Natural Gas as a Ship Fuel: Assessment of Greenhouse Gas and Air Pollutant Reduction Potential

Amir Sharafian, Paul Blomerus, Walter Mérida*

Clean Energy Research Centre, The University of British Columbia, 2360 East Mall, Vancouver, BC, Canada V6T 1Z3

Abstract

Shipping is a significant contributor to global greenhouse gas (GHG) and air pollutant emissions. This study uses a life cycle assessment to compare emissions from domestic and imported liquefied natural gas (LNG), and heavy-fuel oil (HFO) for marine shipping. The findings show that only high-pressure dual-fuel (HPDF) engines robustly reduce well-to-wake GHG emissions by 10% compared with their HFO-fuelled counterparts. This engine technology is only available for large low-speed engines used in ocean-going vessels (OGVs). For smaller vessels, such as ferries, the current deployment of medium speed low-pressure dual-fuel (MS-LPDF) and lean burn spark ignition (LBSI) gas engines cannot reliably reduce GHG emissions. This is primarily due to the high levels of methane slip from these engines. For air pollution reduction, gas engines are found to be an effective means of reducing nitrogen oxides, sulphur oxides and, particulate matter without any additional engine aftertreatment. The HPDF engines, however, need aftertreatment or exhaust gas recirculation to meet the International Maritime Organization Tier III regulations. Sulphur controls, such as the 2020 act, move to limit sulphur to 0.5% globally. However, this will increase the cost of the HFO used by most OGVs, enhancing the economic case for natural gas fuel.

Keywords: Liquefied natural gas, Ship, Engine technology, Greenhouse gas emissions, Air pollutants.

---

* Corresponding author: Tel.: +1 (604) 822-4189; Fax: +1 (604) 822-2403.
E-mail address: walter.merida@ubc.ca (W. Mérida).

1. Introduction

Emissions from marine shipping are an increasingly important issue in global energy systems. This includes both greenhouse gases (GHGs) and air pollutants such as oxides of nitrogen (NOx), oxides of sulphur (SOx) and particulate matter (PM). However, progress in reducing emissions beyond the efficiency gains from larger vessels has been relatively slow, with emissions from shipping proving to be particularly challenging.

Shipping represents 2.5% to 3.5% of global CO_2 emissions [1,2]. Scenarios developed by the International Maritime Organization (IMO) indicated that the GHG emissions from shipping industry will grow between 50% and 250% by 2050 [2]. The main causes of an increase in GHG emissions from ships are due to the growing demand for shipping to support international trade and the challenges with switching to lower-carbon fuels. Table 1 provides further information about the emissions from the global shipping industry from 2007 to 2015.

Figure 1 shows the global GHG emissions broken down by ship type. Container vessels, bulk carriers and oil tankers make up 54% of the shipping GHG emissions in 2015.

The predominant fuel for shipping is currently residual fuel, or heavy fuel oil (HFO) which accounted for 72% of all fuel consumed in 2015 [1]. HFO is the residue product of crude oil in refineries and its combustion releases high levels of air pollutants. Natural gas has been suggested as an alternative transport fuel to decrease these emissions. However, there is some disagreement as to the potential for natural gas to provide significant improvements over emissions emerging from the current transport system [4–7]. Liquefied natural gas (LNG) is currently estimated to make up just 2% of global shipping fuel, predominately from LNG carriers [1].

The primary global pollution control mechanism for shipping is the International Convention for the Prevention of Pollution from Ships (MARPOL), Annex VI which entered into force in 2005 and has been broadly adopted by countries around the world. The convention established limits to sulphur content of fuels and NO_x emissions inside and outside of the emission control areas (ECAs) shown in Figure 2.

To control SO_x and PM emissions, the sulphur content of fuels should be less than 0.1% in SO_x ECAs and is currently in effect in North America and Northern Europe. The sulphur content of fuels outside the SO_x ECAs should not exceed 3.5%[†] until January 1st, 2020 and 0.5% thereafter [9].

The prescribed NO_x emissions as a function of engine speed is shown in Figure 3. NO_x emissions from marine diesel engines constructed after January 1st, 2016 should meet Tier III levels inside NO_x ECAs. These regulations came into effect in North America from January 2016 and will become effective in Northern Europe from January 2021 [10]. The Tier II limit should be met globally by all ships constructed after January 1st, 2011.

The Energy Efficiency Design Index (EEDI) is also contained within MARPOL Annex VI and mandates a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types and sizes [11]. The EEDI was established in January 2013 to reduce the CO_2 emissions of vessels by 10% and tightens every 5 years reaching 30% by 2025-2030. Reductions are measured with respect to the average efficiency of the reference ship type built between 2000 and 2010 [11] and alternative fuels, such as LNG, are an acceptable means of compliance with these rules. These measures take effect at an individual ship level, so despite these measures, growth in global shipping may still cause an increase in GHG emissions.

To tackle this challenge of increasing GHG emissions, the IMO's Marine Environment Protection Committee (MEPC) adopted a resolution in April 2018 setting a target of reducing the total GHG emissions from shipping by at least 50% by 2050 below 2008 levels [12]. This is a challenging target and requires policy supports, optimizing trade operations, improving engine efficiency, and moving toward low- and zero-carbon fuels.

The traditional ranges of potential GHG and pollution reduction promised by using LNG in ships are shown in Table 2. However, the specifics of the engine technology and life cycle of the fuel should be taken into account to give a comprehensive comparison with traditional technologies. The correct baseline for improvements is also an important factor for considerations. For example, a Tier III NO_x compliant engine burning ultra-low sulphur diesel and equipped with a particulate trap would see a much lower emissions reduction when converting to natural gas than a conventional HFO-fuelled engine.

[†] Though the limit on sulphur content is 3.5%, global HFO sulphur levels average is approximately 2.5%.

The number of LNG-fuelled ships is growing and as of May 1st, 2018, it reached 253 vessels (121 ships in service and 132 on order) [14]. This is in addition to the fleet of more than 400 LNG carriers that are also largely fuelled by natural gas. The number of in-service and on-order LNG-fuelled ships in 2018 grew by 17% and 36% with respect to those in 2017 [14]. Further details about the number of LNG-fuelled ships are provided in Table 3.

Norway has pioneered the use of LNG as a ship fuel – outside of LNG carriers – in ferries and offshore service vessels for the oil and gas industry [13]. Other vessel types have been added, including tugs, fish feed carriers, wind farm support vessels, cruise ferries, small chemical tankers and container feeder vessels. More recently, large vessels, including bulk carriers, container vessels, oil tankers, car carriers and cruise ships, have been added to the order book which indicates that almost all vessel types are now possible to be fuelled with LNG.

This study investigates the GHG and air pollutant emissions from LNG- and HFO-fuelled ships built after 2010 with respect to the new emissions control regulations. Using a life cycle assessment (LCA) and recently measured emissions data from ships, a comprehensive model for LNG and HFO supply chains is developed. The accuracy of the model is compared against available data in the literature. Finally, a parametric study is conducted to find the GHG and air pollutant emissions from domestic and imported LNG and HFO, and determine the potentials and challenges of natural gas use in marine vessels.

2. Natural Gas Engine Technologies

The global abundance of affordable natural gas has made using LNG as a fuel an attractive option in the marine sector, particularly as gas engines offer opportunities to reduce NO_x emissions to below the most stringent IMO Tier III levels without the need for costly exhaust aftertreatment. In jurisdictions where low-sulphur fuel is already mandated, for instance in North America, LNG represents a significant cost saving compared to ultra-low sulphur diesel [15]. LNG may also prove to be an economical alternative to low-sulphur heavy fuel oil (HFO) as IMO 2020 limits come into effect. Four types of engines are now available in the market to be used in gas-fuelled ships:

2.1. Medium Speed 4-Stroke Lean Burn Spark Ignition (LBSI) engines

These engines run only on natural gas and operate based on the Otto cycle. A spark plug is used to ignite the air-fuel mixture in the combustion chamber or in a pre-chamber. These engines have an efficiency of about 42% [16] and power output ranging from 316 kW to 9.7 MW. Rolls-Royce Marine/Bergen, Mitsubishi and Hyundai are manufacturer of these engines [13]. Applications have included ferries, small cargo vessels, offshore support vessels and a number of other smaller vessel applications. Adoption has been hampered by the inability to run on traditional liquid fuels as a backup. Rolls-Royce has also recently released a high-speed spark-ignited gas engine for marine propulsion based on its popular MTU 4000 series platform [17]. The stoichiometric spark-ignited engine technology with exhaust gas recirculation that is popular in heavy duty truck engines is not used in marine applications. However, LBSI manufacturers do use richer fuel mixtures (closer to stoichiometric mixtures) in parts of the engine operating range to improve load acceptance as discussed in more detail in Section 2.5.

2.2. Medium Speed 4-Stroke Low Pressure Dual-Fuel (MS-LPDF) engines

These engines also operate based on the Otto cycle and require a lower compression ratio than diesel engines of the same size to prevent pre-ignition or knocking. This results in a lower power output per cylinder. The efficiency of these engines is about 44% [16]. When in gas mode, gas is injected into the air intake of each cylinder and is ignited by a pilot injection of liquid fuel. Alternatively, they can operate in liquid fuel mode, providing flexibility to use different fuels depending on fuel availability or price. LPDF engines were initially developed for LNG bulk carries where boil-off gas could be used to power the auxiliary or main ship engines [18]. They have been successfully deployed in ferries, platform support vessels, service vessels, and several other vessel types. These engines are available in power output ranging from 720 kW to 17.55 MW manufactured by Wärtsilä, MAN and MAK.

2.3. Low Speed 2-Stroke Low-Pressure Dual-Fuel (LS-LPDF) engines

The larger low-speed 2-stroke dual-fuel engines operate on a similar principal to their 4-stroke counterparts, however when in-gas mode, gas under low pressure is injected into the cylinder before the compression stroke. The efficiency of these engines is about 51% [19]. WinGD licences designs for manufacture of 2-stroke LS-LPDF engines in the power range of 4.5 MW to 65 MW [19].

2.4. Low Speed 2-Stroke High Pressure Dual-Fuel (LS-HPDF) engines

Unlike the other three engine types, these engines operate on the diesel cycle. Natural gas at high pressure is injected into the cylinder near the top of the compression stroke. The gas is ignited through an injection of liquid pilot fuel. These dual fuelled engines provide a similar performance to diesel engines with no power loss, though NO_x emissions are higher than Otto cycle engines due to higher combustion chamber temperatures. The direct gas injection system assures much lower methane emissions from the tailpipe exhaust. The efficiency of these engines is the same as the low-speed diesel engines they are derived from, about 50% [20]. Marine LS-HPDF engines are currently manufactured under licence from MAN only for large low-speed 2-stroke engines to provide power up to 42.7 MW [13].

2.5. Engine technology comparison and challenges

One of the main issues with LBSI and LPDF engines is methane slip, particularly at partial loads. Methane slip occurs when methane from the fuel enters the engine exhaust unburned. The primary cause is incomplete combustion either due to incorrect air-fuel mixtures or gas getting trapped in crevices in the combustion chamber. In 2-stroke engines, such as the LS-LPDF, gas is injected into the cylinder while the exhaust valve is still open, and careful timing and direction are required to ensure unburned fuel does not exit through the exhaust valve during this scavenging process. Methane is a potent GHG and has a global warming potential (GWP) of 30 to 85 times greater than CO_2 [21]. In publications before 2015, methane slip from ship engines was estimated to be between 1.9% and 2.6% [4–6]. However, recent measurements by SINTEF Ocean [16] in 2017 showed methane slip of 2.3% and 4.1% from LBSI and MS-LPDF engines, respectively. A recent investigation by Sommer et al. [22] found similarly elevated levels of methane slip by 5.5% (9.2 g $CH_4/kWh_{\text{engine output}}$) from MS-LPDF engines under real operating conditions, especially at partial loads. This is despite improvements made by engine manufacturers in combustion chamber design and tighter air-fuel ratio control to minimize methane slip.

Analysing the methane slip and NOx emissions in marine vessels shows a competing trend between these species, especially at low engine loads. LBSI and LPDF engines can control NO_x emissions (for instance to meet more stringent Tier III NOx emissions) by using lean fuel-air mixture to reduce the combustion temperature [16]. However, this technique increases the chance of incomplete combustion of methane and therefore, higher methane slip. This process also increases the CO emissions. On the contrary, a rich fuel-air mixture can minimize methane slip, improve load acceptance and reduce CO emissions at a cost of increasing NO_x emissions. It seems that despite the best efforts of engine manufacturers, these undesired emissions from LBSI and LPDF engines will continue to reduce the GHG benefits of natural gas fuelled ships using these engine types.

LS-HPDF engines, in contrast, have been found to have almost no methane slip (about 0.01%) [18]. However, the complex fuel gas supply system required to supply the fuel increases costs by about 40% compared to LBSI and LPDF engines, and their NO_x emissions are between diesel and LPDF engines [16]. To comply with the NO_x levels in MARPOL Annex VI-Tier III, these engines should use exhaust gas recirculation (EGR) and/or selective catalytic reduction (SCR) to reduce NOx emissions [16].

The ability for LBSI and LPDF engines to meet IMO NO_x Tier III emissions standards without the need for additional aftertreatment or exhaust gas recirculation makes them an attractive choice for vessels operating consistently in the ECAs where the Tier III standards apply [16]**,** despite the fact that the methane slip from these engine types are higher than that from LS-HPDF engines.

Gas turbines (GTs) have been proposed as an alternative to piston engines due to their more compact and lighter characteristics. However, GTs are less efficient [23]. To increase their efficiency, a combined cycle turbine can be used. GTs are predominantly used in warships, where high power output and rapid response outweigh the operation cost and fuel consumption [13]. GTs have also successfully been deployed in cruise ships. Combined cycle gas turbines with heat recovery have been proposed for LNG-fuelled ships, see Ref. [24] as an example.

3. Alternative Emission Reduction Strategies

CO_2 is the main product of combusting conventional fossil fuels. Compared with HFO and marine gas oil (MGO), natural gas has a lower carbon content, and consequently, burning natural gas reduces CO_2 emissions. However, methane, the main constituent of natural gas, is a potent GHG. As a result of methane emissions across the natural gas supply chain and methane slip from ship engine exhausts [13], the GHG emissions benefit from natural gas used in marine shipping can be reduced to the point that it may exceed the GHG emissions of a conventional liquid-fuelled vessel. It is therefore critical to study and minimize the well-to-wake (WTW) methane emissions across the natural gas supply chain. The amount of GHG emissions (in CO_{2e}) is calculated from the GWP of GHGs given in Table 4. The GWP of methane is 85 and 30 times as high as those of CO_2 under 20- and 100-year horizons, respectively. In the present study, GWP of GHGs under the 100-year time horizon is considered.

SO_x is one of the products of combustion in ships due to the high sulphur content of HFO. On the contrary, LNG has almost no sulphur, and consequently, burning natural gas in ships eliminates or significantly decreases SO_x emissions. The SO_x emissions in LPDF and HPDF engines stem from the pilot fuel. If sulphur-containing HFO is used, then some SO_x emissions will remain.

NO_x is another important air pollutant and its emission level is directly affected by the combustion temperature because it is formed through the oxidation of the nitrogen in the air during combustion. LBSI and LPDF engines have a low combustion temperature and therefore low NO_x emissions, whereas LS-HPDF engines, which work in a similar way to diesel engines, have a high combustion temperature and consequently, high NO_x emissions.

Particulate matter (PM) is the product of combustion and are mainly comprised of metals, organic carbon, black carbon, sulphates, nitrates, and ammonium [26]. For the purposes of this study, we grouped together all PM emissions including both small particle emissions ($PM_{2.5}$) and larger PM (PM_{10}). The sulphur content of fuels has a direct impact on the PM concentration in the exhaust gas. Natural gas combustion has lower PM emissions both because of the absence of sulphur in the fuel and because the simple hydrocarbons tend to form fewer particulates. Natural gas is therefore a very effective means to reduce particulate emissions, however, as the IMO SO_x controls come into place in 2020, the PM emissions of engines currently fuelled by high-sulphur fuels will decrease, and the benefit in PM emissions from switching to natural gas will be reduced.

Black carbon (BC) is a solid material and a product of incomplete combustion of MGO and HFO in marine vessels. According to the International Council on Clean Transportation (ICCT) 2017 report, ships emitted approximately 67 kilotonnes of black carbon in 2015 [27]. The GWPs of BC under 20- and 100-year horizons were estimated to be about 3200 (270 to 6200) and 900 (100 to 1700), respectively [21,28]. However, there is a high uncertainty in these values. Using the GWPs of 900 (100-year horizon) and 3,200 (20-year horizon), BC would add an additional 5 to 8% and 16 to 23% to the global CO_{2e} emissions from shipping, respectively [27]. Intergovernmental Panel on Climate Change (IPCC) specifically reported GWPs for NOx, SO_2, black carbon and organic carbon from ships as shown in Table 5 [21,29].

As highlighted in Table 5, the Arctic region is particularly sensitive to BC. Because this study considers the impact of LNG on global GHG emissions, the effects of BC, SO_2 and NO_x on GHG emissions are not included in the results analysis.

To comply with the emissions regulations, a range of strategies including aftertreatment and fuel switching can be deployed. In fuel switching, ships can use regular fuels with higher emissions in regions outside ECAs and switch to fuels with lower emissions inside ECAs, such as ultra-low sulphur diesel. Ships equipped with dual-fuel engines can use LNG in ECAs as well [13]. Several factors, such as an extra space occupied by the second fuel, the cost of alternative fuels, and capital cost of technology conversion should be considered to select the best solution.

A scrubber can be used to reduce the SO_x emissions from the flue gas by up to 95%. While this is an effective method to reduce SO_x emissions, the scrubber occupies a large space in the engine room and increases energy consumption. To control NO_x emissions, diesel cycle engines can use EGR and SCR to comply with the regulations inside and outside ECAs. These exhaust gas aftertreatment technologies occupy extra space in the engine room and increase the operation cost as shown in Table 6.

From the data presented in Table 6, it is apparent that aftertreatment technologies come with significant upfront costs and operational costs. Fuel switching by contrast comes with an additional operating cost, for instance, ship operators should be expecting to pay a premium of around 25% for fuel that meets the 2020 requirements [35] or consider switching to LNG. Vessels wishing to operate in or enter the NO_x ECAs will need to be equipped with SCR and/or EGR to meet the most stringent Tier III requirements or would need to consider a LBSI or LPDF natural gas engine.

4. Pertinent Literature on GHG Emissions from LNG Shipping

In a fuel LCA, it is conventional to separate life cycle emissions into upstream and downstream components. In this study, we use the term well-to-tank (WTT) to refer to upstream emissions up to the fuel tank on the vessel. We use the term tank-to-wake (TTW) to refer to downstream emissions that occur on the vessel. The total well-to-wake (WTW) life cycle emissions are therefore the sum of WTT and TTW emissions.

Verbeek et al. [4] studied GHG and air pollutant emissions from ships in the Netherlands. Three types of ships were evaluated, namely, a short sea ship (a 800-TEU container feeder), a port ship (an 80-ton harbour tug), and a 110 × 11.5 m inland ship. The GHG emissions were reported in g/MJ_{fuel} because the efficiency of gas engines was assumed to be within 1% of diesel engines. Three routes were considered for the LNG supply chain:

- LNG import: LNG supplied by tanker ship from Qatar (Travel distance: 10,000 km)
- LNG from Rotterdam: Natural gas transported by pipeline from the North Sea (Pipeline length: 250 km)
- LNG from Rotterdam: Natural gas transported by pipeline from Russia (Pipeline length: 7,000 km)

Table 7 shows the WTT and TTW GHG emissions from LNG and HFO supply chains from the Verbeek et al. [4] analysis.

Verbeek et. al. [4] concluded that LNG was beneficial in all cases except pipeline gas from Russia. However, in a subsequent report [36], the authors updated the emissions to take account of methane emissions from LNG tanks and engine efficiency which increased WTW emissions from LNG ships to 97 g $CO_{2e}/MJ_{fuel.corrected}$. Therefore, they concluded that unless methane emissions were controlled to less than 1g per kWh of engine output (1 g/kWh), LNG did not have a beneficial GHG reduction impact.

Laugen [5] analysed the benefit of LNG compared to HFO in Ro-Pax ferries. Laugen assumed that natural gas was extracted, processed and liquefied in Norway, and was transported by ship to Rotterdam in the Netherlands. For HFO, crude oil was extracted in the North Sea, refined in the West coast, and HFO was transported by oil tankers to Rotterdam in the Netherlands. The detailed GHG emissions from the LNG and HFO supply chains are tabulated in Table 8. Laugen concluded that for the example of the Ro-Pax ferry with a LBSI engine fuelled by the LNG imported from Norway to the Netherlands, the WTW GHG emissions from the LNG-fuelled ferry reduced GHG emissions by 2.4% compared with its HFO-fuelled counterpart.

Lowell et al. [6] studied the impacts of domestic and imported LNG on international shipping. In their analysis, they considered eight pathways for LNG delivery and use as a fuel in ships (Table 9). In the baseline case, they did not consider the impact of differences in engine efficiency and showed that on average, LNG can reduce WTW GHG emissions from ships by up to 18% in some cases, and on average by 8%. However, when the authors considered the impact of more realistic engine efficiencies and higher methane emissions as part of a sensitivity analysis, the benefits were reduced. For comparison with HFO-fuelled vessels, they used the WTW GHG emissions of HFO-fuelled vessels reported by Verbeek et. al. [4].

Baresic et al. [7] investigated the impact of LNG as a fuel for ships on GHG emissions between 2010 and 2050. They considered four scenarios, namely, business as usual, high gas demand, transition, and limited gas. The authors assumed a constant methane emission factor of 1.1 g CO_{2e}/MJ_{fuel} which was considered to be a mid to high end estimate for LPDF engines. Table 10 shows the GHG emissions from LNG and HFO supply chains based on these assumptions and shows an 11% benefit for LNG-fuelled ships compared with their diesel counterparts.

Figure 4 summarises the WTW GHG emissions of LNG- and HFO-fuelled ships reported in Refs. [4–7].

Figure 4 illustrates the range of conclusions authors have reached on the benefits of LNG as a fuel. The analysis is particularly sensitive to the choice of engine technology, however in many cases, a single engine technology (usually LBSI or MS-LPDF) was used to approximate the total ship population. This is an over simplification and in the analysis presented for this study, we address the shortcoming and correctly adjust for differences in engine efficiencies and methane emissions.

Figure 4 also illustrates the sensitivity of the analysis to variations in WTT emissions. In order to better understand the WTT component of LNG fuel, we can take advantage of several studies in the literature that analysed the GHG emissions from the LNG supply chain for the purposes of electricity generation or pipeline gas distribution. For example, Taglia and Rossi [37] studied GHG emissions from three import LNG pathways:

- Egypt to Italy: Gas production in West Delta Deep Marine (Scarab and Saffron fields) concession (Egypt), liquefaction in Segas LNG plant (Egypt), regasification in Panigaglia (GNL Italia) and consumption in Italy.

- Qatar to Italy: Gas production in North field (Qatar), liquefaction in Qatar gas 2 LNG plant, regasification in Adriatic LNG plant, and consumption in Italy.
- Trinidad and Tobago to Spain: Gas production in Dolphin field (Trinidad and Tobago), liquefaction in Atlantic LNG plant (Trinidad), regasification in Bahia de Bizkaia (Bilbao) and consumption in Spain.

The WTT GHG emissions from different LNG supply chains are summarized in Table 11. The assumptions for the emissions from gas production used by Taglia and Rossi are very low when compared to other sources, and result in low overall WTT LNG projections.

Skone et al. [38] investigated the emissions from LNG exported to Europe, China and Japan from various sources (Table 12). Overall, the emissions are much higher than those reported by Taglia and Rossi because of using more realistic extraction and processing emissions.

Pace Global [39] studied the LCA of LNG from Haynesville Shale in the US to Japan, South Korea, India, China, and Germany. In this study, two cases of high and low GHG emissions were reported as shown in Table 13. The GHG emissions from natural gas extraction, processing (except liquefaction) and transport reported by Pace Global [39] is almost in the same range as those reported by Skone et al. [38].

A comparison of these WTT emissions data from the literature and the analysis conducted for this study is presented in Section 6.1.

5. Methodology and Assumptions

5.1. Well-to-tank emissions

In the present study, we distinguish between domestic and imported LNG and HFO supply chains for the WTT emissions. In this study, the domestic supply chain applies primarily to North American countries, where the emissions from fuel extraction, processing, storage, and distribution are considered. In the imported scenario, the fuel extraction and processing are assumed to happen in North America, and the LNG is transported by ships to the rest of the world. After offloading the fuel, it is stored and can be distributed by trucks, barges or regional ships.

To cover LNG and HFO supply chains globally, four supply chains are considered as shown in Figure 5. To analyse the LCAs of LNG and HFO for marine vessels, the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model 2017 developed by Argonne National Laboratory is used [40]. The built-in supply chains in the GREET model are modified to generate WTT emissions data for the supply chains shown in Figure 5.

To consider a wide range of LNG and HFO supply chains, a series of options correspond to actual supply chains are considered (Table 14). For example, the pipeline length is considered to vary from 100 to 3000 km. Natural gas transport in the form of LNG is considered for offshore and onshore destinations beyond 2000 and 4400 km, respectively, because of lower transport cost [41]. Therefore, the minimum travel distance of ocean-going vessels (OGVs) is set at 3,000 km. The OGV's travel distance encompasses the main global shipping routes. For instance, the international shipping routes from the port of Vancouver in Canada to Yangshan Port in Shanghai, China and Dahej terminal in Gujarat, India are about 9,380 and 18,042 km, respectively.

The natural gas liquefaction process has a significant contribution in the WTT GHG emissions. Table 15 shows the impact of four natural gas liquefaction technologies on GHG emissions. The industrial gas turbine (IGT) technology is considered as the base-case liquefaction technology.

To transport LNG and HFO by using pipeline, trucks, and OGVs, different fuel mixtures can be used. In this study, customary fuel mixtures recommended by GREET 2017 model are considered (Table 16).

5.2. Tank-to-wake emissions

It has become customary to report WTW and TTW GHG emissions per energy unit of fuel (g/MJ_{fuel}) on the basis that the engine efficiency of gas engines is similar to the engines they replace. This assumption is not valid in most cases and differences in engine efficiency have an important impact on WTW GHG emissions. Verbeek et al. [36] and Lowell et al. [6] have reported "corrected" g/MJ of fuel by increasing the emissions from the lower efficiency natural gas engines, but this approach can be confusing for the reader. In contrast, Laugen [5] reported GHG emissions results on a g/tonne.km basis which provides for a sound comparison, but requires knowledge of the specific vessels being compared. In the analysis conducted for this study, the results will be reported in the more generic and easily understood metric g of $emissions/kWh_{engine\ output.}$

Due to the progress made in the manufacturing of natural gas engines and reduction in methane slip, and the new emissions control regulations, the present study only focuses on the emissions measurements from ship engines constructed after 2010. In this regard, any recent published literature that used emissions from ship engines constructed before 2010 should be considered with caution and more emphasis placed on recent studies. The critical performance and emissions values from different natural gas engines and their conventional-fuelled counterparts were assembled from various sources and are presented in Table 17. Low-speed diesel cycle engines (LSD) and medium-speed diesel/high-speed diesel cycle engines (MSD/HSD) are considered for conventionally-fuelled engines in this study.

6. Results and Discussions

6.1. Well-to-tank GHG emissions

The results of GHG and air pollutant emissions from LNG- and HFO-fuelled ships are reported for WTT and WTW to give a clear understanding on the contribution of each part of the supply chain to GHG and air pollutant emissions. Table 18 shows the WTT GHG and air pollutant emissions from domestic and imported LNG and HFO calculated in the present study at the nominal values given in Table 14.

Table 18 indicates that the natural gas production and liquefaction process account for up to 36% and 30% of WTT GHG emissions, respectively. The impact of four natural gas liquefaction technologies on WTT and WTW GHG emissions are analysed (Table 19). The results show that using an electric-driven compressor technology for liquefaction rather than IGT reduces WTT and WTW GHG emissions by 26% and 7%, respectively.

To evaluate the sensitivity of the domestic and imported LNG supply chains, a comprehensive parametric study is conducted. The impacts of liquefaction technology, and natural gas transfer by pipeline, OGV, and truck are investigated on WTT GHG and air pollutant emissions. Figure 6a and b show that the GHG emissions from natural gas pipeline in the domestic LNG supply chain mainly stem from methane leaks and highlight the importance of controlling methane leaks from pipeline. On the contrary, GHG emissions from LNG distribution by diesel-fuelled trucks mainly originate from the fuel combustion and tailpipe emissions.

Figure 6c indicates that NO_x emissions from the natural gas supply chain is more sensitive to the length of the pipeline than the truck travel distance. On the contrary, the largest sources of SO_x and PM are from trucks across the domestic LNG supply chain, as shown in Figure 6d and e.

Our sensitivity analysis conducted on the imported LNG supply chain shows that GHG emissions from trucks and OGVs are mainly from the engine and tailpipe emissions, whereas GHG emissions from the pipeline is due to the methane leaks as shown in Figure 7a and b.

In imported LNG, NO_x emissions from trucks and OGVs are controlled according to the environmental regulations and therefore, trucks and OGVs have low levels of NO_x emissions (Figure 7c). On the contrary, NO_x emissions across the natural gas pipeline changes significantly by increasing the pipeline length from 100 to 3,000 km.

Figure 7d and e indicate that OGVs are the main contributor in SO_x and PM emissions across the imported LNG supply chain mainly due to burning HFO with high sulphur content. In our analysis, it is assumed that OGVs use a fuel mixture of 54.25% LNG and 45.75% HFO, as shown in Table 16. This shows that replacing HFO with LNG as a fuel in OGVs for LNG transport can significantly reduce SO_x and PM emissions from the imported LNG supply chain.

The accuracy of the present model is compared against the WTT GHG emissions from domestic and imported LNG reported in the literature (Figure 8). The dashed lines and grey areas in Figure 8 represent the WTT GHG emissions at the nominal values and the variation ranges displayed in Figure 6a and Figure 7a, respectively. It can be seen that there are some discrepancies among WTT GHG emissions predicted by the present study and those reported in the literature. Detailed analysis of WTT GHG emissions reported in the literature shows that Verbeek et al. [4] reported a significantly lower WTT GHG emissions compared with other studies due to very low estimates for production. Similarly, the emissions from the natural gas extraction sites reported by Taglia and Rossi [37] are 80% to 90% lower than those reported in the literature.

As the difference in WTT GHG emissions from domestic and imported LNG calculated in the present study was not significant, the average value of 26 g/MJ_{fuel} is used in calculation of WTW GHG emissions.

6.2. Well-to-wake GHG emissions

The analysis of WTW GHG and methane emissions is shown in Figure 9. The error bars in Figure 9a represent the variations in WTT GHG emissions shown in Figure 6a and Figure 7a. An analysis of the results can be divided into two parts, the first being for smaller vessels powered by medium- or high-speed engines. According to the results, it can be concluded that LBSI and MS-LPDF engines have 2% and 7% higher WTW GHG emissions than MSD/HSD engines, respectively (Figure 9a). This is due to the high methane slip from LBSI (4.1 g $CH_4/kWh_{engine\ output}$) and MS-LPDF (6.9 g $CH_4/kWh_{engine\ output}$) engines as demonstrated in Figure 9b. If the methane slip from LSBI and MS-LPDF engines is reduced by 9% and 27% from the current levels, and reaches 3.7 and 5.0 $g/kWh_{engine\ output}$, respectively, LSBI and MS-LPDF engines will emit the same GHG level as MSD/HSD engines.

For the larger engines used to power OGVs, such as container ships or bulk carriers, we compare the results from LSDs to LS-LPDF and LS-HPDF engines. LS-LPDF engines emit 2% lower WTW GHG emissions than LSD engines (Figure 9a). Methane slip from LS-LPDF engines (3.3 g $CH_4/kWh_{engine\ output}$) is the main cause of the high WTW GHG emissions (Figure 9b). It should be noted that the methane emissions for LS-LPDF engines are based on engine test cell results and not in use measurements such as those conducted for the MS-LPDF engines [16]. In-use measurement of emissions may result in an increase in the methane emissions reducing the benefit still further.

LS-HPDF engine are calculated to reduce WTW GHG emissions by 10% compared to LSD engines mainly due to negligible methane slip as low as 0.01 g $CH_4/kWh_{engine\ output}$ as given in Table 17. From this analysis, it can be concluded that LS-HPDF engines produce incontrovertible evidence of GHG reduction in all cases because the error bars do not overlap with those of the corresponding LSD case as shown in Figure 9a.

6.3. Well-to-wake NOx emissions

The WTW NOx emissions are shown in Figure 10 and compared to the IMO NO_x emissions tier standard for the corresponding engine speed. The results indicate that while MSD/HSD and LSD engines meet IMO Tier II emissions standards, they cannot meet the more stringent Tier III standards without any aftertreatment and/or EGR. In contrast, LBSI and MS-LPDF engines are observed to be an effective means to meet IMO Tier III NO_x emissions with 77% and 70% lower

WTW NO_x emissions than MSD/HSD engines, respectively. Similarly, LS-LPDF engines have 74% lower WTW NOx emissions than LSD engines and also meet the Tier III standards for low-speed engines.

Figure 10 shows that LS-HPDF engines, while reducing NO_x emissions by 22% compared to LSD engines, do not meet Tier III standards and would require EGR or SCR in in order to meet Tier III NO_x standards.

6.4. Well-to-wake SO_x emissions

Figure 11 displays the WTW SO_x emissions from LNG- and HFO-fuelled ships. The dashed lines in Figure 11 shows SO_x emissions from LSD and MS/HSD engines burning fuels with sulphur contents less than 2.5% (e.g. 0.5% sulphur). These values are proportionally reduced from the fuel with 2.5% sulphur because SOx emissions are based on the conservation of mass of sulphur in the fuel.

The results show that natural gas engines almost eliminate SO_x emissions reducing them by 95-98% on a WTW basis when compared to LSD and MSD/HSD engines using HFO with 2.5% sulphur content. The residual SO_x emissions in LPDF and HPDF engines are due to the sulphur content of the pilot fuel used to ignite the natural gas, and can be further reduced if low-sulphur pilot fuel is used. Figure 11 indicates that all natural gas engine variants meet even the most stringent 0.1% sulphur equivalent standard that is required in the SO_x ECAs, and easily meet the IMO 2020 global 0.5% sulphur standard.

LSD and MSD/HSD engines require SO_x scrubber to meet SO_x emissions limit in ECAs unless a switch is made to low-sulphur fuels. Considering IMO 2020 limits on sulphur content of fuels shows that using HFO with 0.5% outside of ECAs and 0.1% sulphur content inside ECAs will significantly reduce WTW SO_x emissions. This will reduce SO_x reduction benefits of LNG used as a marine fuel.

6.5. Well-to-wake PM emissions

The WTW PM emissions from the LNG- and HFO-fuelled ships are shown in Figure 12. PM emissions are directly affected by the sulphur content of fuels [2]. The PM emissions from LSD and MSD/HSD engines under varying sulphur content were obtained from Comer et al. [27]. The results of the analysis of WTW PM emissions from LNG and HFO supply chains indicate that

LBSI, MS-LPDF, and LS-LPDF engines have 97-98% lower WTW PM emissions than LSD, and MSD/HSD engines.

Figure 12 indicates that LS-HPDF engines have 35% lower WTW PM emissions than LSD engines. As shown in Figure 12, using fuels with 0.5% and 0.1% sulphur contents will reduce the baseline PM emissions from LSD and MSD/HSD engines up to 85%.

7. Conclusion and Policy Implications

Natural gas fuel is now a viable option for all vessel types and sizes due to the development of large low-speed gas engines. A LCA of domestic and imported LNG compared to HFO for marine shipping was conducted and compared with published literature. The results indicate that for smaller vessels powered by medium- or high-speed engines, the alternative natural gas engines emitted similar or higher levels of GHG compared to their HFO counterparts due to high methane slip from these engines. These results mean that for the majority of early applications, such as ferries, offshore support vessels and other small vessels that use LBSI or MS-LPDF engines, LNG cannot be regarded as a robust means of reducing GHG emissions.

For the larger ocean-going vessels that contribute to the majority of global GHG emissions from shipping, the results of the analysis indicated that LS-LPDF and LS-HPDF engines emitted 2% and 10% lower WTW GHG emissions than LSD engines, respectively. LS-LPDF engine results are based on engine test cell measurements only and may be subject to increases similar to those observed in MS-LPDF engines when in-operation measurements were conducted. This means that LS-HPDF engines are the only option that will reliably produce GHG reductions, however these engines require expensive high-pressure fuel gas supply system.

In terms of NO_x emissions, the results indicated that LBSI, MS-LPDF and LS-LPDF engines had lower NO_x emissions than conventionally-fuelled engines and no exhaust gas aftertreatment was required to meet IMO Tier III standards. However, the NO_x emissions of LS-HPDF engines was only 22% lower than LSD engines and EGR and/or SCR systems will be required to meet the Tier III NO_x emissions requirements in NO_x ECAs. The LCA also indicated that all natural gas engines emitted almost negligible SO_x emissions compared with LSD and MSD/HSD engines. However, the results show that using HFO with low sulphur content can significantly reduce the baseline WTW SO_x and PM emissions. Sulphur controls, such as the 2020 act, move to limit sulphur to 0.5% globally. However, this will increase the cost of the HFO used by most OGVs, enhancing the economic case for natural gas fuel.

In general, the results suggested that LNG as an alternative to HFO for marine shipping has the potential to reduce NO_x, SO_x and PM emissions. Only LS-HPDF engines had shown to reduce GHG emissions based on current technologies. Despite efforts to minimise methane slip from LBSI and LPDF engines, especially at partial loads, these engine types could not be shown to reduce GHG emissions in all cases.

Acknowledgement

The authors gratefully acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and MITACS Elevate Postdoctoral Fellowship.

Nomenclature

BC	Black Carbon
CAC	Criteria air contaminant
ECA	Emission control area
EEDI	Energy Efficiency Design Index
EGR	Exhaust gas recirculation
GHG	Greenhouse gas
GT	Gas turbine
GWP	Global warming potential
HFO	Heavy fuel oil
HPDF	High pressure dual-fuel engine
HSD	High speed diesel engine
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
LBSI	Lean burn spark ignition

LCA	Life cycle assessment
LHV	Lower heating value
LPDF	Low pressure dual-fuel engine
LS	Low speed
LSD	Low speed diesel engine
MDO	Marine diesel oil
MGO	Marine gas oil
MS	Medium speed
MSD	Medium speed diesel engine
NO_x	Oxides of nitrogen
OGV	Ocean-going vessel
PM	Particulate matter
RO/RO	Roll-on/roll-off vessels
SCR	Selective catalytic reduction
SO_x	Oxides of sulphur
ST	Steam turbine
TEU	Twenty-foot equivalent unit
THC	Total hydro carbon
TTW	Tank-to-wake
WTT	Well-to-tank
WTW	Well-to-wake

References

[1] N. Olmer, B. Comer, B. Roy, X. Mao, D. Rutherford, Greenhouse Gas Emissions From Global Shipping, 2013–2015, The International Council on Clean Transportation, 2017. https://www.theicct.org/publications/GHG-emissions-global-shipping-2013-2015.

[2] T.W.P. Smith, J.P. Jalkanen, B.A. Anderson, J.J. Corbett, J. Faber, S. Hanayama, et al., Third IMO Greenhouse Gas Study 2014, International Maritime Organization (IMO), 2014. doi:10.1007/s10584-013-0912-3.

[3] Emission Database for Global Atmospheric Research (EDGAR v4.3.2), Eur. Comm. Jt. Res. Cent. (2016). http://edgar.jrc.ec.europa.eu/overview.php?v=431 (accessed August 24, 2017).

[4] R. Verbeek, G. Kadijk, P. van Mensch, C. Wulffers, B. van den Beemt, F. Fraga, Environmental and economic aspects of using LNG as a fuel for shipping in the Netherlands, TNO-RPT-2011-00166, 2011.

[5] L. Laugen, An environmental life cycle assessment of LNG and HFO as marine fuels, Institutt for marin teknikk, 2013.

[6] D. Lowell, M.J. Bradley, H. Wang, N. Lutsey, Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping, 2013. http://www.theicct.org/sites/default/files/publications/ICCTwhitepaper_MarineLNG_130513.pdf.

[7] D. Baresic, T. Smith, C. Raucci, N. Rehmatulla, K. Narula, I. Rojon, LNG as a marine fuel in the EU: Market, bunkering infrastructure investments and risks in the context of GHG reductions, University Maritime Advisory Services, 2018.

[8] Sulphur Emission Control Areas, Hallmark Fuels Int. Ltd. (n.d.). http://www.hallmarkfuels.com/eca (accessed July 4, 2018).

[9] Sulphur oxides (SOx) and Particulate Matter (PM) – Regulation 14, Int. Marit. Organ. (n.d.). http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-—Regulation-14.aspx (accessed November 21, 2018).

[10] Nitrogen Oxides (NOx) – Regulation 13, Int. Marit. Organ. (n.d.). http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-—-Regulation-13.aspx (accessed July 4, 2018).

[11] Energy Efficiency Measures, Int. Marit. Organ. (n.d.). http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Te

chnical-and-Operational-Measures.aspx (accessed November 21, 2018).

[12] Low carbon shipping and air pollution control, Int. Marit. Organ. (2018). http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx (accessed July 7, 2018).

[13] Alicia Milner, Liquefied Natural Gas: A Marine Fuel for Canada’s West Coast, Canadian Natural Gas Vehicle Alliance, 2014.

[14] Big boys join the LNG-fuelled fleet, LNG World Shipp. (n.d.). http://www.lngworldshipping.com/news/view,big-boys-join-the-lngfuelled-fleet_51714.htm (accessed July 4, 2018).

[15] Clean cities alternative fuel price report (July 2018), U.S. Department of Energy, 2018. https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_july_2018.pdf.

[16] D. Stenersen, O. Thonstad, GHG and NOx emissions from gas fuelled engines, SINTEF Ocean AS (OC2017 F-108 - Unrestricted), 2017.

[17] Rolls-Royce delivers first mobile MTU gas engines for Rederij Doeksen, (2017). https://www.rolls-royce.com/media/our-stories/press-releases/2017/13-12-2017-rr-delivers-first-mobile-mtu-gas-engines-for-rederij-doeksen.aspx (accessed July 18, 2018).

[18] What is the ME-GI Engine?, MAN Diesel & Turbo, Report No. LRJ/LDR2016.14.09, 2016.

[19] Low-speed Engines 2018, 2018. https://www.wingd.com/en/documents/general/brochures/wingd-low-speed-engines-2018.pdf/.

[20] MAN B&W ME-GI: Dual fuel low speed engine, (n.d.). https://marine.man-es.com/docs/librariesprovider6/marine-broschures/1510-0112-03ppr_me-gi_low77ed34f0bf5969569b45ff0400499204.pdf?sfvrsn=0.

[21] G. Myhre, D. Shindell, F.M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, et al., Anthropogenic and Natural Radiative Forcing, Clim. Chang. 423 (2013) 659–740. doi:10.1017/ CBO9781107415324.018.

[22] D. Sommer, M. Yeremi, J. Son, J. Corbin, S. Gagne, P. Lobo, et al., Characterization and

reduction of in-use CH4 emissions from a dual fuel marine engine using a portable, low-cost wavelength modulation spectroscopy sensor, Environ. Sci. Technol. Submitted (2019).

[23] A. Armellini, S. Daniotti, P. Pinamonti, M. Reini, Evaluation of gas turbines as alternative energy production systems for a large cruise ship to meet new maritime regulations, Appl. Energy. 211 (2018) 306–317. doi:https://doi.org/10.1016/j.apenergy.2017.11.057.

[24] LNG fuelled PERFECt: Piston Engine Room Free Efficient Containership, DNV GL, 2015. https://www.dnvgl.com/maritime/lng/perfect-2.html.

[25] T.F. Stocker, Q. Dahe, G.-K. Plattner, M.M.B. Tignor, S.K. Allen, J. Boschung, et al., Climate Change 2013: The Physical Science Basis, Intergovernmental Panel on Climate Change- Fifth Assessment Report, 2014.

[26] K. Adams, D.S. Greenbaum, R. Shaikh, A.M. Van Erp, A.G. Russell, K. Adams, et al., Particulate matter components , sources , and health : Systematic approaches to testing effects, J. Air Waste Manage. Assoc. 65 (2015) 544–558. doi:10.1080/10962247.2014.1001884.

[27] B. Comer, N. Olmer, X. Mao, B. Roy, D. Rutherford, Black carbon emissions and fuel use in global shipping 2015, The Internationa Counsil on Clean Transportation, 2017.

[28] T.C. Bond, S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. Deangelo, et al., Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res. Atmos. 118 (2013) 5380–5552. doi:10.1002/jgrd.50171.

[29] G. Myhre, D. Shindell, F.-M.F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, et al., Anthropogenic and natural radiative forcing: Supplementary material, Clim. Chang. (2013) 1–44. doi:10.1017/ CBO9781107415324.018.

[30] J.S. Fuglestvedt, K.P. Shine, T. Berntsen, J. Cook, D.S. Lee, A. Stenke, et al., Transport impacts on atmosphere and climate: Metrics, Atmos. Environ. 44 (2010) 4648–4677. doi:10.1016/j.atmosenv.2009.04.044.

[31] W.J. Collins, S. Sitch, O. Boucher, How vegetation impacts affect climate metrics for ozone precursors, J. Geophys. Res. Atmos. 115 (2010) 1–14. doi:10.1029/2010JD014187.

[32] K. Ødemark, S.B. Dalsøren, B.H. Samset, T.K. Berntsen, J.S. Fuglestvedt, G. Myhre, Short-lived climate forcers from current shipping and petroleum activities in the Arctic, Atmos. Chem. Phys. 12 (2012) 1979–1993. doi:10.5194/acp-12-1979-2012.

[33] Developing port clean air programs: A 2012 update to the International Association of Ports and Harbor's Air Quality Toolbox, Starcrest Consulting Group, LLC, 2012. https://www.theicct.org/sites/default/files/ICCT_SCG_Developing-Clean-Air-Programs_June2012.pdf.

[34] F. Fung, Z. Zhu, R. Becque, B. Finamore, Prevention and control of shipping and Port Air emissions in China, Natural Resources Defense Council, USA, 2014.

[35] IMO 2020 Updated analysis of the marine fuel sulphur changes, Wood Mackenzie, 2018. https://www.woodmac.com/reports/refining-and-oil-products-imo-2020-updated-analysis-of-the-marine-fuel-sulphur-changes-18902.

[36] R. Verbeek, M. Verbeek, LNG for trucks and ships: fact analysis Review of pollutant and GHG emissions Final, TNO Innovation For Life (Report No.: TNO 2014 R11668), The Netherlands, 2015.

[37] A. Taglia, N. Rossi, European gas imports: GHG emissions from the supply chain, Altran Italia, 2009.

[38] T.J. Skone, G. Cooney, M. Jamieson, J. Littlefield, J. Marriott, Life cycle greenhouse gas perspective on exporting liquefied natural gas from the United States, US Department of Energy (DOE/NETL-2014/1649), 2014.

[39] LNG and coal life cycle assessment of greenhouse gas emissions, Pace Global, A Siemens Business, 2015. http://www.lnginitiative.org/wp-content/uploads/2015/10/PACE_Report.pdf.

[40] The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET 2017), (2017). https://greet.es.anl.gov/.

[41] GATE 2020: Gas Advanced Technology for Europe at the Year 2020, ENI Group and FPI, European Commission. Directorate-General for Energy and Transport, European Commission. Directorate General for Research, Ente nazionale idrocarburi (Roma), 2001.

[42] LNG production in British Columbia: Greenhouse gas emissions assessment and benchmarking, Delphi Group, 2013.

[43] I.A. Fernández, M.R. Gómez, J.R. Gómez, Á.B. Insua, Review of propulsion systems on LNG carriers, Renew. Sustain. Energy Rev. 67 (2017) 1395–1411. doi:10.1016/j.rser.2016.09.095.

[44] ME-GI Dual Fuel MAN B & W Engines: A Technical, Operational and Cost-effective Solution for Ships Fuelled by Gas, MAN Diesel & Turbo, 2013.

[45] MAN Diesel, ME-GI Dual Fuel MAN B & W Engines: A Technical, Operational and Cost-effective Solution for Ships Fuelled by Gas, MAN Diesel & Turbo, 2013.

[46] MAN B&W ME-B Engines: Stronger, Shorter, Lighter, (n.d.). https://marine.man-es.com/docs/librariesprovider6/marine-broschures/1510-0091-02ppr_me-b-engines_press9cf034f0bf5969569b45ff0400499204.pdf?sfvrsn=0.

[47] M. Efficiency, H. Reliability, M 43 C: Long-Stroke Diesel Engines for Maximum Efficiency and High Reliability, (n.d.). https://s7d2.scene7.com/is/content/Caterpillar/C10752923.

[48] M. Ott, I. Nylund, R. Alder, T. Hirose, Y. Umemoto, T. Yamada, The 2-stroke low-pressure dual-fuel technology: From concept to reality, in: 28th CIMAC CIMAC World Congr. Combust. Engine, Helsinki, 2016.

Figure Captions

Figure 1. GHG emissions from global shipping in 2015. % of total 932 million tonnes of $CO_{2\text{-equivalent}}$ (CO_{2e}) [1].

Figure 2. The map of ECAs in North America and Northern Europe (Adopted from Ref. [8]).

Figure 3. NOx emissions regulations in marine shipping [10].

Figure 4. A comparison of WTW GHG emissions reported in the literature comparing conventional fuels to LNG.

Figure 5. Domestic and international well-to-tank supply chains for LNG and HFO.

Figure 6. Variations in WTT GHG and air pollutant emissions from domestic LNG supply chain with respect to nominal values given in Table 14.

Figure 7. Variations in WTT GHG and air pollutant emissions from imported LNG supply chain with respect to nominal values given in Table 14.

Figure 8. A comparison of WTT GHG emissions from domestic and imported LNG supply chains reported in the literature and the present study.

Figure 9. (a) WTW GHG and (b) WTW methane emissions from LNG- and HFO-fuelled engines.

Figure 10. Effects of LNG and HFO supply chains on WTW NOx emissions. The dashed lines show the Tier II and III NOx emissions limits. The Tier II NOx emissions limit for medium speed engines are rated based on the engine speed of 130-1999 rpm as shown in Figure 3.

Figure 11. Effects of LNG and HFO supply chains on WTW SOx emissions. The dashed lines show the WTW SOx emissions from fuels with 2.5%, 0.5%, and 0.1% sulphur content to meet IMO 2020 limits.

Figure 12. WTW PM emissions for different engine types with HFO of 2.5%, 0.5% and 0.1% sulphur content. The dashed lines show the WTW PM emissions from fuels with 2.5%, 0.5%, and 0.1% sulphur content.

List of Tables

Table 19. Effect of four natural gas liquefaction technologies on WTT and WTW GHG emissions from LNG supply chain.

Table 1. Annual GHG and air pollutant emissions from shipping industry.

	Source of emissions	**Third IMO report (million tonnes)** [2]						**ICCT Report (million tonnes)** [1]		
		2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
GHG	International Shipping	881	916	858	773	853	805	801	813	812
	Domestic Shipping	133	139	75	83	110	87	73	78	78
	Fishing	86	80	44	58	58	51	36	39	42
NOx	International Shipping	19.93	20.64	19.07	16.71	18.00	17.00	-	-	-
	Domestic Shipping	1.50	1.79	1.00	1.00	1.36	1.21	-	-	-
	Fishing	1.29	1.21	0.64	1.07	0.86	0.79	-	-	-
SOx	International Shipping	10.75	11.08	11.14	9.87	10.85	9.74	-	-	-
	Domestic Shipping	0.32	0.29	0.23	0.26	0.32	0.26	-	-	-
	Fishing	0.52	0.52	0.26	0.45	0.45	0.26	-	-	-
PM	International Shipping	1.50	1.54	1.50	1.33	1.44	1.32	-	-	-
	Domestic Shipping	0.05	0.06	0.04	0.04	0.06	0.04	-	-	-
	Fishing	0.08	0.07	0.04	0.06	0.06	0.04	-	-	-
CO	International Shipping	0.83	0.87	0.82	0.76	0.84	0.81	-	-	-
	Domestic Shipping	0.10	0.11	0.05	0.08	0.08	0.08	-	-	-
	Fishing	0.07	0.07	0.05	0.06	0.05	0.05	-	-	-
BC	Global Shipping	0.12	-	-	0.12-0.283 [3]	-	-	-	-	0.067

Table 2. Ship exhaust emissions reduction by using natural gas-fuelled engines compared with traditionally HFO-fuelled engines [13].

Air pollutant	**The percentage of emissions reduction by using LNG**
SO_x	Over 90%
NO_x	Up to 35% for Diesel cycle compression ignition engines Up to 85% for Otto cycle engines
PM	Over 85%
CO_2	Up to 29%
GHG (in CO_{2e})	Up to 19%

Table 3. Total number of LNG-fuelled ships in May 2017 and May 2018 [14].

Fleet segment	**1 May 2017**	**1 May 2018**
Tankers and bulkers		
In-service	19	24
On-order	28	43
Container and cargo ships		
In-service	11	12
On-order	14	28
Passenger ships		
In-service	40	41
On-order	32	42
Supply and service vessels		
In-service	33	44
On-order	13	19
Fleet totals		
In-service	103	121
On-order	97	132

Table 4. GWP of GHGs for 20- and 100-year horizons based on IPCC Fifth Assessment Report 2014 [25].

Greenhouse gas	**GWP**	
	20-year	**100-year**
CO_2	1	1
CH_4	85	30
N_2O	264	265

Table 5. GWP of air pollutants from ships based on IPCC- 5th Assessment Report [21,29].

Air pollutant	**GWP**		**Ref.**
	20-year	**100-year**	
NOx	-76 to -31	-36 to -25	[30]
NOx	-107	-73	[31]
SO_2	-150 to -37	-43 to -11	[30]
SO_2, Arctic	-47	-13	[32]
Organic carbon, Arctic	-151	-43	[32]
Black carbon aerosol-radiation interaction, Arctic	2037	579	[32]
Black carbon on snow, Arctic	764	217	[32]

Table 6. Exhaust gas aftertreatment technologies in ships (Adopted from Refs. [33,34]).

Emissions control strategy	**Pollutant**		**Costs for ocean-going vessels**	**Considerations**
	PM/SOx	**NOx**		
SCR		√	Capital cost: \$40–135 per kW Operational cost: 7–10% of fuel cost	Best to use with 0.1% sulphur fuel
EGR		√	Capital cost: \$60–80 per kW Operational cost: 4–6% of fuel cost	May need to be coupled with SOx scrubber to remove sulphur and other impurities from the recirculated exhaust gas
Scrubber	√		Capital cost: \$700k–4M Operational cost: 1–3% of fuel cost, plus costs for maintenance and other consumables, such as caustic soda, where applicable	Take up space and wet scrubber discharges may cause ocean acidification

Table 7. WTT and TTW GHG emissions from different LNG and HFO supply chains reported by Verbeek et al. [4].

	GHG (g CO_{2e}/MJ_{fuel})			
	LNG			**HFO**
	Qatar-Netherlands	**North Sea-Netherlands**	**Russia-Netherlands**	
WTT CO_2	9.00	7.5	17.2	9.10
WTT CH_4+N_2O	1.70	1.4	5.9	0.70
TTW CO_2	56.10	56.1	56.1	77.30
TTW CH_4+N_2O	13.40	13.4	13.4	0.40
Total	80.20	78.40	92.60	87.50

Table 8. Comparison of GHG emissions from LNG and HFO reported by Laugen [5].

	GHG (g CO_{2e}/MJ_{fuel})	
	LNG Norway-Netherlands	**HFO**
WTT CO_2	16.86	19.99
WTT CH_4	9.04	2.19
WTT N_2O	2.92	0.54
TTW CO_2	53.31	71.08
TTW CH_4	9.52	0.00
TTW N_2O	0.38	0.49
Total	92.04	94.29

Table 9. Comparison of GHG emissions from LNG supply chains reported by Lowell et al. [6].

	GHG (g CO_{2e}/MJ_{fuel})							
	Imported LNG			**Domestic LNG**				
Pathways	**At import site**	**Distributed with storage**	**Distributed without storage**	**At production site**	**Distributed with storage**	**Distributed without storage**	**New - At production site**	**New - Distributed without storage**
WTT CO_2	11.5	11.8	11.8	19.2	19.5	19.5	11	11.4
WTT CH_4	1.6	6.1	2.7	9.5	13.8	10.6	9.5	10.6
TTW CO_2	48.4	48.4	48.4	48.4	48.4	48.4	48.4	48.4
TTW CH_4	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6
Total	72.1	76.9	73.5	87.7	92.3	89.1	79.5	81

Table 10. Comparison of GHG emissions from LNG and HFO supply chains reported by Baresic et al. [7].

	GHG (g CO_{2e}/MJ_{fuel})	
	LNG	**HFO**
WTT GHG emissions	6.90	11.10
TTW GHG emissions	74.00	79.90
Total	80.90	91.00

Table 11. WTT GHG emissions from different LNG supply chains reported by Taglia and Rossi [37].

	GHG (g CO_{2e}/MJ_{fuel})		
	Egypt-Italy	**Qatar-Italy**	**Trinidad-Spain**
Production	1.446	1.124	1.124
Processing	2.088	2.570	1.767
NG liquefaction	5.141	4.980	5.944
Tanker transport	1.767	4.980	4.016
WTT Total	10.442	13.655	12.852

Table 12. WTT GHG emissions from different LNG supply chains reported by Skone et al. [38].

	GHG (g CO_{2e}/MJ_{fuel})					
	LNG					
	US-Netherlands	**Algeria-Netherlands**	**Russia-Netherlands**	**US-China**	**Russia-China**	**Australia-Japan**
Natural Gas Extraction	4.37	3.78	3.45	4.45	3.53	3.79
Natural Gas Processing	4.45	4.40	4.02	4.52	4.12	4.42
Domestic Pipeline Transport	4.16	4.12	17.58	4.24	23.65	4.14
Liquefaction	8.20	8.11	-	8.34	-	8.15
Tanker/Rail Transport	3.22	1.04	-	6.82	-	1.92
Tanker Berthing & Deberthing LNG Regasification	0.19	0.19	-	0.19	-	0.19
WTT Total	24.59	21.64	25.06	28.56	31.31	22.61

Table 13. WTT GHG emissions from different LNG supply chains reported by Pace Global [39].

	High GHG (g CO_{2e}/MJ_{fuel})				
	LNG				
	US-Japan	**US-South Korea**	**US-India**	**US-China**	**US-Germany**
Natural Gas Extraction	3.15	3.15	3.15	3.15	3.15
Natural Gas Processing	13.05	13.05	13.20	13.20	12.90
Transport	10.50	10.80	10.80	10.95	8.40
WTT Total	26.70	27.00	27.15	27.30	24.45
	Low GHG (g CO_{2e}/MJ_{fuel})				
Natural Gas Extraction	2.55	2.55	2.55	2.55	2.55
Natural Gas Processing	9.30	9.30	9.45	9.30	9.15
Transport	9.45	9.60	9.60	9.75	7.65
WTT Total	21.30	21.45	21.60	21.60	19.35

Table 14. Changes in the lengths of LNG and HFO supply chains and different transport systems.

Parameters	**Nominal value**	**Variation range**
Pipeline length (km)	1,500	100-3,000
Truck travel distance (km)	500	50-2,000
OGV travel distance (km)	9,000	3,000-18,000

Table 15. Effect of four natural gas liquefaction technologies on GHG emissions [42].

Liquefaction technology	**Emissions from liquefaction**	
	g_{CO2e}/kg $_{LNG}$	**g_{CO2e}/MJ$_{fuel}$**†
Industrial gas turbine (IGT)*	360	7.41
Aero-derivative gas turbine (AGT)	220	4.53
AGT and helper motor	150	3.09
Electric-driven compressor	50‡	1.03

* Reference liquefaction technology (Emissions from IGT is similar to the emissions data from natural gas liquefaction used in the GREET 2017 model (7.67 g/MJ$_{fuel}$)).

† Lower heating value of LNG (LHV$_{LNG}$) = 48.6 MJ/kg

‡ Based on electricity grid GHG intensity of 100 g CO_{2e}/kWh$_{electricity}$ [42]

Table 16. Fuel mixtures used in different fuel transport modes.

Fuel transport mode	**Fuel mixture**	
	LNG	**HFO**
Pipeline	Natural gas (98%) + electricity (2%)	Electricity (100%)
Truck	Diesel (100%)	Diesel (100%)
OGV	LNG (54.25%) + HFO (45.75%)	HFO (100%)

Table 17. GHG and air pollutant emissions for different engine technologies and their efficiency.

		Engine type					
		LNG-fuelled engines				**HFO-fuelled engines (HFO with 2.5% sulphur)**	
		LBSI [16]	**MS-LPDF** [16]	**LS-LPDF** [43]	**LS-HPDF** [44]	**LSD** [45]	**MSD/HSD** [27]
Engine Efficiency (J/J)		0.42	0.44	0.505 [19]	0.5 [20]	0.50 [19,46]	0.48 [47]
Emission factor							
NOx	$\text{g/kWh}_{\text{engine output}}$	1.3	1.9	2.68	8.76	11.58	7.70
	$\text{g/MJ}_{\text{fuel}}$	0.15	0.23	0.37	1.22	1.61	1.03
	$\text{g/kg}_{\text{fuel}}$	7.37	11.29	18.27	59.13	62.73	40.04
CO	$\text{g/kWh}_{\text{engine output}}$	1.7	1.9	1.9 [16]	0.79	0.64	0.54
	$\text{g/MJ}_{\text{fuel}}$	0.20	0.23	0.27	0.11	0.09	0.07
	$\text{g/kg}_{\text{fuel}}$	9.64	11.29	12.95	5.33	3.47	2.81
THC	$\text{g/kWh}_{\text{engine output}}$	4.4	7.3	3.3 [48]	0.39	0.19	-
	$\text{g/MJ}_{\text{fuel}}$	0.51	0.89	0.46	0.06	0.03	-
	$\text{g/kg}_{\text{fuel}}$	24.95	43.36	22.50	2.63	1.03	-
CH_4	$\text{g/kWh}_{\text{engine output}}$	4.1	6.9	3.3 [48]	0.01 [27]	0.01 [27]	0.01
	$\text{g/MJ}_{\text{fuel}}$	0.48	0.84	0.46	0.00139	0.0014	0.0013
	$\text{g/kg}_{\text{fuel}}$	23.25	40.99	22.50	0.068	0.054	0.052
	%	2.33	4.10	2.25	0.0068	0.0054	0.0052
CO_2	$\text{g/kWh}_{\text{engine output}}$	472.4	444.2	412	446	577	670
	$\text{g/MJ}_{\text{fuel}}$	55.11	54.29	57.79	61.95	80.14	89.33
	$\text{g/kg}_{\text{fuel}}$	2678.5	2638.6	2808.8	3010.5	3125.4	3484.0
SOx	$\text{g/kWh}_{\text{engine output}}$	0.114	0.17	0.17	0.41	10.29	11.35
	$\text{g/MJ}_{\text{fuel}}$	0.013	0.021	0.024	0.057	1.429	1.513
	$\text{g/kg}_{\text{fuel}}$	0.65	1.01	1.16	2.78	55.74	59.02
PM	$\text{g/kWh}_{\text{engine output}}$	0.03 [27]	0.02 [27]	0.01	0.92 [16]	1.42 [27]	1.43
	$\text{g/MJ}_{\text{fuel}}$	0.0035	0.0024	0.0015	0.128	0.1972	0.1907
	$\text{g/kg}_{\text{fuel}}$	0.17	0.12	0.068	6.23	7.69	7.44

Lower heating value (LHV) of LNG: 48.6 MJ/kg
Lower heating value of HFO: 39.0 MJ/kg
Emissions per unit of fuel energy ($\text{g/MJ}_{\text{fuel}}$) = $1/3.6 \times \text{g/kWh}_{\text{engine output}} \times \text{efficiency}_{\text{engine}}$
Emissions per mass of fuel ($\text{g/kg}_{\text{fuel}}$) = $\text{g/MJ}_{\text{fuel}} \times \text{LHV}_{\text{fuel}}$ (MJ/kg)
Methane slip from engine (%) = $\text{g}_{\text{CH4}}/\text{kg}_{\text{fuel}} \times 0.001$ (kg/g) × 100%

Table 18. WTT GHG and air pollutant emissions from domestic and imported LNG and HFO calculated in the present study.

Supply Chain	**Domestic LNG (g/MJ$_{fuel}$)**					**Imported LNG (g/MJ$_{fuel}$)**				
	CO_{2e}	**CH_4**	**NOx**	**SOx**	**PM**	**CO_{2e}**	**CH_4**	**NOx**	**SOx**	**PM**
NG production	9.14	0.15	0.016	0.0106	0.0008	9.19	0.15	0.016	0.0106	0.0008
NG transport to liquefaction plant	3.71	0.03	0.031	0.0006	0.0001	3.71	0.03	0.031	0.0006	0.0001
NG Liquefaction	7.67	0.04	0.008	0.0016	0.0008	7.67	0.04	0.008	0.0016	0.0008
LNG transport to storage	1.86	0.01	0.004	0.0003	0.0002	3.29	0.01	0.035	0.0102	0.0029
LNG storage and distribution	2.87	0.09	0.001	0.0001	0.0000	2.88	0.09	0.001	0.0002	0.00005
WTT Total	25.25	0.32	0.059	0.0133	0.0020	26.73	0.32	0.091	0.0233	0.0047
	Domestic HFO with 2.5% sulphur (g/MJ$_{fuel}$)					**Imported HFO with 2.5% sulphur (g/MJ$_{fuel}$)**				
Oil extraction and processing	10.15	0.14	0.021	0.009	0.0021	10.15	0.14	0.021	0.009	0.0021
HFO production	4.26	0.01	0.004	0.003	0.0009	4.26	0.01	0.004	0.003	0.0009
HFO storage and distribution	3.01	0.01	0.004	0.003	0.0005	4.21	0.01	0.030	0.021	0.0049
WTT Total	17.41	0.16	0.028	0.015	0.0035	18.61	0.16	0.055	0.034	0.0079

Table 19. Effect of four natural gas liquefaction technologies on WTT and WTW GHG emissions from LNG supply chain.

	Emissions from liquefaction		**WTT emissions**		**WTW emissions (g/MJ$_{\text{engine output}}$)**				**WTW emissions (% reduction)**			
	g$_{\text{CO2e}}$/kg $_{\text{LNG}}$	**g$_{\text{CO2e}}$/MJ$_{\text{fuel}}$**	**g$_{\text{CO2e}}$/MJ$_{\text{fuel}}$**	**% reduction**	**LSD**	**MS-LPDF**	**LS-LPDF**	**LS-HPDI**	**LSD**	**MS-LPDF**	**LS-LPDF**	**LS-HPDI**
Industrial gas turbine (IGT)	360	7.41	24.98	-	224.87	237.67	191.91	182.07	-	-	-	-
Aero-derivative gas turbine (AGT)	220	4.53	22.10	12%	218.01	231.12	186.15	175.37	3%	3%	3%	3%
AGT and helper motor	150	3.09	20.66	17%	214.58	227.85	183.27	172.02	5%	4%	4%	5%
Electric-driven compressor	50	1.03	18.60	26%	209.68	223.17	179.15	167.24	7%	6%	7%	7%
LHV$_{\text{LNG}}$ = 48.6 MJ/kg WTT emissions excluding liquefaction = 17.58 g/MJ												

Figure(s)

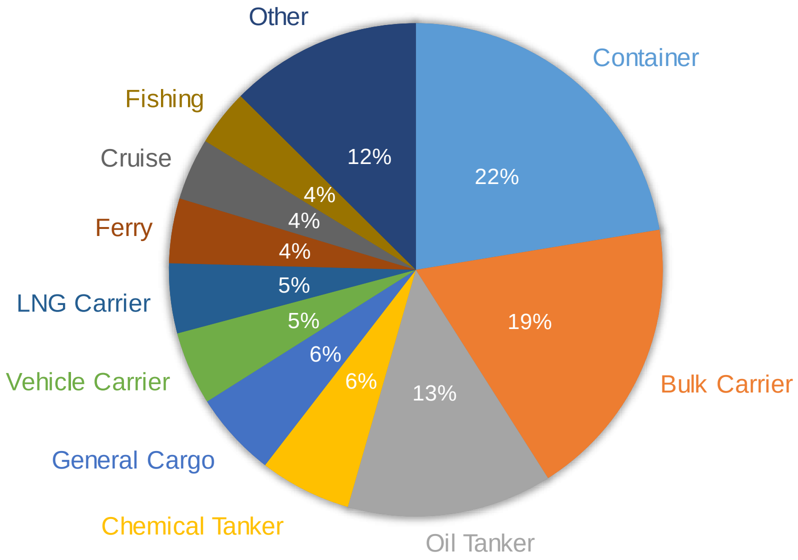

Figure 1. GHG emissions from global shipping in 2015. % of total 932 million tonnes of $CO_{2\text{-equivalent}}$ (CO_{2e}) [1].

Figure 2. The map of ECAs in North America and Northern Europe (Adopted from Ref. [8]).

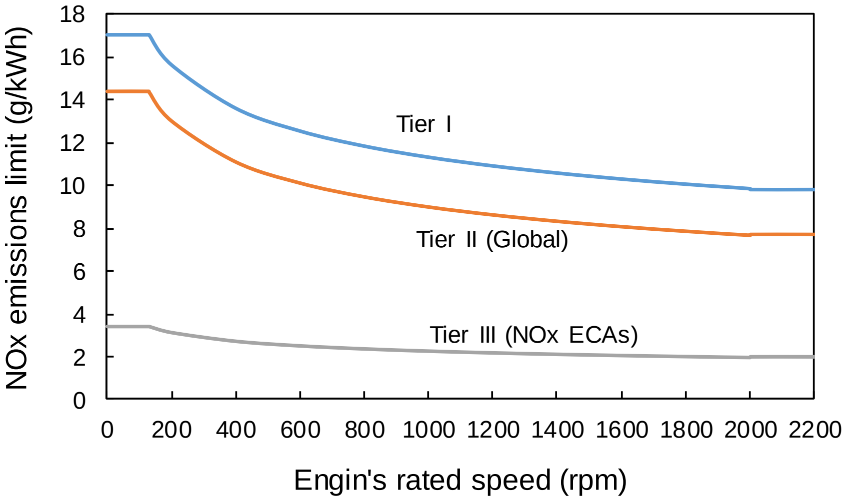

Figure 3. NOx emissions regulations in marine shipping [10].

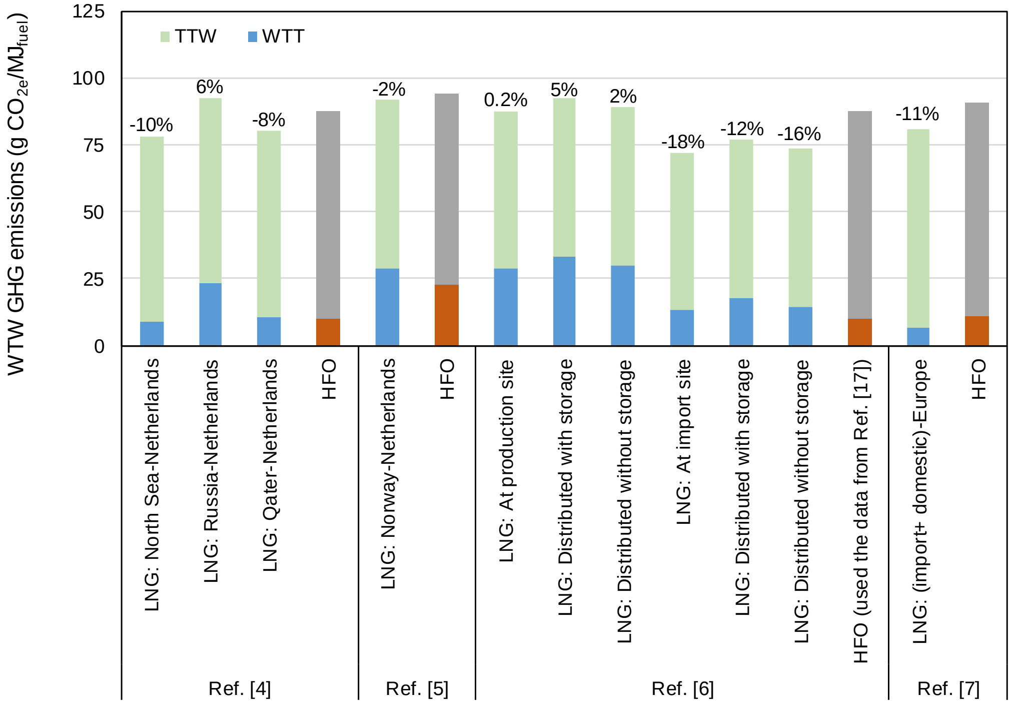

Figure 4. A comparison of WTW GHG emissions reported in the literature comparing conventional fuels to LNG.

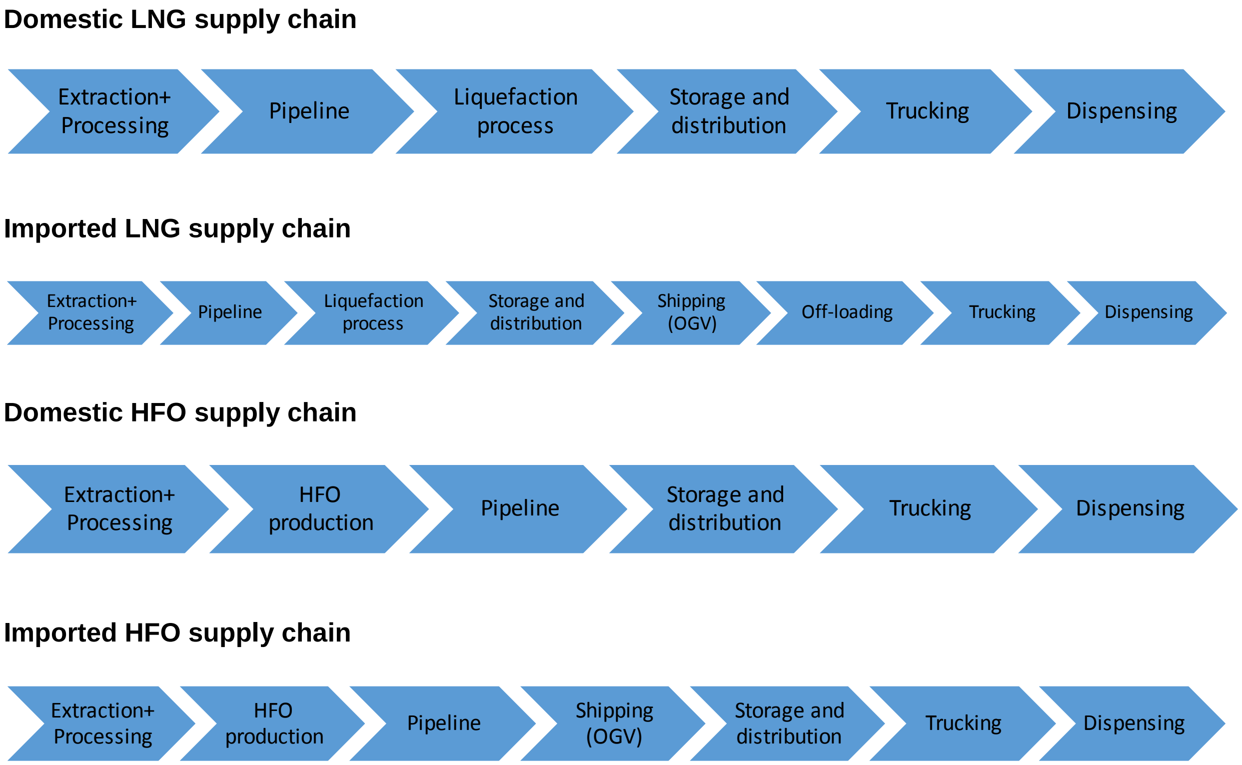

Figure 5. Domestic and international well-to-tank supply chains for LNG and HFO.

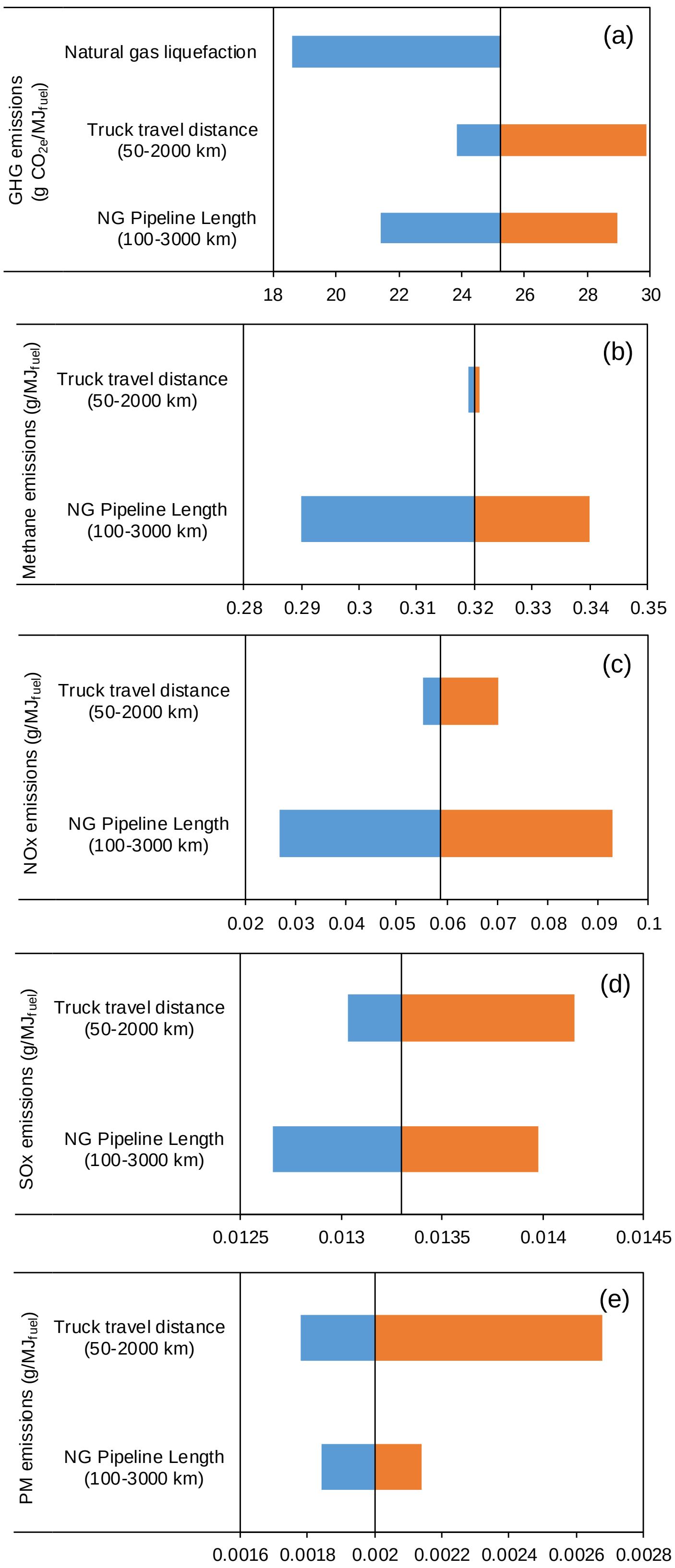

Figure 6. Variations in WTT GHG and air pollutant emissions from domestic LNG supply chain with respect to nominal values given in Table 14.

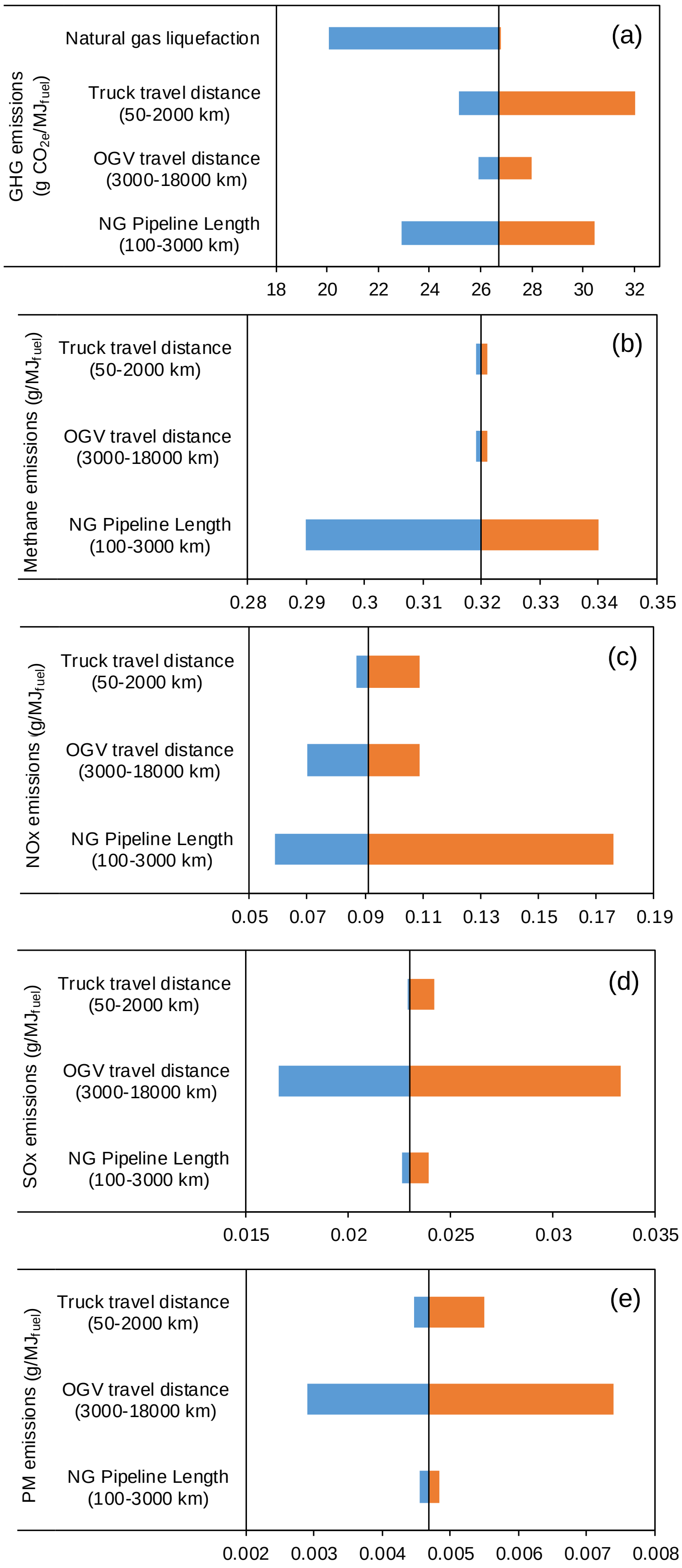

Figure 7. Variations in WTT GHG and air pollutant emissions from imported LNG supply chain with respect to nominal values given in Table 14.

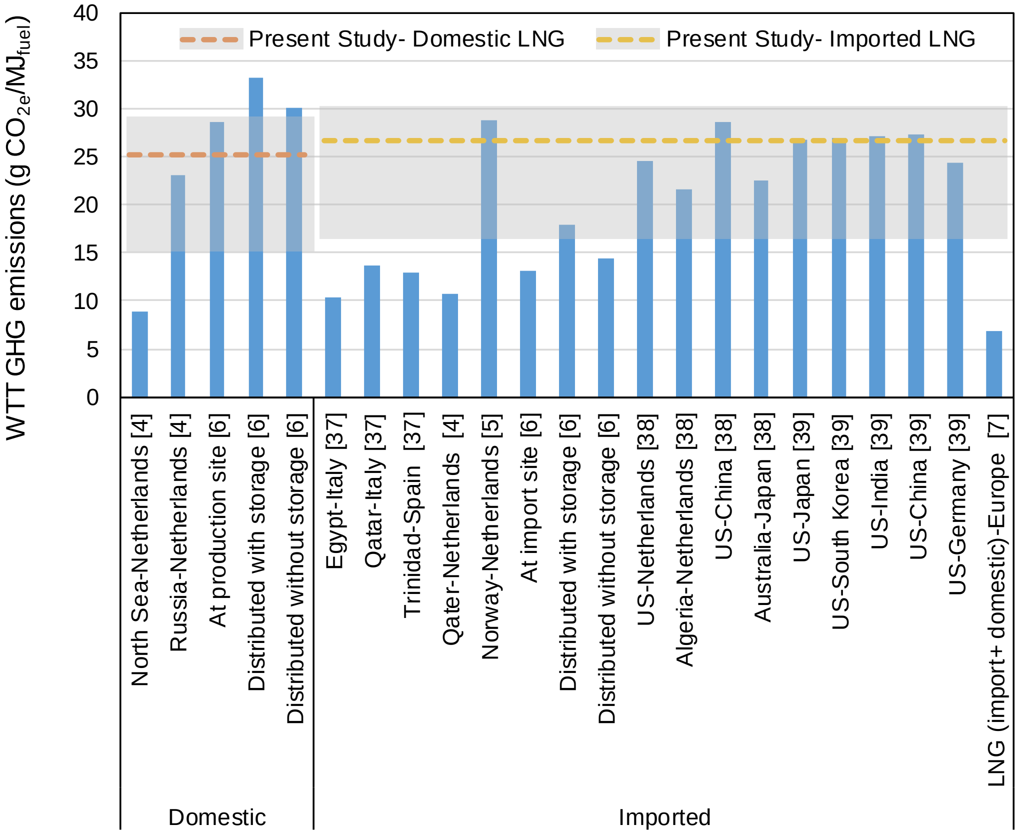

Figure 8. A comparison of WTT GHG emissions from domestic and imported LNG supply chains reported in the literature and the present study.

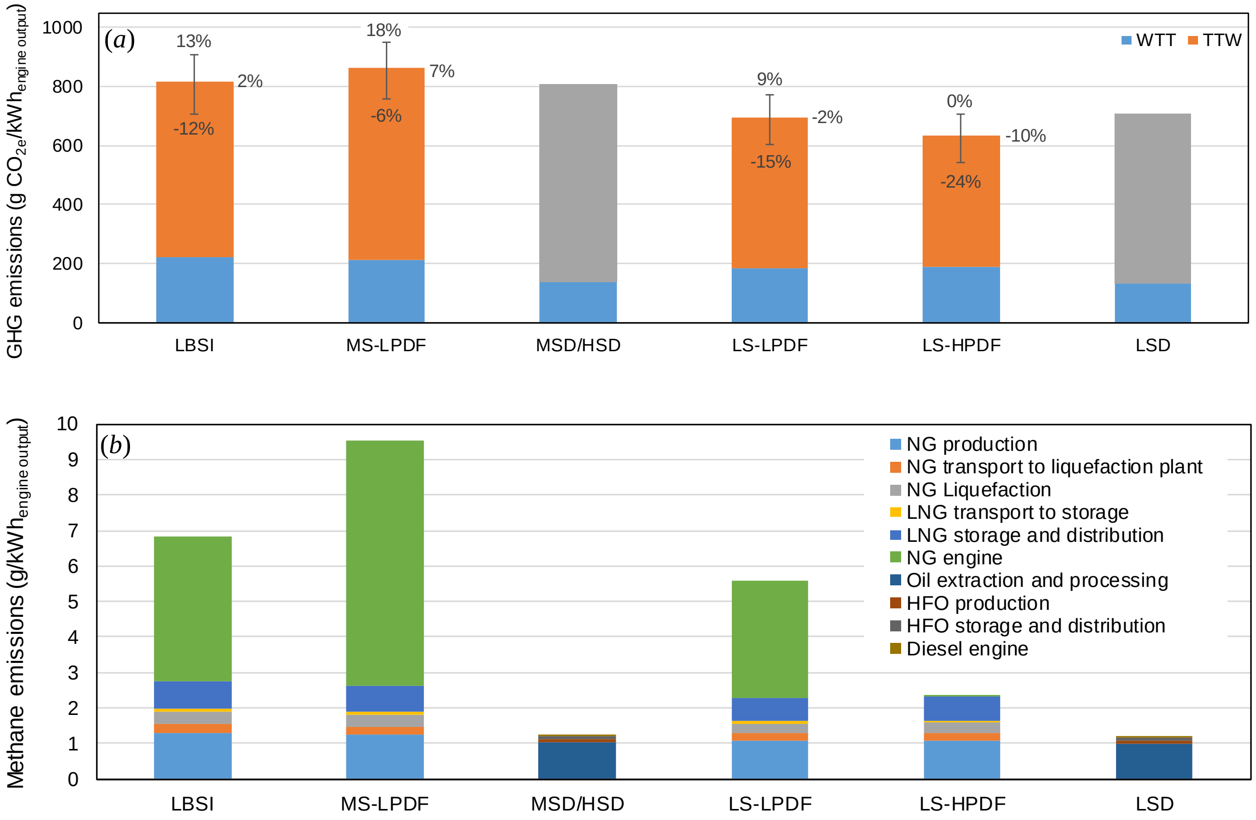

Figure 9. (a) WTW GHG and (b) WTW methane emissions from LNG- and HFO-fuelled engines.

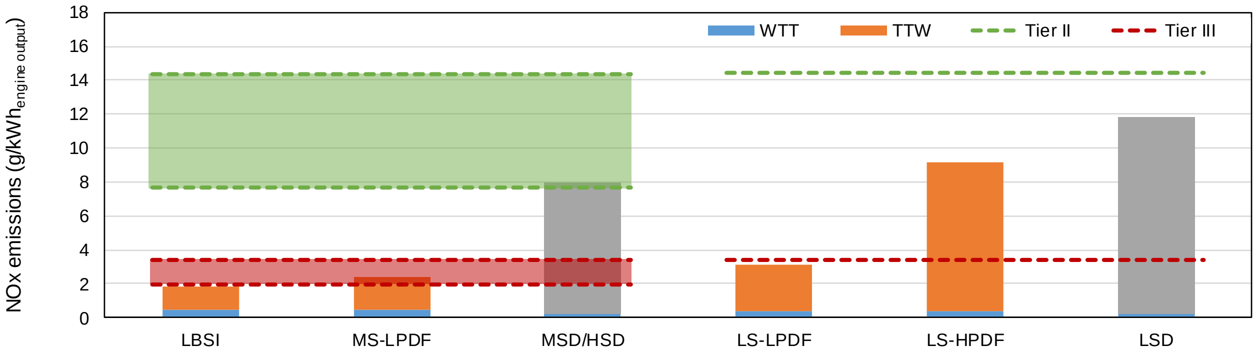

Figure 10. Effects of LNG and HFO supply chains on WTW NOx emissions. The dashed lines show the Tier II and III NOx emissions limits. The Tier II NOx emissions limit for medium speed engines are rated based on the engine speed of 130-1999 rpm as shown in Figure 3.

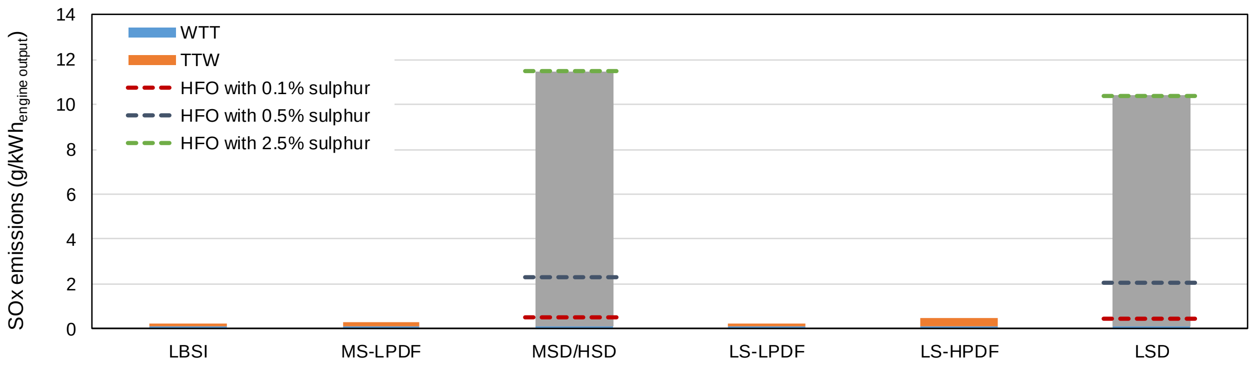

Figure 11. Effects of LNG and HFO supply chains on WTW SOx emissions. The dashed lines show the WTW SOx emissions from fuels with 2.5%, 0.5%, and 0.1% sulphur content to meet IMO 2020 limits.

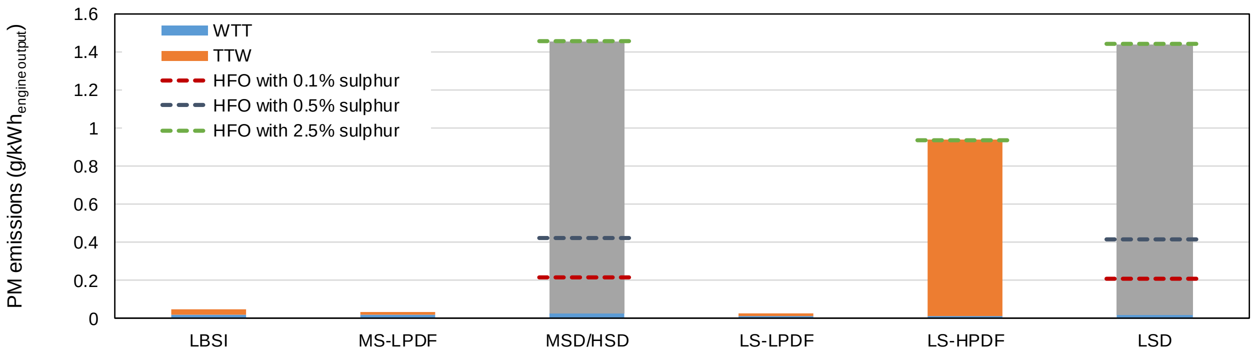

Figure 12. WTW PM emissions for different engine types with HFO of 2.5%, 0.5% and 0.1% sulphur content. The dashed lines show the WTW PM emissions from fuels with 2.5%, 0.5%, and 0.1% sulphur content.