roman-White, S., et al., 2019. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update.

- Sharafian, A., Blomerus, P., Mérida, W., 2019. Natural gas as a ship fuel: assessment of greenhouse gas and air pollutant reduction potential. *Energy Policy* 131, 332–346. <http://dx.doi.org/10.1016/j.enpol.2019.05.015>.
- Sommer, D.E., et al., 2019. Characterization and reduction of in-use CH<sub>4</sub> emissions from a dual fuel marine engine using wavelength modulation spectroscopy. *Environ. Sci. Technol.* 53 (5), 2892–2899. <http://dx.doi.org/10.1021/acs.est.8b04244>.
- Stenersen, D., Thonstad, O., 2017. GHG and NO<sub>x</sub> emissions from gas fuelled engines.
- Stephenson, T., Valle, J.E., Riera-Palou, X., 2011. Modeling the relative GHG emissions of conventional and shale gas production. *Environ. Sci. Technol.* 45 (24), 10757–10764. <http://dx.doi.org/10.1021/es2024115>.
- Taglia, A., Rossi, N., 2009. European gas imports: GHG emissions from the supply chain.
- The Total Energy and Emissions Analysis in Marine Systems (TEAMS) model, 2018. (Online). Available: <http://www.rit.edu/~w-teams/overview.htm>. (Accessed 02 October 2018).
- Thomson, H., Corbett, J.J., Winebrake, J.J., 2015. Natural gas as a marine fuel. *Energy Policy* 87, 153–167. <http://dx.doi.org/10.1016/j.enpol.2015.08.027>.
- Tyrovola, Theodora, Dodos, George, Kalligeros, Stamatis, Zannikos, Fanourios, 2017. The introduction of biofuels in marine sector. *J. Environ. Sci. Eng. A* 6 (8), <http://dx.doi.org/10.17265/2162-5298/2017.08.006>.
- U.S. Energy Information Administration, U.S. Energy Facts. (Online). Available: <https://www.eia.gov/totals/energy/>.
- U.S. Energy Information Administration (EIA), EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia - Today in Energy - U.S. Energy Information Administration (EIA). (Online). Available: <https://www.eia.gov/todayinenergy/detail.php?id=41433#>. (Accessed 16 February 2020).
- U.S. Environmental Protection Agency (EPA), U.S. Greenhouse Gas Inventory Report: 1990–2014. (Online). Available: <https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014>. (Accessed 31 July 2018).
- Usama, M.N., Sherine, A., Shuhaimi, M., 2011. Technology review of natural gas liquefaction processes. *J. Appl. Sci.* 11 (21), 3541–3546. <http://dx.doi.org/10.3923/jas.2011.3541.3546>.
- Žaglinskis, J., Rapalis, P., Lazareva, N., 2018. An overview of natural gas use in ships: necessity and engine supply. *Period. Polytech. Transp. Eng.* 46 (4), 185–193. <http://dx.doi.org/10.3311/PPtr.11708>.
- Winnes, H., Fridell, E., 2009. Particle emissions from ships: dependence on fuel type. *J. Air Waste Manag. Assoc.* 59 (12), 1391–1398. <http://dx.doi.org/10.3155/1047-3289.59.12.1391>.