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The climate implications of using LNG as a marine fuel

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Summary

Although liquefied natural gas (LNG) contains less carbon per unit of energy than conventional marine fuels, its use might not reduce greenhouse gas (GHG) emissions on a life-cycle basis. This paper compares the life-cycle GHG emissions of LNG, marine gas oil (MGO), very low sulfur fuel oil, and heavy fuel oil when used in engines suitable for international shipping, including cruise ships. The analysis includes upstream emissions, combustion emissions, and unburned methane (methane slip), and we evaluate the climate impacts using 100-year and 20-year global warming potentials (GWPs).

Over a 100-year time frame, the maximum life-cycle GHG benefit of LNG is a 15% reduction compared with MGO, and this is only if ships use a high-pressure injection dual fuel (HPDF) engine and upstream methane emissions are well-controlled. However, the latter might prove difficult as more LNG production shifts to shale gas, and given recent evidence that upstream methane leakage could be higher than previously expected. Additionally, only 90 of the more than 750 LNG-fueled ships in service or on order use HPDF engines.

Using a 20-year GWP, which better reflects the urgency of reducing GHGs to meet the climate goals of the International Maritime Organization (IMO), and factoring in higher upstream emissions for all systems and crankcase emissions for low-pressure systems, there is no climate benefit from using LNG, regardless of the engine technology. HPDF engines using LNG emitted 4% more life-cycle GHG emissions than if they used MGO. The most popular LNG engine technology is low-pressure dual fuel, four-stroke, medium-speed, which is used on at least 300 ships; it is especially popular with LNG-fueled cruise ships. Results show this technology emitted 70% more life-cycle GHGs when it used LNG instead of MGO and 82% more than using MGO in a comparable medium-speed diesel (MSD) engine.

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Given this, we conclude that using LNG does not deliver the emissions reductions required by the IMO's initial GHG strategy, and that using it could actually worsen shipping's climate impacts. Further, continuing to invest in LNG infrastructure on ships and on shore might make it harder to transition to low-carbon and zero-carbon fuels in the future. Investing instead in energy-saving technologies, wind-assisted propulsion, zero-emission fuels, batteries, and fuel cells would deliver both air quality and climate benefits.

Background

In 2018, the IMO adopted an initial strategy to reduce and eventually eliminate GHGs from the international maritime shipping sector. This transition will require using fuels that contain less carbon and, eventually, zero carbon. LNG contains less carbon per unit of energy than conventional marine fuels, which means that burning it emits less carbon dioxide (CO_2). However, there are other GHG emissions to consider.

LNG consists mainly of methane. Over a 20-year time period, methane traps 86 times more heat than the same amount of CO_2. If even a small amount of methane escapes anywhere along the process of extracting it from the earth and burning it in an engine, using LNG could emit more life-cycle GHGs than conventional fuels. Judging the climate implications of using LNG as a marine fuel therefore requires comparing the life-cycle GHG emissions of LNG to those of conventional marine fuels.

This is a timely issue. LNG represented less than 3% of ship fuel consumption in the years 2013 through 2015 (Olmer, Comer, Roy, Mao, & Rutherford, 2017), but more ships than ever are now using LNG. In 2019, there were 756 LNG-powered ships, of which 539 were LNG carriersup from 355 ships, including 309 LNG carriers, in 2012, according to internal ICCT analysis based on IHS (2019) data. As illustrated in Figure 1, the number of LNG-fueled ships of all kinds has increased steadily over the past decade, especially in the ferry, offshore, tanker, and container segments. New cruise ships are also being built with LNG engines. Additionally, LNG carriers, which use their cargo as fuel, continue to be built as global demand for LNG grows (see Figure 2).

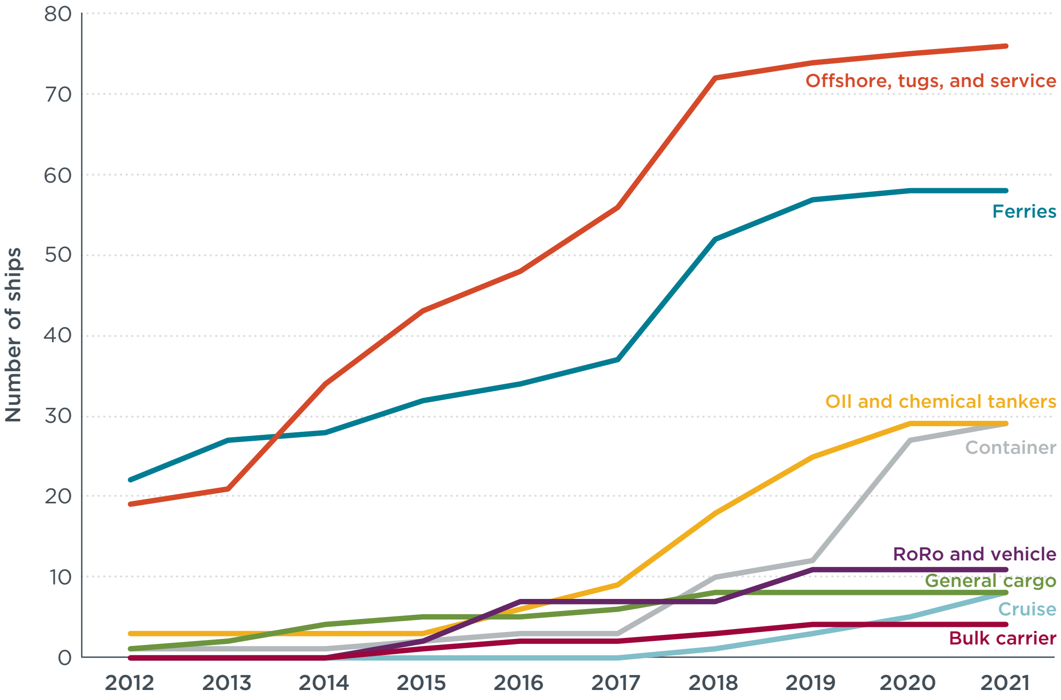

Figure 1. Cumulative LNG-fueled ships built or on order as of mid-2018 (excluding LNG carriers). Source: IHS (2019)

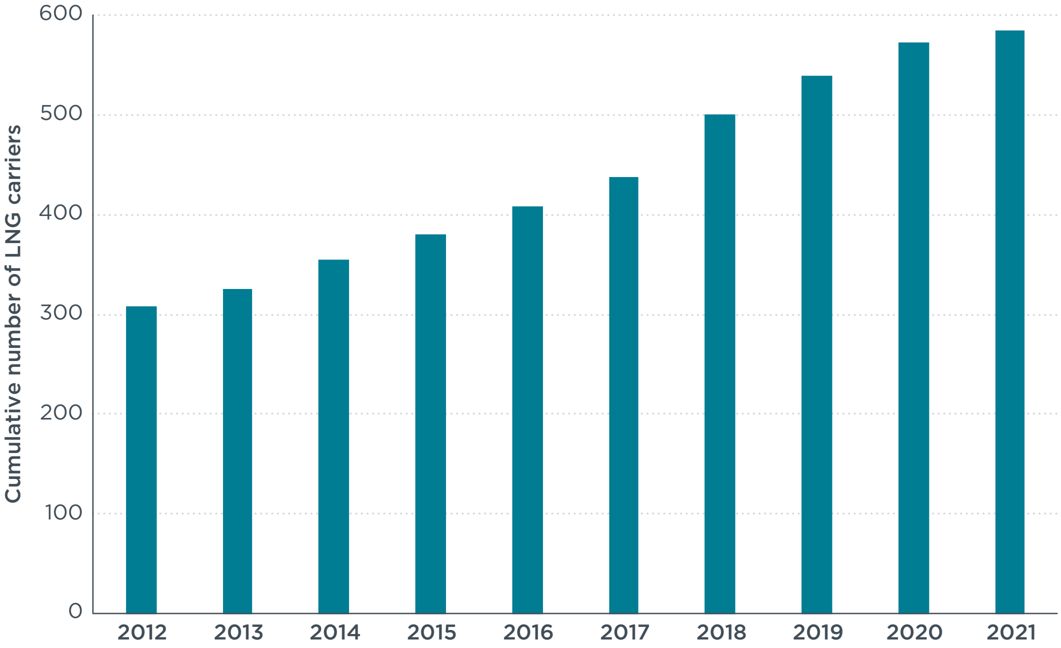

Figure 2. Cumulative LNG carriers built or on order as of mid-2018. Source: IHS (2019)

LNG is becoming popular for several reasons. First, it contains very little sulfur. Additionally, LNG engines are tuned to either emit low nitrogen oxide (NO_x) emissions—at the cost of higher methane emissions in some cases—or to incorporate NO_x reduction technologies such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR). These low sulfur oxide (SO_x) and NO_x emissions make LNG an attractive fuel for ships that operate in Emission Control Areas (ECAs), where ships must comply with more stringent air quality standards.

Second, LNG is, and has been, less expensive than MGO and is now in some regions cheaper than heavy fuel oil (HFO). Moreover, to comply with IMO's 2020 global sulfur limit, ships must either switch from HFO to more expensive very low sulfur fuel oil (VLSFO) or use HFO with a scrubber, if they have one installed. However, the use of scrubbers has recently come under intense scrutiny and is undergoing regulatory review due to concerns about both the reliability of these systems to deliver consistent air pollution compliance and because of the water pollution produced by open-loop operations. Increasing numbers of national, sub-national, and local regions have disallowed the use of open-loop scrubbers, including Malaysia, China, Singapore, and the port of Fujairah; the Panama Canal also recently banned the use of open-loop scrubbers. California disallows the use of all scrubbers—open-loop or closed-loop—because of evidence that suggests that scrubbers may not result in equivalent emissions reductions as ECA-compliant fuels.

As of November 2019, VLSFO was nearly as expensive as MGO. LNG will likely remain less expensive than VLSFO in the future and might be less expensive than HFO, depending on how the price of HFO responds to the IMO's 2020 global sulfur limit (CE Delft et al., 2016). Therefore, some ship owners are finding that it makes economic sense to invest in an LNG-fueled ship.

In this paper, we compare the life-cycle GHG emissions of LNG, MGO, VLSFO, and HFO when used in engines suitable for international shipping, including cruise ships. We include upstream emissions, combustion emissions, and unburned methane (methane slip), and we evaluate climate impacts using 100-year and 20-year GWPs.

Policy context

Several regional and global policy developments help explain the recent surge of interest in LNG as a marine fuel. These include stricter air pollution regulations, energy efficiency regulations, Arctic protection efforts, and climate concerns.

In addition to global fuel sulfur limits, stricter air pollution regulations for shipping are found in the four IMO-designated ECAs: the Baltic Sea, the North Sea, North America (United States and Canada with some polar regions excepted), and the U.S. Caribbean. LNG has been certified as a key compliance technology to reduce both SO_x, which is regulated by a fuel quality requirement, and NO_x, which is reduced through engine combustion improvement or exhaust aftertreatment. The Baltic Sea ECA in particular is supported by a Norwegian NO_x fund that allows companies that make investments in NO_x-reducing technologies to avoid taxation. LNG has been the major beneficiary of investments under the NO_x fund (Bectas, Hubatova, & O'Leary, 2019; NOx Fondet, 2019). Importantly, Ushakov, Stenersen, and Einang (2019) observed that "it is quite often that engines appear to be 'overtuned' resulting in very low nitrogen oxides emission, far below the limit set by the standards" (p. 19). This overtuning, which involves leaner mixtures, would contribute to combustion methane slip. There are cases in which engines may emit low NO_x or low methane, but not both simultaneously.

The IMO's Energy Efficiency Design Index (EEDI) regulations require new ships to become less carbon intensive over time. The EEDI regulates the amount of CO_2 that can be emitted to move goods or people a given distance. Because the EEDI currently only regulates CO_2, ship owners who buy LNG-fueled ships have an easier time meeting the standards. This is because LNG emits approximately 25% less CO_2 than conventional marine fuels in providing the same amount of propulsion power. Until the IMO regulates GHGs, as it has signaled it will do under its initial GHG strategy (Rutherford & Comer, 2018), LNG will remain an effective way for ship owners to meet the standards. The EEDI applies to new ships, but the IMO is also working to regulate GHGs from the existing fleet. Concerns about stranded investments have been raised (Birkett, 2019). Additionally, investing in LNG infrastructure on ships and on shore can make it harder to transition to low-carbon and zero-carbon fuels in the future, sometimes referred to as "carbon lock-in" (Abbasov, 2019).

Another driver of LNG investment may be Arctic protection efforts. As the Earth warms, larger expanses of the Arctic are opening up for deep sea shipping. This, in turn, is driving year-on-year increases in traffic across the Northern Sea Route (Russian waters) and, to a smaller extent, the Northwest Passage (Canadian waters). Shipping and fishing are already a major source of black carbon (BC) near and in the Arctic (Comer, Olmer, Mao, Roy, & Rutherford, 2017a; Comer et al., 2017b), and governments and civil society are concerned about the ecological and climate impacts of increased Arctic shipping, especially BC emissions and the risks of an HFO spill (Comer et al., 2017b). In response, the IMO has called for proposals to regulate BC by 2021 and has agreed to develop a ban on using and carrying HFO as fuel in the Arctic; this ban could be in effect by 2023, and LNG could be used to comply with both policies.

Climate concerns also seem to be driving interest in LNG. While international maritime shipping is not explicitly included in the Paris Agreement, ratifying parties agreed that all sectors should make efforts to reduce GHG emissions consistent with limiting anthropogenic warming well below 2°C and aiming to limit warming to no more than 1.5°C. That principle subsequently spurred the IMO to develop its own climate strategy. Thus it is important to establish a comprehensive understanding of the life-cycle GHG emissions resulting from the use of LNG as marine fuel before significant investments in LNG infrastructure and newbuilds are made.

Agreed to in April 2018, IMO's initial GHG strategy aims to peak GHG emissions as soon as possible, to reduce the carbon intensity of shipping by at least 40% by 2030 compared with 2008 levels, to reduce absolute GHG emissions from 2008 levels by at least 50% by 2050, and to eliminate GHGs from the sector as soon as possible and consistent with the Paris Agreement temperature goals (International Maritime Organization [IMO], 2018). This implies at least a 70% reduction from business-as-usual emissions in 2050 (Rutherford & Comer, 2018). LNG is viewed by some as a key bridge fuel for meeting those targets. However, there is upstream methane leakage and downstream methane slip from LNG that needs to be considered.

Methodology

Methane slip emission factor assumptions

Several ship engine technologies can use natural gas. Among them are:

- steam turbines
- lean burn spark-ignited (LBSI) engines, usually four-stroke, medium-speed
- low-pressure injection dual-fuel (LPDF) engines that are four-stroke, medium-speed
- LPDF engines that are two-stroke, slow-speed
- high-pressure injection dual-fuel (HPDF) engines that are two-stroke, slow-speed (medium-speed is being introduced)
- gas turbines

Each of these engine technologies emits unburned methane (methane slip). Unburned methane arises primarily from incomplete combustion and fuel concealed in crevices in the combustion chamber during compression. Lean mixtures injected at low pressure are associated with more methane slip than high-pressure injection.

For each engine technology, Table 1 describes the types of ships that use them, provides our assumptions for the amount of methane slip from each, and indicates whether we included the technology in our analysis. Methane slip emission factors are weighted to represent IMO's E2 or E3 test cycles. A full description of each technology and the literature that led to our methane slip assumptions is provided in Appendix B. For most engine technologies, the literature includes measurement campaign data on methane slip. However, for HPDF engines, only manufacturer-reported methane slip is available. This is explained in more detail in Appendix B.

Table 1: LNG engines, the ships that use them, and our methane slip emission factor assumptions

Engine type[a]	Example ship types (and engines)	Ships in operation and on order as of mid-2018[b]	Year with the most installations[b]	Thermal efficiency when using LNG[c]	Methane slip (gCH_4/kWh)	Included in our analysis?
LBSI, medium-speed	Car/passenger ferries mostly (e.g., Rolls-Royce/Bergen C26:33L9PG), offshore supply vessels (OSVs), a few general cargo, tugs, and roro vessels	At least 45	2014	48%	4.1	No; has few international shipping or cruise ship applications
LPDF, medium-speed, four-stroke	LNG carriers mostly (e.g., Wärtsilä 12V50DF) with some OSVs and car/passenger ferries; also used for LNG-fueled cruise ships (e.g., MaK 16M46DF)	At least 300, including at least 13 cruise ships	2018	48%	5.5	Yes; has current and future international shipping and cruise ship applications
LPDF, slow-speed, two-stroke	LNG carriers (e.g., Wärtsilä/Winterthur Gas & Diesel (WinGD) 5X72DF) and mega container ships (e.g., Wärtsilä/WinGD 12X92DF). Also, some oil and chemical tankers	At least 50	2020	50%	2.5	Yes; has current and future international shipping and cruise ship applications
HPDF, slow-speed, two-stroke	LNG carriers (e.g., MAN-B&W 5G70ME-C9-GI) as well as container ships and a few car carriers, general cargo carriers, and a bulk carrier	At least 90	2018	53%	0.2	Yes; has current and future international shipping and cruise ship applications
Steam turbine	LNG carriers (e.g., Kawasaki UA-400)	At least 280	2006	28%	0.04	No; has limited future international shipping applications and is an older and less efficient technology compared with other LNG engines
Gas turbine	High-speed ferries (e.g., GE LM2500)	At least 1	2013	37%	0.06	No; has limited, if any, international shipping or cruise ship applications and is less efficient than other LNG engines

[a] LBSI means lean burn spark-ignited; LPDF means low-pressure injection, dual fuel; HPDF means high-pressure injection, dual fuel.
[b] Source: IHS (2019).
[c] For dual-fuel engines, thermal efficiency can be slightly lower when using conventional marine fuels.

Estimating well-to-wake emissions for LNG relative to other marine fuels

For this analysis, we used the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model(Argonne National Laboratory, 2018) to estimate upstream emissions for LNG and conventional marine fuels. GREET provides a robust dataset of emissions related to fuel production and breaks them into various life-cycle phases; there is also the option to supplement with user data to assess the impact of various assumptions on a fuel's full well-to-wake (WtWa) GHG emissions. GREET is used widely by government agencies, industries, and academia because it is transparent, flexible, and contains high-quality data.

While the "downstream" (i.e., the hull-to-wake) emissions from LNG combustion in a given engine are consistent regardless of the source of the LNG, the "upstream" (i.e., well-to-hull) emissions can vary widely across LNG sources. Our literature review, presented in Appendix A, assesses the range of possible upstream life-cycle emissions for LNG. We found substantial variation depending on region of origin, processing assumptions, and transport distance. For this analysis, we used a representative upstream emission factor that reflects typical LNG production practices in the United States because we found that this mix results in well-to-hull (WtH) emissions in the middle of the range we found in the literature.

We used the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) 100-year and 20-year GWP factors for methane, which normalize the climate forcing impact of methane into CO_2 equivalents (CO_2e). Depending on the study, the 100-year GWP for methane in the AR5 can range from 28 to 36 (Balcombe, Speirs, Brandon, & Hawkes, 2018). This variation is created by two factors: First, fossil methane has a higher GWP than biogenic methane because the fraction that oxidizes into CO_2 in the atmosphere is treated as fossil CO_2 rather than biogenic CO_2; this increases the GWP from 28 to 30. Second, one can consider methane's climate-carbon feedbacks by accounting for its impacts on other gases such as ozone (O_3) and hydroxyl (OH), which can slow the removal of GHGs from the atmosphere; this increases the GWP from 30 to 36. We therefore use a 100-year GWP of 36 in this analysis. The equivalent 20-year GWP is 86, which is also used in this analysis.

Well-to-hull emissions from LNG and conventional marine fuels

We use GREET's default assumptions for natural gas and petroleum extraction, which reflect a typical 2017 mix of fuel sources. For LNG, we assume a mix of conventional (48%) and shale gas (52%) produced in the United States and use the most recent baseline in the GREET model.[2] For petroleum, we use the GREET default mix of crude sources, which includes domestic U.S. crude oil (57%), Canadian oil sands crude (10%), and conventional Canadian crude oil (10%); the remainder comes from the Middle East, Africa, and Latin America. For VLSFO, which is not modeled in GREET, we assume a weighted average of 20% HFO and 80% MGO to approximate the blend ratio needed to meet IMO's 2020 global sulfur limit of no more than 0.50%.

We summarize the WtH emissions from conventional marine fuels in Table 2. The emissions from each are broken down by the three primary GHGs attributable to fuel production and then totaled into CO_2e using IPCC AR5 GWP values. HFO has the lowest WtH emissions because it requires less hydrogen and energy at the refinery for processing, and a lower share of refinery energy is allocated to it within the life-cycle analysis than for higher-quality products. LNG has higher WtH emissions than conventional fuels because of its higher upstream methane emissions, and these are primarily due to leakage from extraction, processing, and transport. The liquefaction phase also increases the energy demand and emissions attributable to LNG production, as this increases its emissions relative to natural gas supplied through pipelines.[3]

Table 2: Well-to-hull emissions for LNG and a selection of conventional marine fuels, in grams (g)/megajoule (MJ)

	HFO	VLSFO	MGO	LNG
CH_4	0.1	0.1	0.1	0.3
N_2O	0.0	0.0	0.0	0.0
CO_2	10.7	12.9	13.5	11.0
CO_2e (100-year)	**14.3**	**16.8**	**17.4**	**21.5**
CO_2e (20-year)	**19.2**	**22.0**	**22.7**	**35.6**

Source: GREET (2018)
Note: GWP values from IPCC AR5 (IPCC, 2013)

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[2] This analysis does not assume that all LNG would be sourced from the United States; rather, we use the upstream emission factor associated with LNG produced in the United States as our base case because it falls in the middle of the range of upstream emission factors described in Appendix A.

[3] Liquefaction is a process that cools natural gas to liquid form. Emissions from this process are described in Appendix A.

Hull-to-wake emissions from LNG and conventional marine fuels

Hull-to-wake (HtWa) represents the emissions associated with burning the fuels in a given engine and Table 3 details these combustion emissions by fuel type. The CO_2 combustion emissions from GREET are a function of the carbon content of each fuel except for VLSFO, which we calculate as a 20:80 ratio of HFO and MGO, and for each fuel a portion of the carbon is emitted as volatile organic compounds (VOCs) and carbon monoxide (CO). Burning LNG generates the lowest amount of CO_2 on a per-MJ basis; conversely, HFO has the highest combustion emissions. Fossil fuel combustion also emits small quantities of nitrous oxide (N_2O) and methane (CH_4), both of which are potent climate-forcing agents. The CH_4 amounts in Table 3 represent combustion emissions only; methane slip is a separate and additional source of methane emissions and was included in Table 1.

Table 3: Hull-to-wake combustion emission factors by fuel (g/MJ fuel)

	HFO	VLSFO	MGO	LNG
CH_4	7.5×10^{-4}	7.4×10^{-4}	7.5×10^{-4}	1.8×10^{-2}
N_2O	3.9×10^{-3}	3.8×10^{-3}	3.9×10^{-3}	1.6×10^{-3}
CO_2	80.1	75.6	73.6	56.5
CO_2e (100-year)	**81.2**	**76.6**	**74.7**	**57.5**
CO_2e (20-year)	**81.2**	**76.7**	**74.7**	**58.4**

Source: GREET (2018)
Note: GWP values from IPCC AR5 (IPCC 2013)

Table 4 contains the specific fuel consumption for the engines analyzed. We converted the grams per kilowatt-hour (g/kWh) specific fuel consumption reported by the manufacturers of the example engines listed in Table 1 to MJ of energy demand per kWh of delivered energy. Sources for specific fuel consumption of LNG and MGO come from engine manufacturers: for LPDF, medium-speed, four-stroke (Wärtsilä, 2019a); for LPDF, medium-speed, four-stroke cruise ship version (Caterpillar, 2016); for LPDF, slow-speed, two-stroke (WinGD, 2019); for HPDF, slow-speed, two-stroke (MAN Energy Solutions, 2018); for slow-speed diesel, two-stroke (MAN Energy Solutions, 2017); and for medium-speed diesel, four-stroke (Wärtsilä, 2019b). Specific fuel consumption for other fuels is based on assumed relative energy contents of 40 MJ/kg fuel for HFO, 41.8 MJ/kg fuel for VLSFO, 42.7 MJ/kg for MGO, and 50 MJ/kg for LNG. For HFO, we assumed that the fuel is used in conjunction with a scrubber system, necessitating an additional 2% energy consumption per kWh of delivered energy ('t Hoen & den Boer, 2015). The LPDF, slow-speed, two-stroke and HPDF engines require a small amount of MGO pilot fuel.

We estimated the 100-year and 20-year CO_2e/kWh combustion emission factors for each engine-fuel pair by multiplying the specific fuel consumption listed in Table 4 by the fuel-specific CO_2e emission factors in Table 3. We then added the methane slip emissions from Table 1, assuming a 100-year GWP for methane of 36 and a 20-year GWP of 86. The result is the total life-cycle GHG emissions for each engine-fuel pair.

Table 4: Specific fuel consumption for analyzed engines

Engine type	SFC	HFO[a]	VLSFO	MGO	LNG
LPDF, medium-speed, four-stroke	g/kWh	201	188	184	149
	equivalent MJ/kWh	8.03	7.87	7.87	7.45
LPDF, medium-speed, four-stroke, cruise ship version	g/kWh	199	187	183	147
	equivalent MJ/kWh	7.97	7.81	7.81	7.37
LPDF, slow-speed, two-stroke	g/kWh	198	186	182	142.3[b]
	equivalent MJ/kWh	7.94	7.78	7.78	7.12[b]
HPDF, slow-speed, two-stroke	g/kWh	177	167	163	130.7[c]
	equivalent MJ/kWh	7.10	6.96	6.96	6.54[c]
Slow-speed diesel, two-stroke	g/kWh	180	169	165	N/A
	equivalent MJ/kWh	7.19	7.05	7.05	N/A
Medium-speed diesel four-stroke	g/kWh	188	176	173	N/A
	equivalent MJ/kWh	7.52	7.37	7.37	N/A

[a] Includes a 2% energy consumption penalty for using scrubbers
[b] Requires an additional 0.8 g/kWh (0.034 MJ/kWh) of MGO pilot fuel
[c] Requires an additional 6.1 g/kWh (0.26 MJ/kWh) of MGO pilot fuel

Higher methane scenario

Higher upstream leakage

Researchers have devoted substantial effort in recent years to improving the measurement and mitigation of methane leakage from natural gas extraction, particularly for natural gas extracted from shale formations, which is a more technically demanding method of extraction. As shale has quickly grown to provide a majority of U.S. natural gas over the past decade, the climate implications of shale gas have grown in significance (Energy Information Administration, 2019). This section assesses the impact of higher leakage assumptions for both methane extraction (WtH) and LNG use (HtWa) on upstream methane emissions. For the HtWa phase of LNG use, we also include the emissions from crankcase leakage, as described in Appendix A.

Recent research suggests that methane leakage may be higher for shale gas than for conventional natural gas, largely due to the increased gas venting following high-volume hydraulic fracturing (Howarth, 2015). A review of peer-reviewed analyses by Howarth (2015) suggested the U.S. Environmental Protection Agency's (EPA) assumptions about the upstream methane leakage from shale gas may understate actual emissions. A recent analysis by Alvarez et al. (2018) used surface monitoring at facilities in conjunction with aircraft observations to assess methane leakage assumptions, and found that the U.S. natural gas industry overall has a leakage rate of 2.3%. That is more than 60% higher than the EPA's assumption of 1.4%.

We summarize the baseline EPA assumptions of upstream methane leakage from natural gas in Table 5. Due to the possibility of high upstream methane emissions changing our understanding of the relative climate impacts of LNG compared with conventional marine fuels, we also include a higher leakage scenario based on the analysis developed by Alvarez et al. (2018).

Table 5: Upstream (well-to-hull) methane leakage assumptions

	U.S. conventional natural gas (EPA) – used in conventional portion of baseline	U.S. shale-derived natural gas (EPA) – used in shale portion of baseline	U.S. natural gas (Alvarez et al., 2018) – used in our higher methane scenario
Leakage assumptions (gCH_4/GJ natural gas)			
Extraction	129.9	133.2	203.1
Processing	5.6	5.6	5.6
Transmission and storage	41.4	41.4	41.4
Distribution	18.4	18.4	18.4
Total	**195.3**	**198.6**	**287.8**

Source: GREET (2018) and Alvarez et al. (2018)

We find that with the Alvarez et al. (2018) higher leakage assumptions, upstream LNG emissions increase by nearly 15% relative to the baseline EPA case. However, as combustion emissions are much larger than upstream emissions, this change only increases WtWa emissions (without methane slip) for LNG systems by 4% relative to the baseline case.

Higher downstream slip

Some low-pressure engines may have open crankcases that allow methane to escape without being burned. Our literature review suggests that crankcase losses could amount to 1 gCH_4/kWh. This is consistent with Caterpillar (2015) estimates for crankcase emissions, assuming 0.75% blow-by, as discussed in the literature review in Appendix A. We add 1 g/kWh of methane for each LPDF engine in this scenario.

Results

In this section, we summarize our analysis of life-cycle GHG emissions for engines that are suitable for international shipping and cruise ships. We compared life-cycle GHG emissions from dual-fuel engines using LNG and conventional fuels. We also assessed life-cycle GHG emissions from slow-speed diesel engines (international shipping) and medium-speed diesel engines (cruise ships).

While most life-cycle assessments use 100-year GWP, we also considered the short-term impacts of using LNG. Methane has an atmospheric lifetime of only 12.4 years—a fraction of the lifetime of CO_2—but has a much larger impact on the climate in the near-term. Recall from above that the 20-year GWP, which evaluates the climate-forcing impact of GHGs in a 20-year timeline, for methane is 86. Using this figure, the climate impact of LNG more than doubles.

Additionally, because shale gas is becoming more popular as a source for LNG and because actual methane leakage may be higher than reported (Alvarez et al. 2018), upstream emissions assumptions to date may be too low. Further, using low-pressure engines may result in unburned methane escaping from the crankcase that has not previously been assessed. For these reasons, we also assessed a scenario where the upstream methane leakage and the downstream methane slip are higher.

We present our results under four scenarios:

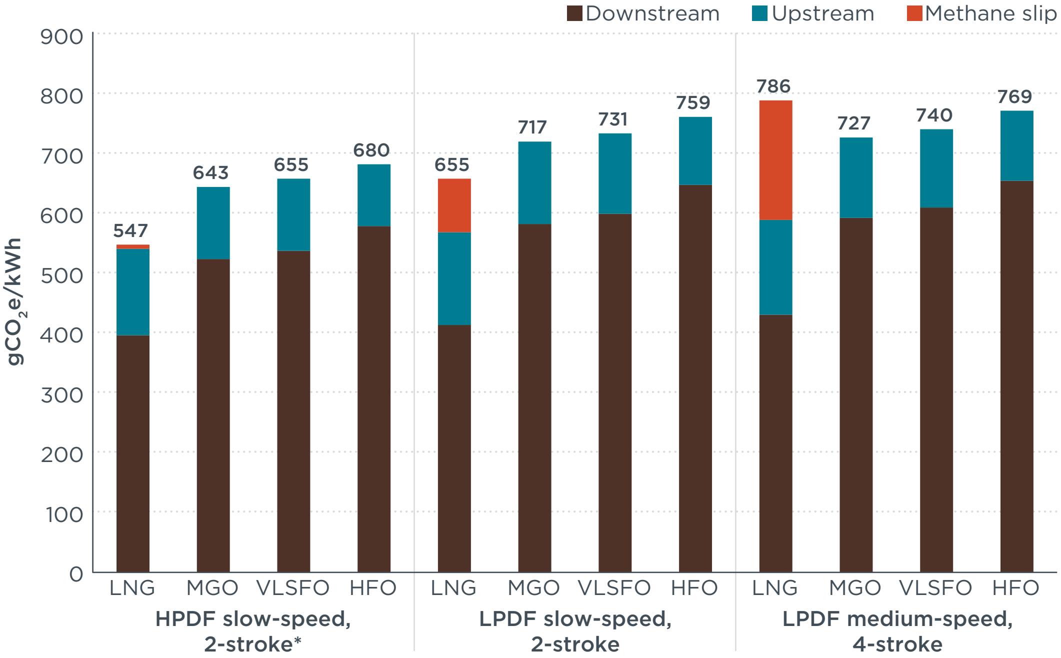
1. 100-year GWP
2. 20-year GWP
3. 100-year GWP with higher upstream leakage and crankcase emissions
4. 20-year GWP with higher upstream leakage and crankcase emissions

Life-cycle emissions considering long-term (100-year) and short-term (20-year) climate impacts

We compare life-cycle GHG using LNG and conventional marine fuels and organize the results by considering engines that are suitable for international shipping, including those more commonly used in cruise ships.

International shipping

As shown in Figure 3, accounting for only upstream (blue bars) and combustion emissions (brown bars) and ignoring methane slip, using LNG in dual-fuel engines would generate life-cycle emissions savings of between 16% and 21% relative to MGO on a 100-year timescale. When we add methane slip (orange bars), those savings erode or disappear. Considering a 100-year time frame, HPDF engines using LNG emit 15% fewer life-cycle GHG emissions compared with when they use MGO and compared with a slow-speed diesel (SSD) using MGO.[4] LPDF slow-speed, two-stroke engines emit about 9% fewer life-cycle GHGs than MGO when using LNG; however, they emit about 1% more lifecycle GHGs than an SSD using MGO. LPDF medium-speed, four-stroke engines emit 8% more lifecycle GHGs when they use LNG instead of MGO and 16% more compared to a 4-stroke medium-speed diesel (MSD) using MGO, as shown in Figure 5.



*SSD has similar life-cycle emissions as HPDF for conventional fuels.

Figure 3: Life-cycle GHG emissions by engine and fuel type, 100-year GWP

Using a 20-year GWP, the only engine type that has lower life-cycle emissions using LNG is the HPDF, and here the emissions savings are relatively small: 3% lower than when it uses MGO (as well as compared with an SSD engine using MGO). Using LNG in either LPDF technology results in much higher life-cycle emissions on a 20-year basis: 17% higher than using MGO for LPDF slow-speed, two-stroke and 52% higher than using MGO for LPDF medium-speed, four-stroke. Using LPDF slow-speed, two-stroke with LNG emits 30% more lifecycle GHG emissions than an SSD using MGO. An LPDF medium-speed, four-stroke emits 62% more lifecycle GHG emissions than an MSD using MGO (see Figure 6).

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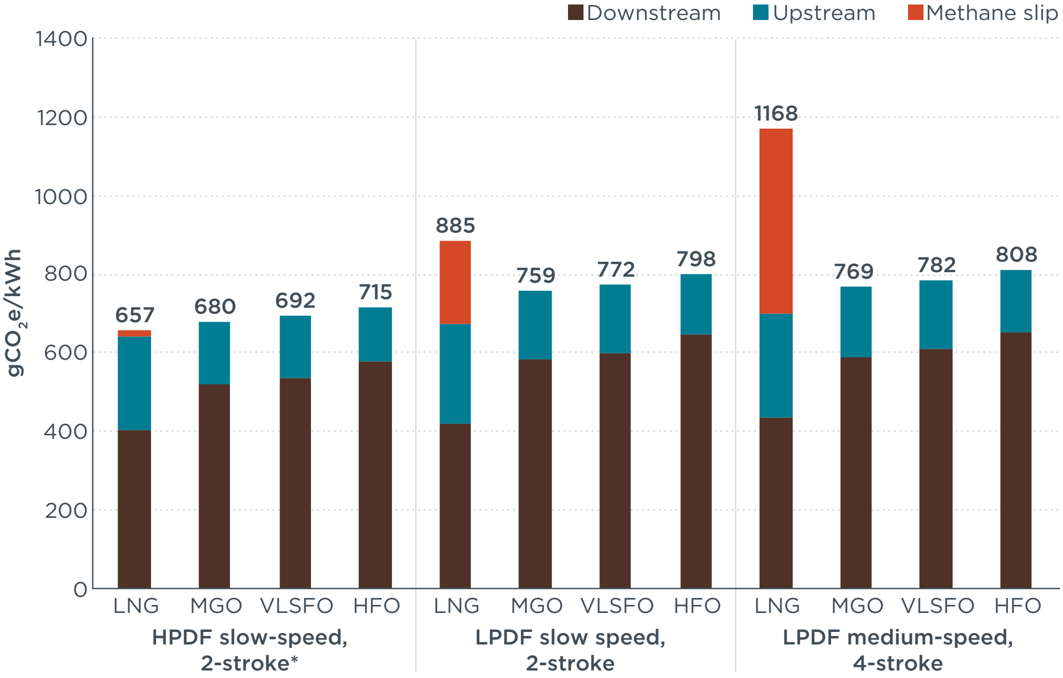
[4] We found that, for conventional fuels, SSD engines emit similar lifecycle emissions as HPDF engines; as such, SSD is excluded from the figure to save space.



*SSD has similar life-cycle emissions as HPDF for conventional fuels.

Figure 4. Life-cycle GHG emissions by engine and fuel type, 20-year GWP

Cruise ships

For cruise ships, we compare LNG and conventional fuels in both LPDF medium-speed, four-stroke engines and medium-speed, four-stroke marine diesel engines. Because low-pressure injection engines emit higher amounts of unburned methane than high-pressure injection engines, using LNG emits more GHGs than conventional fuels on a timescale of 100 years, where it is 8% more than MGO, as shown in Figure 5, as well as on a timescale of 20 years, where it is 52% more than MGO, as illustrated in Figure 6. Also, using the LPDF medium-speed, four-stroke engine with conventional marine fuels emits more life-cycle GHG emissions than a similar marine diesel engine. While the LPDF's thermal efficiency of 48% when using LNG is the same as the marine diesel engine, the LPDF's thermal efficiency drops to 46% when using conventional fuels. This explains the higher combustion and, therefore, life-cycle emissions compared with the marine diesel engine.

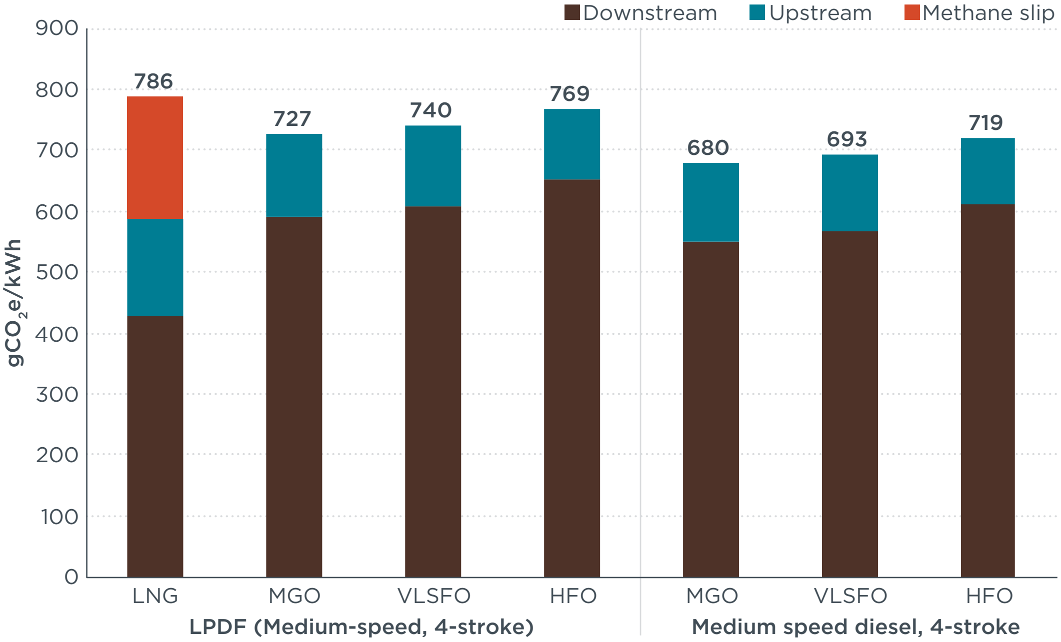


Figure 5: Life-cycle GHG emissions by fuel type for engines suitable for cruise ships, 100-year GWP

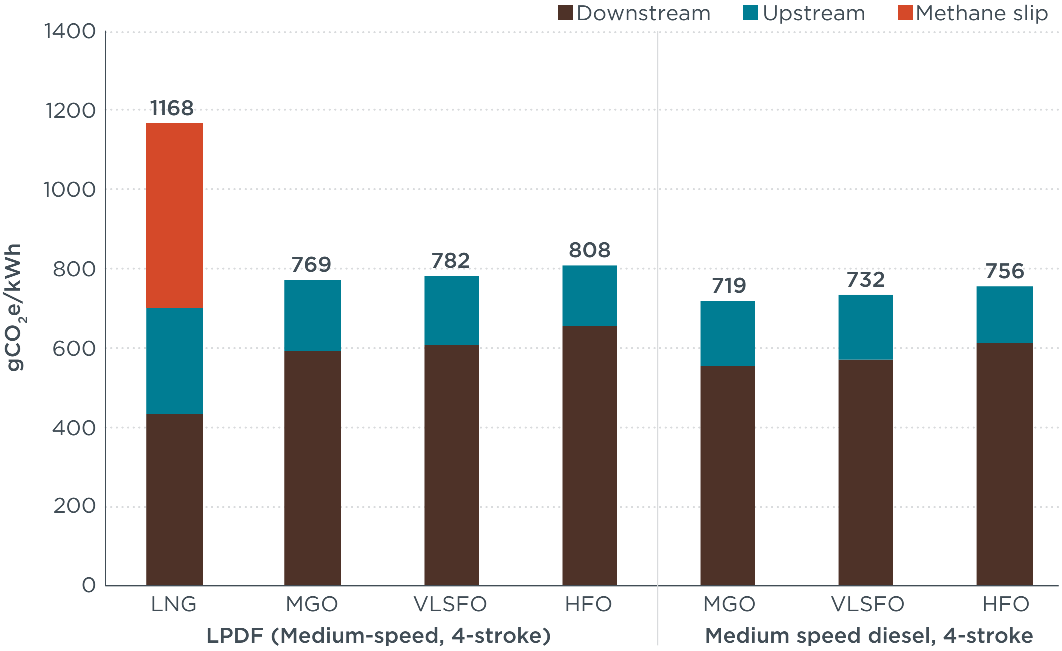


Figure 6. Life-cycle GHG emissions by fuel type for engines suitable for cruise ships, 20-year GWP

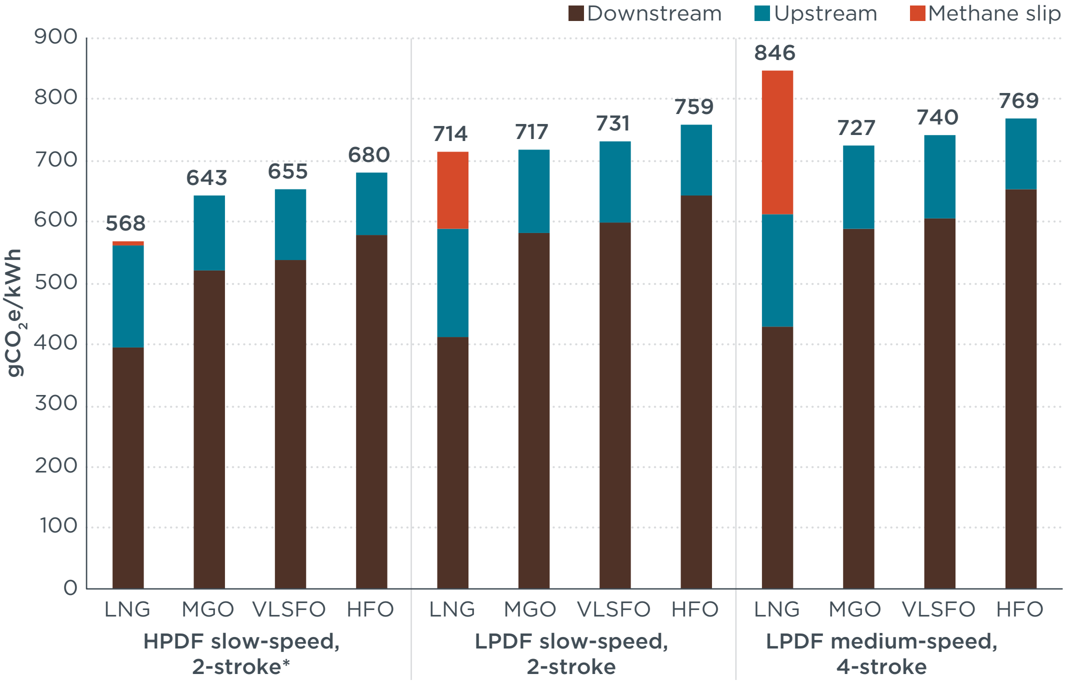
Life-cycle emissions using higher leakage and crankcase assumptions

International shipping

Using a 100-year GWP, higher upstream methane emissions reduce the life-cycle GHG savings of an HPDF using LNG compared with MGO from 15% to 12%, as shown in Figure 7. The impact is greater for low-pressure injection engines, which can have crankcase methane emissions. LPDF, slow-speed, two-stroke engines using LNG see their life-cycle emissions savings compared with MGO reduced from 9% to less than 1%. Note, however, that using LNG in the LPDF slow-speed, two-stroke engine emits 10% more lifecycle GHGs than an SSD using MGO. For LPDF, medium-speed, four-stroke engines, higher methane emissions mean that life-cycle emissions using LNG are 16%

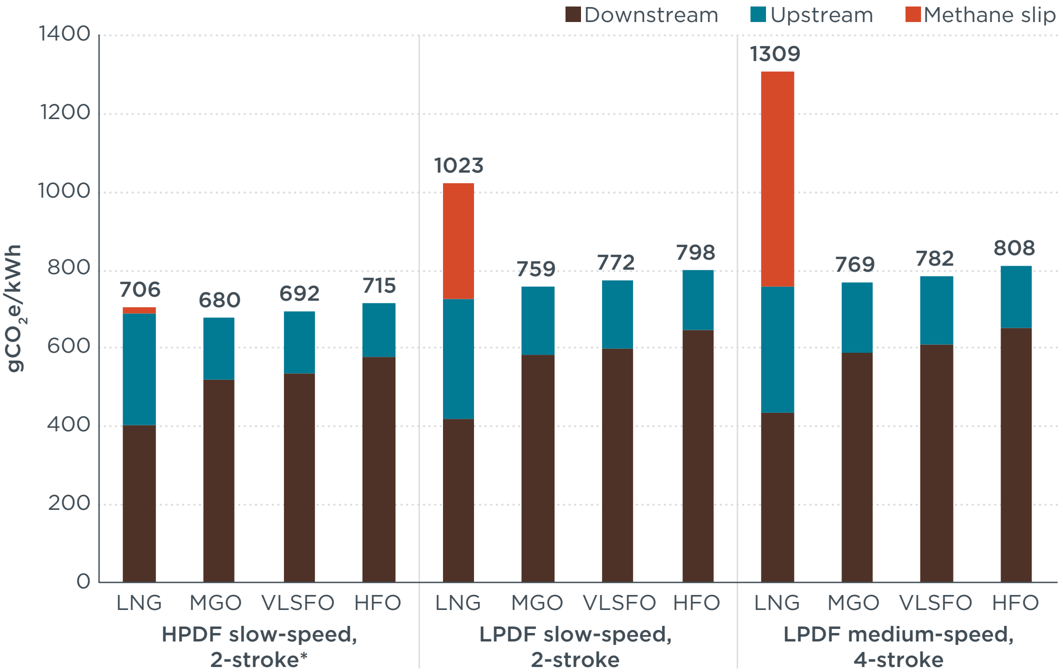
higher than MGO instead of 8% higher under the base scenario. It also emits 24% more lifecycle GHG emissions than an MSD using MGO.

Using a 20-year GWP, we find that using LNG as a marine fuel has no short-term climate benefit when combined with a trend toward higher upstream methane emissions and crankcase emissions. HPDF engines, which were the only engine to have lower life-cycle emissions than when they operated on MGO in the higher leakage scenario when 100-year GWP was used, emit 4% more than MGO using a 20-year GWP, as shown in Figure 8. HPDF engines do not have crankcase emissions, so this result is purely a consequence of higher upstream emissions. Using a 20-year GWP for LPDF engines, which can have crankcase methane emissions, we find they emit 35% (slow-speed, two-stroke) to 70% (medium-speed, four-stroke) greater GHGs on a life-cycle basis than when they use MGO. In all cases, an SSD using MGO emits the lowest amount of lifecycle GHG emissions. Specifically, an LPDF, slow-speed, two-stroke using LNG emits 50% more lifecycle GHG emissions than an SSD using MGO. An LPDF, medium-speed, four-stroke using LNG emits 82% more lifecycle GHG emissions than an MSD using MGO.



*SSD has similar life-cycle emissions as HPDF for conventional fuels.

Figure 7: Life-cycle GHG emissions by engine and fuel type, 100-year GWP, higher methane scenario



*SSD has similar life-cycle emissions as HPDF for conventional fuels.

Figure 8. Life-cycle GHG emissions by engine and fuel type, 20-year GWP, higher methane scenario

Cruise ships

For cruise ships, when we consider higher upstream emissions and crankcase emissions, we find that using LNG in a LPDF four-stroke, medium-speed engine emits 16% more life-cycle GHGs than if it used MGO on a 100-year time frame and 70% more on a 20-year time frame. Comparing it to an MSD using MGO, using LNG in an LPDF four-stroke, medium-speed engine emits 50% to 82% more life-cycle GHGs on 100-year and 20-year time frames, respectively. Like before, we also find that using the LPDF engine with conventional marine fuels emits more life-cycle GHG emissions than a similar marine diesel engine.

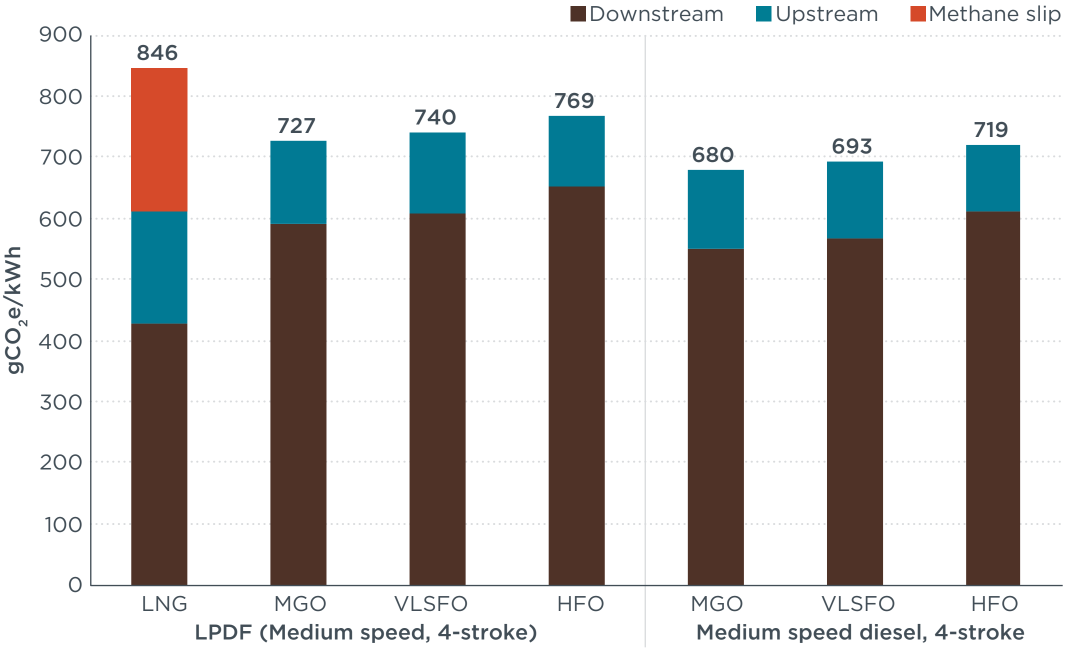


Figure 9: Life-cycle GHG emissions by fuel type for engines suitable for cruise ships, 100-year GWP, higher methane scenario

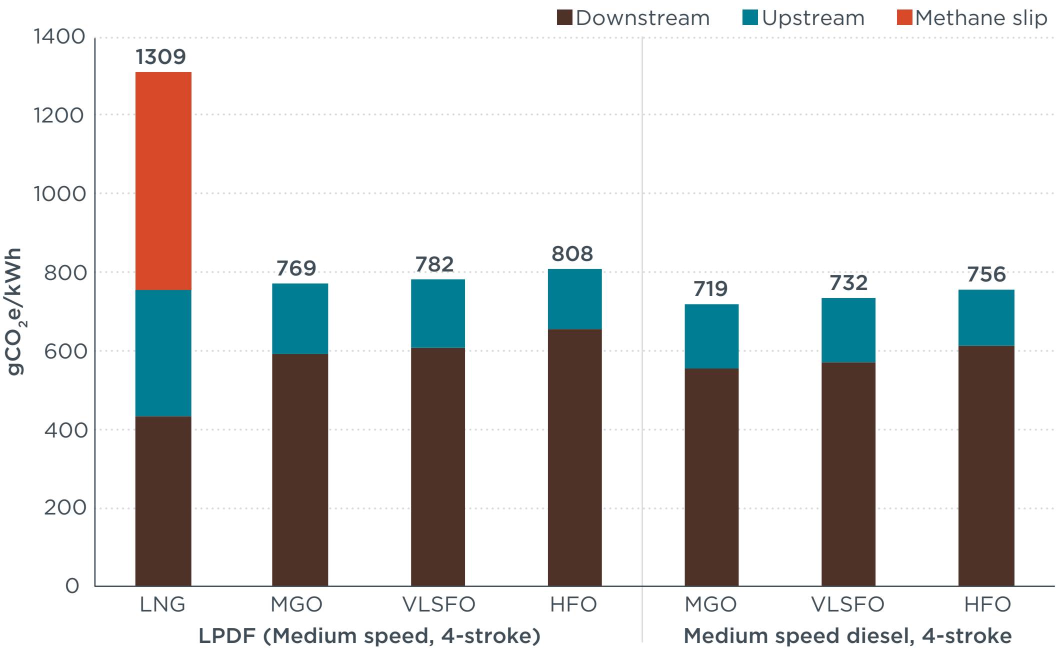


Figure 10. Life-cycle GHG emissions by fuel type for engines suitable for cruise ships, 20-year GWP, higher methane scenario

Discussion

Our results are sensitive to the choice of GWP (100-year or 20-year) and assumptions about upstream emissions and downstream methane slip. In comparing our results against others, we keep these parameters in mind.

Thinkstep (2019) and Lindstand (2019) are two recent analyses that examined the life-cycle GHG impacts of using LNG instead of conventional marine fuels. There are differences in key parameters among Thinkstep (2019), Lindstad (2019), and this study. While all three studies consider 100-year and 20-year GWPs, Thinkstep (2019) focused on 100-year GWP scenarios and included 20-year GWPs only for sensitivity analysis. Lindstad (2019), like us, draws conclusions using 100-year and 20-year GWPs, noting that 20-year GWPs better reflect the urgent need to reduce GHG emissions.

Regarding upstream emissions, our base assumption of 100-year GWP and well-controlled upstream emissions is 21.5 gCO_2e/MJ, 16% higher than the Thinkstep (2019) and Lindstad (2019) studies. However, our assumption for upstream MGO emissions (17.4 gCO_2e/MJ) is 20% higher than those studies (14.4 gCO_2e/MJ). Our assumptions, therefore, make it easier for LNG to emit fewer life-cycle GHG emissions than MGO compared with Thinkstep (2019) and Lindstad (2019). We assume 20% higher upstream emissions than Thinkstep for VLSFO (16.8 gCO_2e/MJ in our study compared with 14.0). We also assume 6% higher upstream HFO emissions than Thinkstep (14.3 gCO_2e/MJ compared with 13.5) and 49% higher than Lindstad (9.6 gCO_2e/MJ), who argues that HFO should be considered a byproduct because modern refineries are built to convert all crude into distillates and, from 2020, HFO will come from older refineries. Therefore, refining emissions should not be attributed to HFO. In our view, refining emissions should be included as part of HFO's upstream emissions because HFO is a product with economic value and demand for HFO will continue beyond 2020, especially as more ship owners install scrubbers.

Regarding methane slip, our assumptions tend to fall between Thinkstep (2019) and Lindstad (2019), except for HPDF engines, where we assume higher slip than both studies, consistent with the manufacturer's measured values.[5] Recall that a full discussion of our slip emission factor assumptions is provided in Appendix B.

Using a 100-year GWP and assuming that upstream methane leakage and downstream methane slip are well-controlled, we found that HPDF engines and slow-speed, two-stroke LPDF engines emitted fewer life-cycle GHGs when using LNG than when they used conventional fuels. Combined, these engines power at least 140 ships, including LNG carriers, container ships, and other cargo ships. These results are consistent with Thinkstep (2019). Lindstad (2019) also found lower life-cycle GHG emissions for HPDF engines when they used LNG instead of conventional fuels, but not for slow-speed, two-stroke LPDF engines. However, Lindstad (2019) shows that using MGO in an HPDF engine or an SSD engine would emit fewer life-cycle GHGs than using LNG in an LPDF, slow-speed, two-stroke engine, which is consistent with our results. Considering the medium-speed, four-stroke LPDF engines that power at least 300 ships, including LNG carriers, offshore supply vessels, car and passenger ferries, and cruise ships, we found that they emitted more life-cycle GHGs when using LNG than conventional fuels. This is consistent with Lindstad (2019), but not with Thinkstep (2019), which found a 5% life-cycle benefit of using this engine on LNG instead of MGO. Using 100-year GWP and assuming higher upstream emissions, we found that only the HPDF engine had a life-cycle GHG reduction compared with using MGO in that same engine, and the reduction was 12%.

The IPCC (2018) Special Report on Global Warming of 1.5°C suggests that limiting warming to 1.5°C requires anthropogenic methane emissions to begin to decline immediately and to be at least 35% below 2010 levels by 2050. Given that methane has strong warming effects, using 20-year GWP better aligns with an urgent need to reduce GHGs. Such urgency is reflected in IMO's initial GHG strategy: "IMO remains committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century" (IMO, 2018, para 2).

Using a 20-year GWP, and consistent with Lindstad (2019), we found that only one engine technology, HPDF, reduced life-cycle GHG emissions when using LNG instead of conventional fuels. Even then, the benefit was 3% and only if upstream emissions were well-controlled. Unfortunately, well-controlled emissions may not be the case as we see a trend toward shale gas, which releases more methane when extracted than other natural gas sources, as well as evidence that actual methane leakage upstream may be higher than expected (Alvarez et al., 2018). When we factored in the higher upstream emissions to account for this trend, we found that the HPDF engine emitted more life-cycle GHG emissions using LNG instead of MGO.

Several new-build cruise ships are LNG-fueled. They usually use combinations of medium-speed, four-stroke engines to provide propulsion and auxiliary power. LNG-powered cruise ships provide air quality and health benefits for passengers, crew members, and port communities, but at a climate cost. Under all conditions, the LPDF medium-speed, four-stroke engines that are popular with cruise ships have higher life-cycle GHG emissions when using LNG than conventional marine fuels.

Using LNG could have some regional benefits, for example by reducing black carbon emissions in the Arctic. However, there are low- and zero-emission alternatives to fossil fuels for Arctic shipping (Comer, 2019) and international shipping. Using zero-emission solutions such as batteries, hydrogen fuel cells, and wind-assisted propulsion would deliver both air quality and climate benefits.

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[5] Lindstad (2019)'s methane slip values are taken from Stenersen and Thonstad (2017).

Future Work

Additional work could be done to model methane emissions as a function of engine load, to incorporate black carbon and perhaps sulfur into the analysis, and to explore the life-cycle consequences of using non-fossil sources of LNG, such as biogas. Each of these is discussed briefly below.

Methane slip as a function of engine load

Methane slip varies as a function of engine load, with higher slip at lower loads. Our analysis relied on weighted methane slip emission factors that represent the IMO's E3 or E2 test cycles. We know from Olmer et al. (2017) that actual ship operations are different. It is possible to model the methane slip from each LNG-fueled ship hour-by-hour by modifying the approach of Olmer et al. (2017). This would likely show that the real-world consequences of using LNG as a marine fuel are worse, from a climate perspective, than we find here. In the wake of the global financial crisis, many ships have responded by sailing slower, operating at low engine loads. Olmer et al. (2017) found that container ships, in particular, operated at very low engine loads in the years 2013, 2014, and 2015. As more container ships opt for LNG, their methane slip emissions could be higher than we estimate here.

Black carbon

Future analyses could incorporate other short-lived climate pollutants, such as BC. The ICCT has published inventories of BC emissions from global shipping (Comer et al., 2017a; Olmer et al., 2017) and Arctic shipping (Comer et al., 2017b). Comer et al. (2017a) presented a detailed analysis of BC emission factors. They showed that, based on laboratory tests and a few on-water measurements, BC emissions are a function of fuel type, engine type, and engine load. LNG has very low BC emissions.

Black carbon was not incorporated into this analysis for several reasons. First, there are few, if any, published test results of BC emissions for dualfuel engines. Second, BC emission factors increase as engine load decreases, as does methane. Thus, the engine load conditions under which BC emission factors could be high are also those where methane emission factors could be high. Lastly, it is difficult to estimate upstream BC emissions from natural gas and oil extraction. Therefore, even if we estimated downstream BC emissions, the upstream BC emissions would remain unaccounted for, introducing uncertainty into the life-cycle assessment.

Biomethane

Liquefied biomethane produced from biogas has begun to attract attention as a source of low-carbon LNG for shipping applications that could be generated with low or in some cases negative life-cycle GHG emissions (Baker, 2019). Both the climate implications and economics for biomethane can vary considerably depending on the feedstock used for its production, its production region, and the costs of its specific production process. Biogas produced from wastes that would otherwise decompose and release methane has very low GHG emissions, though the availability of these feedstocks may be limited (Searle, Baldino, & Pavlenko, 2018). Biogas produced from purpose-grown crops such as silage maize has higher emissions than those made from wastes and residues, as these crops may displace existing crop production and thus generate indirect land-use change (Valin et al., 2015).

The availability of bio-LNG for marine applications is likely to be limited due to high cost, limited feedstock availability, and competition with the power sector. Baldino, Pavlenko, Searle, and Christensen (2018) explained the challenging economics of many waste-derived biogas pathways, particularly for use in the transportation sector. Linking some sources of biogas to the natural gas grid may be more cost-prohibitive than onsite combustion for electricity. Baldino et al. (2018) estimated that the bulk of waste-derived biogas for transportation in the EU context only becomes cost-viable between €0.3 and €1.1 per cubic meter of gas, compared with a wholesale fossil LNG cost of €0.20 per cubic meter. Given that the projected future energy demand for international shipping is expected to continue to grow, bio-LNG could likely only meet a small share of future demand.

Conclusions

We compared the life-cycle GHG emissions of LNG, MGO, VLSFO, and HFO for engines that are used in international shipping, including on cruise ships. The maximum life-cycle GHG benefit of LNG was a 15% reduction compared with MGO over a 100-year time frame. Note that this is only achieved by ships using an HPDF engine and only if upstream methane emissions are well-controlled. Controlling upstream methane emissions could be challenging as more LNG production shifts to shale gas and given recent evidence that upstream methane leakage might be higher than previously thought.

Using a 20-year GWP, which better reflects the urgency of reducing GHGs to meet IMO's climate goals, and factoring in higher upstream and downstream emissions, we found no life-cycle GHG emissions benefit to using LNG for any engine technology. HPDF engines using LNG emitted 4% more life-cycle GHG emissions than if they used MGO. At least 90 ships that are in service or on order use HPDF engines. The most popular LNG engine technology—LPDF, four-stroke, medium-speed, which is used on at least 300 ships and is especially popular with LNG-fueled cruise ships—emitted 70% more life-cycle GHGs when it used LNG instead of MGO and 82% more than using MGO in a comparable MSD engine.

These results show that LNG does not deliver the emissions reductions demanded by the IMO's initial GHG strategy and that using it might actually worsen shipping's climate impacts. Given this, it is fair to question continued investments in LNG infrastructure on ships and on shore, as these could make it harder to transition to low- and zero-carbon fuels in the future. Investing instead in energy-saving technologies, wind-assisted propulsion, zero-emission fuels, batteries, and fuel cells would deliver both air quality and climate benefits.

References

Abbasov, F. (2019, July 10). LNG remains a deadend for decarbonising maritime transport [Blog post]. Retrieved from the Transport & Environment website: https://www.transportenvironment.org/newsroom/blog/lng-remains-deadend-decarbonising-maritime-transport

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., ... Hamburg, S. P. (2018, July). Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*, 361(6398), 186-188. Retrieved from https://science.sciencemag.org/content/361/6398/186.full

Argonne National Laboratory (2018). Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. Retrieved from https://greet.es.anl.gov/

Balcombe, P., Speirs, J. F., Brandon, N. P., & Hawkes, A. D. (2018). Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes & Impacts,* 20, 1323–1339. doi: 10.1039/C8EM00414E. Retrieved from https://spiral.imperial.ac.uk/handle/10044/1/63392

Baldino, C., Pavlenko, N., Searle, S., Christensen, A. (2018). *The potential for low-carbon renewable methane in heating, power, and transport in the European Union*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/methane-heat-power-transport-eu

Baker, J. (2019, October 24) Maersk calls for focused development of new fuels. Lloyd's List. Retrieved from https://lloydslist.maritimeintelligence.informa.com/LL1129672/Maersk-calls-for-focused-development-of-new-fuels

Bectas, C., Hubatova, H, & O'Leary, A. (2019). The Norwegian NOx Fund [Factsheet]. Retrieved from the Environmental Defense Fund website: https://europe.edf.org/file/375/download?token=2fsAHP74

Bengtsson, S., Andersson, K., & Fridell, E. (2011). *Life cycle assessment of marine fuels: A comparative study of four fossil fuels for marine propulsion*. Department of Shipping and Marine Technology, Division of Sustainable Ship Propulsion, Chalmers University of Technology, ISSN 1652-9189 Report No. 11:125, Gothenburg, Sweden. Retrieved from https://research.chalmers.se/en/publication/138908

Birkett, H. (2019). LNG-fuelled ships risk becoming stranded in zero-carbon future. Retrieved from TradeWinds News https://www.tradewindsnews.com/gas/lng-fuelled-ships-risk-becoming-stranded-in-zero-carbon-future/2-1-671533

Brünnet, H., Reppekus, D., Theobald, M., & Kornatz, G. (2018). *Formation and avoidance of crankcase explosions in large oil, dual-fuel and gas engines*. September 2018 Conference: 5th Rostock Large Engine Symposium, Rostock, Germany. Retrieved from https://www.researchgate.net/publication/327883546_Formation_and_avoidance_of_crankcase_explosions_in_large_oil_dual-fuel_and_gas_engines

Caterpillar. (2015). *Application & installation guide: Crankcase ventilation systems*. Retrieved September 2019 from https://s7d2.scene7.com/is/content/Caterpillar/CM20160713-53120-62603

Caterpillar. (2016). *Marine power solutions: Edition 2016 (September)*. Retrieved from https://www.finning.com/content/dam/finning/en_gb/Documents/Industries/Marine/Cat-Marine-Engine-Selection-Guide-LEDM3457-21.pdf

CE Delft, Stratas Advisors, UMAS, NMRI, Petromarket Research Group, & Shinichi Hanayama (2016). Assessment of fuel oil availability: Final report. Prepared for The International Maritime Organization. Retrieved from https://cedelft.eu/publicatie/assessment_of_fuel_oil_availability/1858

CIMAC. (2016). *Conference report: 2016 CIMAC Congress*. Retrieved from https://www.cimaccongress.com/upload/program/press/diesel_net_2016_06_28_news__Conference_report__2016_CIMAC_Congress.pdf

Clark, N. N., McKain, D. L., Johnson, D. R., Wayne, W. S., Li, H., Akkerman, V., ... Ugarte, O. J. (2017). Pump-to-wheels methane emissions from the heavy-duty transportation sector. *Environmental Science & Technology, 51*(2), 968-976. https://doi.org/10.1021/acs.est.5b06059

Comer, B., Olmer, N., Mao, X., Roy, B., & Rutherford, D. (2017a). *Black carbon emissions and fuel use in global shipping, 2015*. Retrieved from The International Council on Clean Transportation website: https://theicct.org/publications/black-carbon-emissions-global-shipping-2015.

Comer, B., Olmer, N., Mao, X., Roy, B., & Rutherford, D. (2017b). *Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025*. Retrieved from the International Council on Clean Transportation website: https://www.theicct.org/publications/prevalence-heavy-fuel-oil-and-black-carbon-arctic-shipping-2015-2025

Comer, B. (2019). *Transitioning away from heavy fuel oil in Arctic shipping*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/transitioning-away-heavy-fuel-oil-arctic-shipping.

Delgado, O. & Muncrief, R. (2015). *Assessment of heavy-duty natural gas vehicle emissions: implications and policy recommendations*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/sites/default/files/publications/ICCT_NG-HDV-emissions-assessmnt_20150730.pdf

Delprete, C., Selmani, E., & Bisha, A. (2019). Gas escape to crankcase: impact of system parameters on sealing behavior of a piston cylinder ring pack. *International Journal of Energy and Environmental Engineering*, *10*(2), 207–220. https://doi.org/10.1007/s40095-019-0296-x

Dobrota, D., Lalić, B., and Komar, I. (2013). Problem of boil-off in LNG supply chain. *Transactions on Maritime Science*, *2*(2),91-100. doi: 10.7225/toms.v02.n02.001. Retrieved from https://pdfs.semanticscholar.org/e752/5088c710c1955b67679e12851ba3948b9b0c.pdf

El-Houjeiri, H., Monfort, J-C., Bouchard, J., & Przesmitzki, S. (2018). Life cycle assessment of greenhouse gas emissions from marine fuels. *Journal of Industrial Ecology*, *32*(2), 374-388. Retrieved from https://doi.org/10.1111/jiec.12751

Energy Information Administration. (2019). Natural gas gross withdrawals and production. Retrieved from https://www.eia.gov/dnav/ng/ng_prod_sum_dc_NUS_mmcf_m.htm

Equasis. (2017). The world merchant fleet in 2017. Retrieved from http://www.equasis.org/EquasisWeb/public/PublicStatistic?fs=HomePage

Fernández, I. A., Gómez, M. R., Gómez, J. R., Insua, A. B. (2017). Review of propulsion systems on LNG carriers. *Renewable and Sustainable Energy Reviews 67*, 1395–1411, http://dx.doi.org/10.1016/j.rser.2016.09.095

Gilbert, P., Walsh, C., Traut, M., Kesime, U., Pazouki, K., & Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production 172*, 855-866. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652617324721

Globe Advisors. (2014). *British Columbia LNG greenhouse gas (GHG) life cycle analysis: Discussion draft.* Prepared for British Columbia Ministry of Environment Climate, Action Secretariat. Retrieved from https://www2.gov.bc.ca/assets/gov/environment/climate-change/ind/lng/british_columbia_lng_greenhouse_gas_ghg_life_cycle_analysis.pdf

Hanjy, K. D.,Salmon, O. E., Rudek, J., Lyon, D. R., Stuff, A. A., Stirm, B. H., ... Shepson, P. B. (2019). Observations of methane emissions from natural gas-fired power plants. *Environmental Science & Technology*, *53*(15), 8976−8984. Retrieved from https://pubs.acs.org/doi/10.1021/acs.est.9b01875

Horiba. (2019). *PTFM-1000*. Retrieved from http://www.horiba.com/at/automotive-test-systems/products/emission-measurement-systems/further-systems/details/ptfm-1000-982/

Howarth, R. W. (2015). Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: Implications for policy. *Energy and Emission Control Technologies*, *3*, 45–54. Retrieved from https://www.dovepress.com/methane-emissions-and-climatic-warming-risk-from-hydraulic-fracturing--peer-reviewed-article-EECT

Huan, T., Hongjun, F., Wei, L., & Guoqiang, Z. (2019). Options and evaluations on propulsion systems of LNG carriers. Retrieved from https://www.intechopen.com/online-first/options-and-evaluations-on-propulsion-systems-of-lng-carriers

IEA & KEEI. (2019). *LNG market trends and their implications: Structures, drivers and developments of major Asian importers*. Retrieved from the IEA website: https://www.iea.org/publications/reports/LNGMarketTrendsandTheirImplications/

IHS (2019). *Ship registry data.* Bespoke dataset prepared for and delivered to the International Council on Clean Transportation.

Intergovernmental Panel on Climate Change. (2007). Climate change 2007: Synthesis report in the *Contribution of working groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri, R. K. & Reisinger, A. (Eds.). Geneva, Switzerland: IPCC.

Intergovernmental Panel on Climate Change. (2013). Anthropogenic and natural radiative forcing. In *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the International Panel on Climate Change*. Retrieved from https://www.ipcc.ch/report/ar5/wg1/

Intergovernmental Panel on Climate Change. (2018). Summary for policymakers. In *Global warming of 1.5°C*. Retrieved from https://www.ipcc.ch/sr15/chapter/spm/.

International Maritime Organization. (2018). *Initial IMO strategy on reduction of GHG emissions from ships*. Resolution MEPC.304(72). Retrieved from http://www.imo.org/en/OurWork/Documents/Resolution%20MEPC.304(72)%20on%20Initial%20IMO%20Strategy%20on%20reduction%20of%20GHG%20emissions%20from%20ships.pdf

Jensen, T., Schramm, J., & Morgen, C. (1999). Unburned hydrocarbon emissions from SI engines using gaseous fuels. *SAE Transactions 108*(3), 915-926, https://www.jstor.org/stable/pdf/44743424.pdf?seq=1#page_scan_tab_contents

Johnson, D. J., Covington, A. N., & Clark, N.N. (2015). Methane emissions from leak and loss audits of natural gas compressor stations and storage facilities. *Environmental Science & Technology 49*, 8132–8138. doi: 10.1021/es506163m. Retrieved from https://pubs.acs.org/doi/10.1021/es506163m

Joss, M. (2017). *Natural gas pathway analysis for heavy duty vehicles.* Report for Energy Technologies Institute LLP. Retrieved from https://d2umxnkyjne36n.cloudfront.net/teaserImages/Natural-Gas-Pathway-Analysis-for-Heavy-Duty-Vehicles-Matthew-Joss.pdf?mtime=20171101113809

Lindstad, E. (2019). *Increased use of LNG might not reduce maritime GHG emissions at all – June 2019*. Retrieved from the Transport & Environment website: https://www.transportenvironment.org/sites/te/files/publications/2019_06_Dr_Elizabeth_Lindstad_commentary_LNG_maritime_GHG_emissions.pdf.

Lofholm, P., Pettersson, D., & Vestergard, J. (2009). Clean crankcase ventilation. *Wärtsilä Technical Journal, January 2009*. Retrieved from https://cdn.wartsila.com/docs/default-source/service-catalogue-files/engine-services---4-stroke/oil-mist-separator.pdf?sfvrsn=9efc1d45_4

MacQueen, J. (2011, April). *More vessels fail to meet new sulphur limits*. Lloyd's List.

MAN Energy Solutions. (2017). *MAN B&W S60ME-C8.5 product guide.* Retrieved from https://marine.man-es.com/applications/projectguides/2stroke/content/epub/S60ME-C8_5.pdf

MAN Energy Solutions. (2018). *MAN B&W G70ME-C9.5-GI-TII product guide: Electronically controlled dual fuel two-stroke engines.* Retrieved from https://marine.man-es.com/applications/projectguides/2stroke/content/printed/G70ME-C9_5-GI.pdf

Merrin, Z. & Francisco, P. W. (2019). Unburned methane emissions from residential natural gas appliances. *Environmental Science & Technology 53*(9), 5473-5482. doi: 10.1021/acs.est.8b05323

Motorship. (2017). *Dual-fuel two stroke technology advances*. Retrieved from https://www.motorship.com/gfsconference/latest-news101/dual-fuel-two-stroke-technology-advances

Murillo Hernandez, A. (2015). *Exhaust gas recirculation study on dual-fuel methane combustion*. Retrieved from the Aalto University website: https://aaltodoc.aalto.fi/bitstream/handle/123456789/15960/master_Murillo_Hern%C3%A1ndez_Alberto_2015.pdf?sequence=1&isAllowed=y

Nielsen, J. B. & Stenersen, D. (2010). *Emission factors for CH_4, NO_x, particulates and black carbon for domestic shipping in Norway, revision 1*. Norwegian Marine Technology Research Institute. Retrieved from https://www.miljodirektoratet.no/globalassets/publikasjoner/klif2/publikasjoner/2746/ta2746.pdf

Nieman, D., Morris, A., Miwa, J., & Denton, B. (2019). *Methods of improving combustion efficiency in a high-efficiency, lean burn dual-fuel heavy-duty engine*. SAE technical paper. doi:10.4271/2019-01-0032.

NOx Fondet. (2019). The NOx Fund. Retrieved from https://www.nho.no/samarbeid/nox-fondet/the-nox-fund/

Olmer, N., Comer, B., Roy, B., Mao, X., & Rutherford, D. (2017). *Greenhouse gas emissions from global shipping, 2013-2015*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf

Pace. (2015). *LNG and coal life cycle assessment of greenhouse gas emissions*. Retrieved from https://www.ourenergypolicy.org/resources/lng-and-coal-life-cycle-assessment-of-greenhouse-gas-emissions/

Peng, T., Zhou, S., Yuan, Z., & Ou, X. (2017). Life cycle greenhouse gas analysis of multiple vehicle fuel pathways in China. *Sustainability*, *9*(12), 2183. Retrieved from https://www.mdpi.com/2071-1050/9/12/2183

Rolls-Royce. (2012). *Rolls-Royce Marine - The Environship Concept*. 2012 SNAME Annual Meeting and Expo. Retrieved from https://higherlogicdownload.s3.amazonaws.com/SNAME/3c0e6c2a-f51c-462d-86f6-7061658df062/UploadedImages/Winter%202012/Odd%20Magne%20Horgen%20-%20Rolls%20Royce%20Bergen%20Engines%20Presentation-%20SNAME%20GL&GR%20Meeting%20-%20Cleveland,%20Ohio%20-%20February%2023-24,_%202012.pdf

Rolls-Royce. (2018, September 5). *Rolls-Royce launches new Bergen B36:45 marine gas engine* [Press release]. Retrieved from https://www.rolls-royce.com/media/press-releases/2018/05-09-2018-rr-launches-new-bergen-b36-45-marine-gas-engine.aspx

Rutherford, D. & Comer, B. (2018). *The International Maritime Organization's initial greenhouse gas strategy*. Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/IMO-initial-GHG-strategy

Sapkota, K. (2017). *Techno-economic life cycle assessments of oil sands products and liquefied natural gas supply chains from Canada to Asia-Pacific and Europe* (Master's Thesis, University of Alberta, Alberta, Canada). Retrieved from https://era.library.ualberta.ca/items/14244c5f-133b-454b-a175-fc4a69d6bfb9

Skone, T. J., Cooney, G., Jamieson, M., Littlefield, J., Marriott, J. (2014). *Life cycle greenhouse gas perspective on exporting liquefied natural gas from the United States*. Prepared for U.S. Department of Energy National Energy Technology Laboratory Office of Fossil Energy. DOE/NETL-2014/1649. Retrieved from https://www.energy.gov/fe/downloads/life-cycle-greenhouse-gas-perspective-exporting-liquefied-natural-gas-united-states

Searle, S., Baldino, C., & Pavlenko, N. (2018). *What is the role for renewable methane in European decarbonization?* Retrieved from the International Council on Clean Transportation website: https://theicct.org/publications/role-renewable-methane-eu

Siemens (2016). *Improving the flexibility and efficiency of gas turbine-based distributed power plant*. Retrieved from https://etn.global/wp-content/uploads/2018/09/Improving_the_flexibility_and_efficiency_of_gas_turbine-based_distributed_power_plant.pdf

Sommer, D. E., Yeremi, M., Son, J., Corbin, J., Gagné, S., Lobo, P., … Kirchen, P. (2019). Characterization and reduction of in-use CH_4 emissions from a dual fuel marine engine using wavelength modulation spectroscopy. *Environmental Science & Technology*, *53*(5), 2892-2899. doi: 10.1021/acs.est.8b04244

Speirs, J., Balcombe, P., Blomerus, P., Blomerus, P., Stettler, M., Brandon, N., & Hawkes, A. (2019). *Can natural gas reduce emissions from transport? Heavy goods vehicles and shipping*. Sustainable Gas Institute: Imperial College London. Retrieved from https://www.sustainablegasinstitute.org/wp-content/uploads/2019/02/SGI-can-natural-gas-reduce-emissions-from-transport-WP4.pdf

Stenersen, D. & Thonstad, O. (2017). *GHG and NOx emissions from gas fuelled engines*. SINTEF Ocean AS, Trondheim, Norway. Retrieved from https://midc.be/wp-content/uploads/2018/06/methane-slip-from-gas-engines-mainreport-1492296.pdf

Stone, R. & Ball, J. K. (2004). *Automotive engineering fundamentals*. SAE International. ISBN 10: 0768009871. ISBN 13: 9780768009873

Subramanian, R., Williams, L.L., Vaughn, T.L., Zimmerle, D., Roscioli, J.R., Herndon, S.C., … Robinson, A.L. (2015). Methane emissions from natural gas compressor stations in the transmission and storage sector: Measurements and comparisons with the EPA greenhouse gas reporting program protocol. *Environmental Science & Technology* *49*(5), 3252-3261. Retrieved from https://doi.org/10.1021/es5060258

't Hoen & den Boer. (2015). *Scrubbers – An economic and ecological assessment*. CE Delft. Retrieved from https://www.cedelft.eu/en/publications/1618/scrubbers-an-economic-and-ecological-assessment

Tagliaferri, C., Clift, R., Lettieri, P., & Chapman, C. (2017). Liquefied natural gas for the UK: A life cycle assessment. *International Journal of Life Cycle Assessment*, *22*(12), 1944-1956. doi: 10.1007/s11367-017-1285-z. Retrieved from https://link.springer.com/article/10.1007/s11367-017-1285-z

Tan, Y., Dagaut, P., Cathonnet, M., & Boettner, J.-C. (1994). Oxidation and ignition of methane-propane and methane-ethane-propane mixtures: Experiments and modeling. *Combustion Science and Technology*, *103*, 133-151. doi: 10.1080/00102209408907691

Tatli, E. & Clark, N. N. (2009). Crankcase particulate emissions from diesel engines. *SAE International Journal of Fuels and Lubricants*, *1*(1), 1334-1344.

Thinkstep. (2019). *Life cycle GHG emission study on the use of LNG as marine fuel*. Retrieved from https://www.thinkstep.com/content/life-cycle-ghg-emission-study-use-lng-marine-fuel-1

Thomson, H., Corbett, J. J., & Winebrake, J. J. (2015). Natural gas as a marine fuel. *Energy Policy*, *87*, 153–167. Retrieved from https://www.sciencedirect.com/science/article/pii/S0301421515300665

Ushakov, S., Stenersen, D., & Einang, P. M. (2019). Methane slip from gas fueled ships: a comprehensive summary based on measurement data. *Journal of Marine Science and Technology*, 24(4), 1308-1325. https://doi.org/10.1007/s00773-018-00622-z

UT99. (2019). *Closed crankcase ventilation and highly efficient oil mist separation*. Retrieved from https://www.ut99.com/en/upf-ccv-product-range

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., & Hamelinck, C. (2015). The land use change impact of biofuels consumed in the EU: Quantification of area and greenhouse gas impacts. Retrieved from the European Commission website: https://ec.europa.eu/energy/sites/ener/files/documents/Final%20Report_GLOBIOM_publication.pdf

Verbeek, R., Kadijk, G., van Mensch, P., Wulffers, C., van den Beemt, B., & Fraga, F. (2011). *Environmental and economic aspects of using LNG as a fuel for shipping in the Netherlands*. TNO-RPT-2011-00166. Retrieved from the TNO website: https://repository.tudelft.nl/view/tno/uuid:b458abfc-482f-4e11-ba4c-7ea7923552f8

Wagemakers, A. & Leermakers, C. (2012). *Review on the effects of dual-fuel operation, using diesel and gaseous fuels, on emissions and performance*. SAE Technical Paper 2012-01-0869. https://doi.org/10.4271/2012-01-0869

Wärtsilä. (2007). *Oil mist separator – Clean crankcase ventilation* [Factsheet]. Retrieved from https://cdn.wartsila.com/docs/default-source/Service-catalogue-files/Engine-Services---4-stroke/oil-mist-separator-sales-leaflet.pdf?sfvrsn=4

Wärtsilä. (2009). *Wärtsilä 50DF engine technology*. Retrieved from http://cdn.wartsila.com/docs/default-source/Power-Plants-documents/w%C3%A4rtsil%C3%A4-50df.pdf

Wärtsilä. (2019a). *Wärtsilä 50DF product guide*. Retrieved from https://cdn.wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9

Wärtsilä. (2019b). *Wärtsilä 46F product guide*. Retrieved from https://www.wartsila.com/docs/default-source/product-files/engines/ms-engine/product-guide-o-e-w46f.pdf?utm_source=engines&utm_medium=dieselengines&utm_term=w46f&utm_content=productguide&utm_campaign=msleadscoring

Winebrake, J. J., Corbett, J. J., Umar, F., & Yuska, D. (2019). Pollution tradeoffs for conventional and natural gas-based marine fuels. *Sustainability, 11*(8), 2235. doi:10.3390/su11082235

Winterthur Gas & Diesel (2018). *Low-pressure X-DF engines FAQ.* Retrieved from https://www.wingd.com/en/documents/general/brochures/x-df-faq-brochure.pdf/

Winterthur Gas & Diesel (2019). *X72DF*. Retrieved from https://www.wingd.com/en/engines/engine-types/x-df-dual-fuel/x72df/

Appendix A: Literature review of upstream greenhouse gas emissions and sources of methane slip from marine engines

Upstream greenhouse gas (GHG) emissions

Upstream emissions associated with liquefied natural gas (LNG) include natural gas production and processing to remove impurities from the feed gas, liquefaction, domestic transportation, fugitive emissions during bunkering, if reported, and sometimes international transport. For more consistent comparisons among studies, we applied two approaches. First, we noted that different studies assessed in this literature review assume different global warming potential (GWP) values of CH_4 and N_2O. To eliminate the variations caused by this, we applied the GWP from the Fifth Assessment Report (AR5) of the IPCC, listed in Table A1, for our own modeling of marine fuels and adjusted the emission values from other studies when possible. Unless noted, the results are on a 100-year GWP basis. Second, we conducted separate comparisons of emissions excluding and including international transport.

Table A1. GWP used in this study and used to adjust values from other studies for consistent comparison

GHG	100-year GWP	20-year GWP
CO_2	1	1
CH_4	36	86
N_2O	265	264

Source: IPCC (2013)

Figure A1 shows the upstream GHG emissions of LNG, excluding international transport, from the studies assessed in the literature review. The figure includes the exact GWP value from each study and the adjusted GWP value, and compares these to baseline heavy fuel oil (HFO) upstream emissions from our model results. Studies missing adjusted values lack the data needed to differentiate emissions from CO_2 or CH_4. Studies using the same GWP as in Table A1 have the same original and adjusted numbers. Adjusted emissions of LNG range from 8.8 to 26.77 gCO_2e/MJ, with an average of 17.1 gCO_2e/MJ. Higher upstream LNG emissions are generally due to greater methane leakage from natural gas production together with longer domestic transportation (El-Houjeiri, Monfort, Bouchard, & Przesmitzki, 2018). Although original values from previous studies show a wide range of LNG upstream emissions, about 68% of them indicate greater emissions than from HFO. Note that some of the studies used smaller GWP in their estimations and that data deficiencies prevented us from making the adjustment; therefore, the percentage is likely to be higher than 68%.

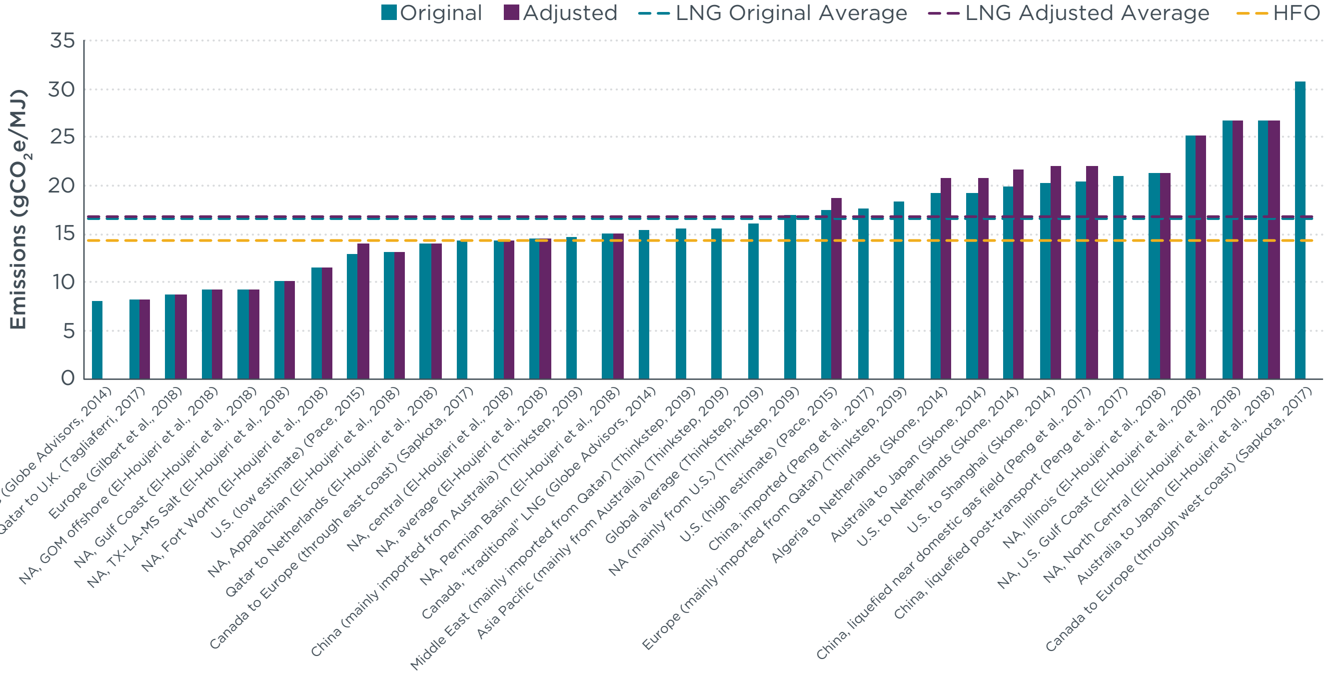

Figure A1. Upstream GHG emissions of LNG excluding international transport, 100-year GWP.
Note: NA means North America; GOM means Gulf of Mexico; TX-LA-MS Salt means the Texas-Louisiana-Mississippi Salt Basin.

Liquefaction is a process that cools the pre-treated natural gas down to a liquid form. It contributes about 30% to 60% of total upstream emissions, and the rest mainly comes from production and processing. Figure A2 shows the variations of liquefaction emissions from the studies we reviewed. It shows a range of 2.41 to 10.2 gCO_2e/MJ. The variation is caused by different liquefaction technologies using different refrigerants. On average, emissions from the liquefaction process contribute approximately 6.55 gCO_2e/MJ to upstream emissions.

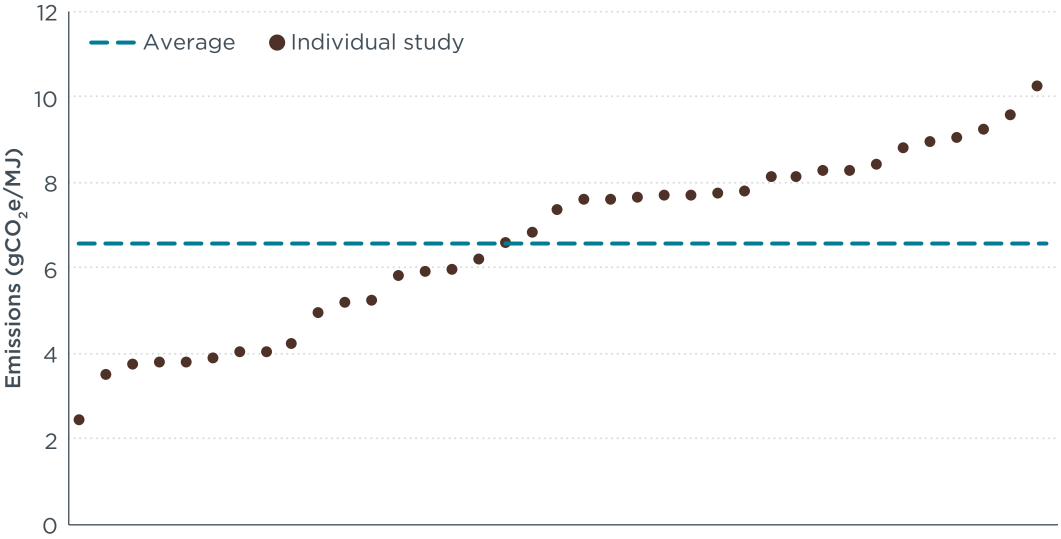

Figure A2. GHG emissions during natural gas liquefaction, 100-year GWP.

The transport of LNG includes domestic transport, such as between extraction wells and liquefaction plants, and international transport from production sites to where it is consumed. Domestic transport of LNG is usually by truck, rail, or pipeline, depending on the volume, distance, and facility availability. Domestic transport typically represents 15% to 20% of upstream emissions.

Countries with LNG resources are not necessarily its largest consumers, and international maritime shipping is often the most cost-efficient way of transporting LNG over a long distance. Based on 2018 market data, top LNG exporters are Qatar, Australia, Malaysia, the United States, and Nigeria, while Asia Pacific countries including Japan and China, and some European countries including Spain and France are major importers (IEA and KEEI, 2019). Figure A3 presents the upstream GHG emissions of LNG including international transport. Like Figure A1, studies missing adjusted values lack the data needed to differentiate emissions from CO_2 or CH_4. Studies using the same GWP as in Table A1 have the same original and adjusted numbers. Emissions from international transport range from 1.0 to 6.5 gCO_2e/MJ, depending on distance, and adding this means the adjusted total upstream emissions including shipping range from 14.7 to 28.57 gCO_2e/MJ, with an average of 21.2 gCO_2e/MJ. It is important to clarify that studies that include international transport are not necessarily comparable to one another, as they may use different sets of origins and destinations from one another. Nevertheless, when adding the emissions from international transport, average LNG GHG emissions are 20% higher than HFO.

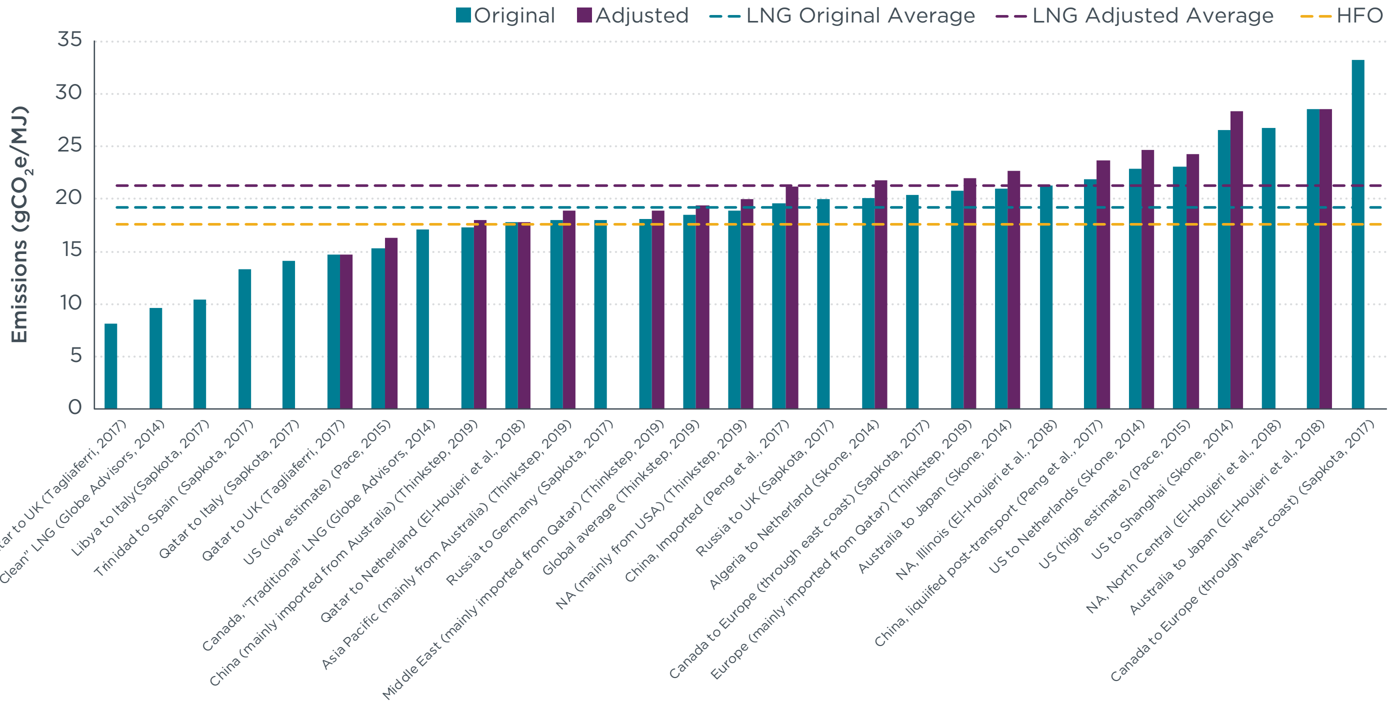

Figure A3. Upstream GHG emissions of LNG including international transport, 100-year GWP.
Note: NA means North America; GOM means Gulf of Mexico; TX-LA-MS Salt means the Texas-Louisiana-Mississippi Salt Basin.

To understand potential regional variations, we organized study results by production region, shown in Figure A4a, and by shipping region, shown in Figure A4b. On average, LNG from Qatar has relatively low upstream emissions and this might be due to the lower CO_2 content in feed gas (i.e., raw gas from the production field), the shorter domestic transport distance (El-Houjeiri et al., 2018), and the lower carbon intensity of Qatar's electricity grid (Thinkstep, 2019). In contrast, natural gas reservoirs in Australia tend to have high CO_2 content (El-Houjeiri et al., 2018) and the domestic transport distance in Australia and Algeria is relatively long (Thinkstep, 2019). Considering international transport emissions, shown in Figure A4b, the regional variation is less obvious, but still follows the same rank. One exception is the case of exporting LNG from the United States to Asia Pacific, which has high emissions because of the long shipping distance (Pace, 2015). This indicates that emissions from international transport can offset some of the benefit of using less carbon-intensive LNG.

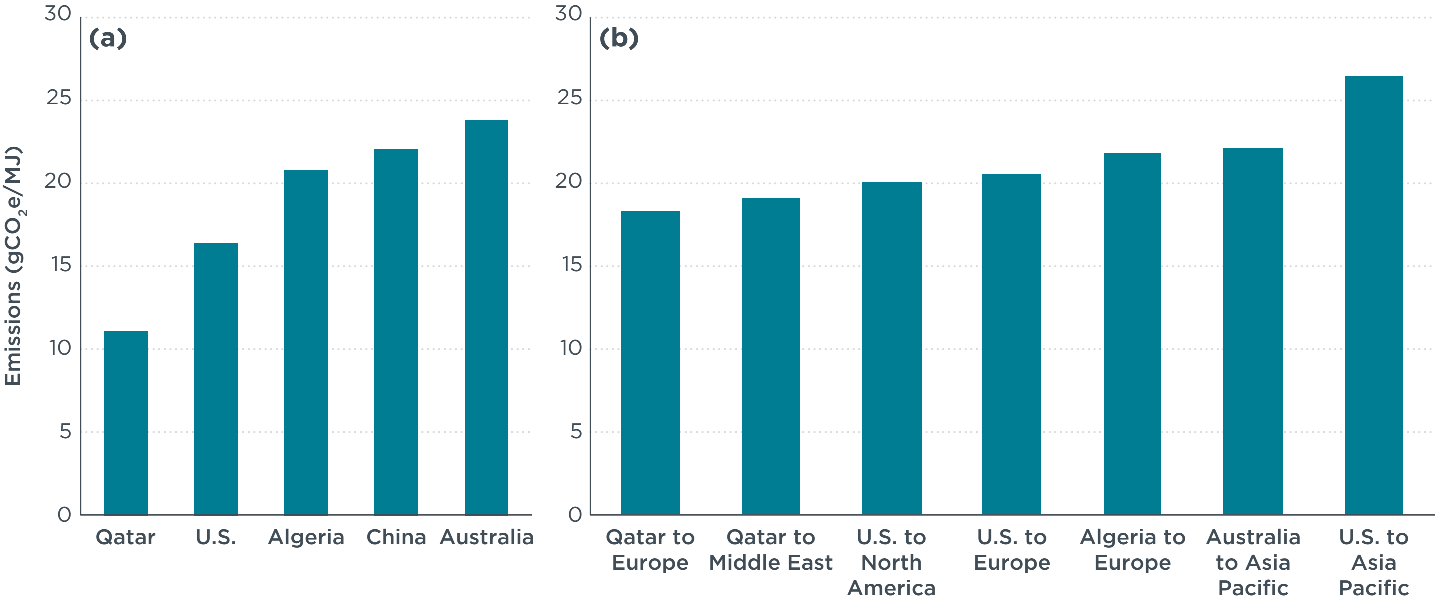

Figure A4. Average upstream GHG emissions of LNG by production region (excluding emissions from international transport) and by shipping region (including emissions from international transport), 100-year GWP

Methane is a more potent GHG than CO_2, and methane emissions play a larger role in determining the total upstream emissions for LNG than for other fuels.[6] Figure A5 shows total upstream GHG emissions for LNG and the portion of these that are from methane. Methane contributes approximately 30% to the total upstream carbon dioxide equivalent emissions in most studies. We observed two extreme cases: In one, methane leakage contributes 61% of life-cycle emissions because of high extraction emissions (El-Houjeiri et al., 2018), and in the other, no leakage was estimated (Tagliaferri, Clift, Lettieri, & Chapman, 2017). In general, methane emissions of LNG tend to be greater than those of HFO.

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[6] N_2O emission is not discussed because its amount is very small and contributes little to upstream emissions of LNG.

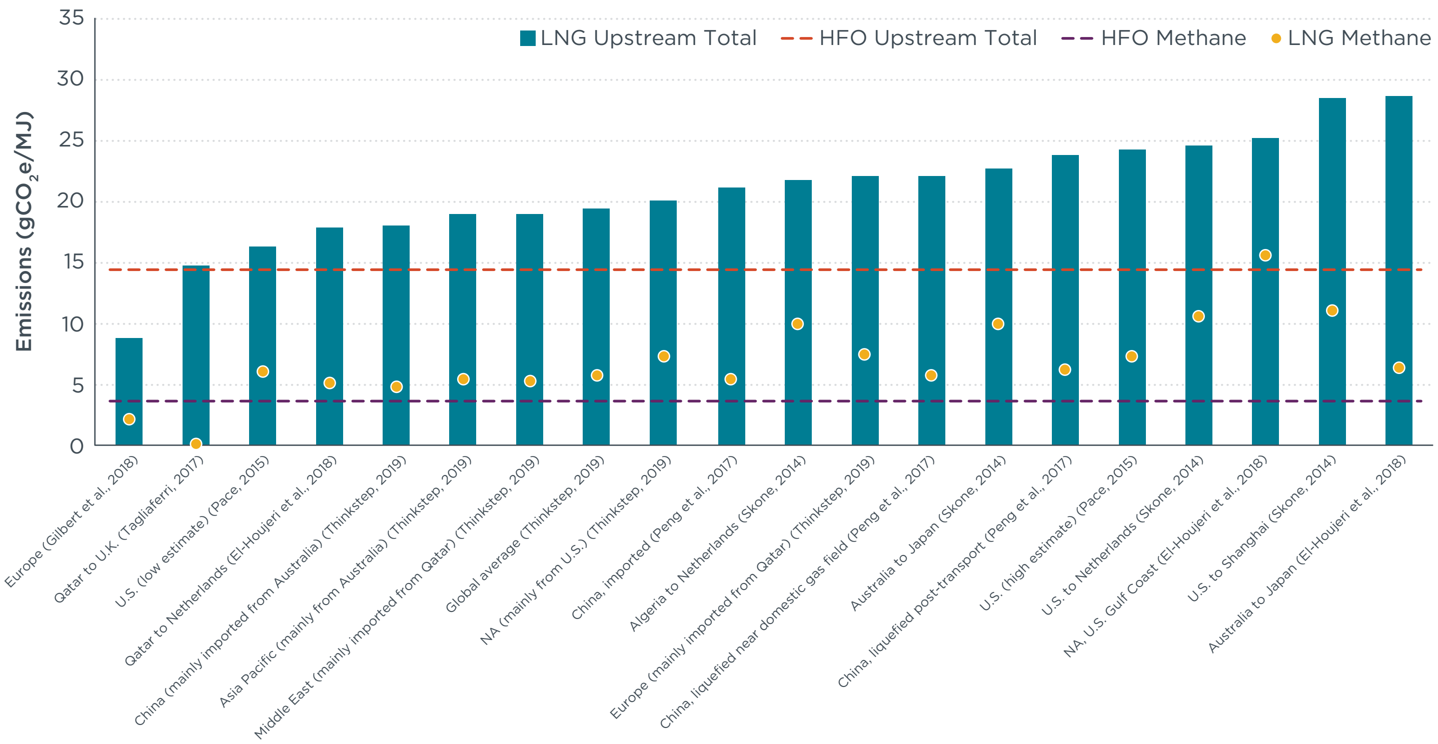

Figure A5. Total upstream LNG emissions and the emissions due to methane leakage, 100-yr GWP

We also applied the 20-year GWP from Table A1 to understand the short-term impacts of LNG, and that is presented in Figure A6. As shown, the global warming impact from LNG would be much greater in the near term and much worse than HFO. This diminishes the potential of using LNG to meet short-term climate change mitigation targets.

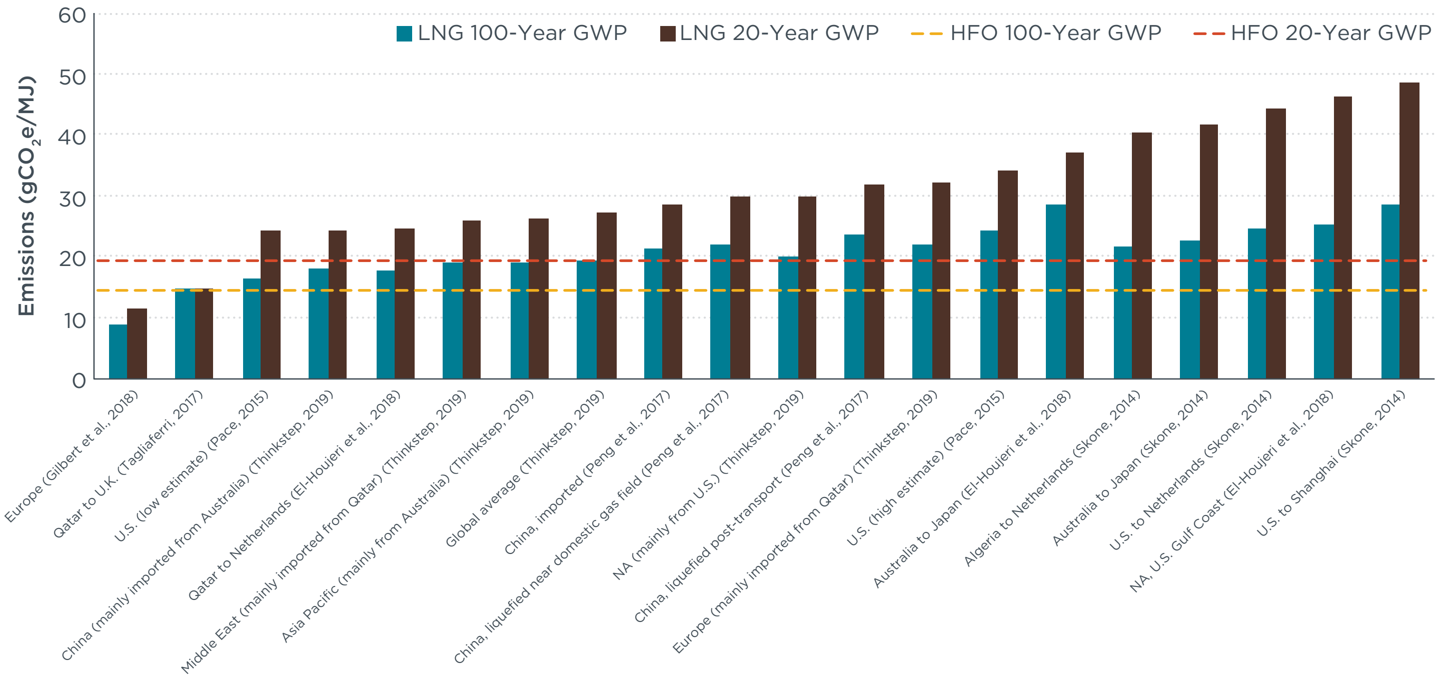

Figure A6. Total upstream emissions of LNG using 100-year GWP and 20-year GWP

We summarize the range of GHG emissions from literature in Table A2. Four key factors that contribute to the variation are production region, methane leakage during gas production and processing, difference in liquefaction technology, and international transport distance. Regardless of the variation, more than 85% of the 15 data points collected from previous studies show higher upstream emissions for LNG than HFO. This alone raises concerns about the climate change mitigation potential for LNG in the international maritime shipping sector.

Table A2. Upstream LNG emissions range from literature, 100-year GWP

gCO_2e/MJ	Liquefaction	International transport	LNG upstream total
Minimum	2.41	1.0	14.7
Average	6.55	3.2	21.2
Maximum	10.2	6.43	28.57

Methane slip from marine engines

LNG is the only cargo permitted for use as a fuel by the IMO (Dobrota, Lalić, & Komar, 2013). Historically, LNG was used to power LNG carriers, in part because boil-off methane from the LNG is freely available. The only other method to prevent boil-off to the atmosphere is to re-liquefy the boil-off gas, and that requires massive amounts of energy. But now LNG is generating wider interest and use from merchant and service vessels for which the boil-off motivation does not apply.

Many different units and measures are employed in the literature to describe the quantity of methane lost to the atmosphere or the GWP of methane loss. Perhaps the simplest is the fraction of methane lost as a ratio to the total methane transmitted or used. However, this becomes more difficult when the composition of the natural gas deviates from pure methane and the composition is not known. In a recent study of fugitive methane (Clark et al., 2017), the loss was reported as grams of fugitive methane per kilogram of natural gas used, a "parts per thousand" measure. Since losses are typically small relative to the total amount, this introduces little difference between the total amount either before or after the loss. However, the measure changes if the fuel gas composition is high in species other than methane. Further, if the natural gas used is determined from CO_2 measurements, the stoichiometry also causes a minor change.

A variant on the method above is to cite the loss in mixed units, such as mass of methane per volume of either liquid LNG or gaseous natural gas. Usually methane alone is cited as the loss, but in the case of leaks, species other than methane are also emitted. From an energy-loss perspective, these other gases should be included in the measure. In practice, the tools used to estimate or measure the loss will determine whether methane alone is considered.

Fugitive methane has also been characterized by the mass of methane lost as a fraction of the energy of the fuel available (g/MJ). To do this, the heating value must be defined. For engine operation, losses may be on a brake-specific basis where the methane loss is expressed as a ratio to the useful shaft work produced by the engine (g/kWh). Engine efficiency is therefore included in this measure, and this is the most common approach for quantifying other pollutants, such as NO_x.

Methane losses are also cited in terms of CO_2 equivalency in GWP. Hence the methane may be cited in units such as "CO_2 equivalent GWP by mass per basis of LNG," where the basis may be a mass or volume of LNG, or the LNG heating value, or the work produced by an engine operating on that LNG. The GWP must be known for translation of these units into methane mass. Across the literature, the 100-year GWP equivalency has been presented variously at values from 23 to 36, and 20-year values from 62 to 96. A previous ICCT marine methane emissions study (Olmer et al., 2017) employed IPCC (2007) values of 25 for 100-year GWP and 72 for 20-year GWP.

In our analysis of hull-to-wake emissions, the ratio of the brake-specific mass of methane is employed. Where other units are used, a best effort is made to translate the data equitably. In calculating brake-specific units from other measures, the engine efficiency must be used; if the efficiency is not reported, assumptions at part load may be approximate. Often, if methane alone is not reported as a fraction of the total hydrocarbons (HCs), values of 85% or 90% are used for the ratio of methane emissions to HC emissions for natural gas engines. Finally, fugitive methane is released in several different ways during marine propulsion. Only hull-to-wake (HtWa) losses are considered in this analysis.

System leaks

One obvious source of loss is from leaks across the fuel system, from the tank to the engine cylinders. This system may include pumps, scavenging compressors (for boil-off gas), filters, valves, injectors, and associated plumbing. In many cases, for reasons of safety, methane fuel plumbing is jacketed; this ensures that leaks are not released into the engine room, and those jackets are then vented to the atmosphere. No data are available to quantify losses of this kind. Studies (Johnson, Covington, & Clark, 2015; Subramanian et al., 2015) have examined losses from other systems, such as those at land-based gas compressor stations or at well sites, but these are not readily extended to shipboard analysis. Although many of these land-based leaks are a climate concern, few represent an immediate safety hazard. Losses of methane from natural gas buses, trucks, LNG fueling stations, and CNG fueling stations were reported by Clark et al. (2017). Although the researchers examined the on-board fuel systems for all of the vehicles in the study, “no continuous leaks were found from CNG vehicles while a single leak was identified on an LNG vehicle that was below the quantification limit of 0.24 g/h” (p. 972). Extending this finding to the marine world, no emissions factor should be assigned to engine fuel system leaks without further research.

Intentional gas discharge

Methane may be lost due to intentional discharge of gas. This may be associated with maintenance, as happens when systems are cleared of gas or blown down to permit safe maintenance operations. The quantities discharged during maintenance are likely to be small relative to methane slip from the engines during revenue service. Venting may also be associated with general engine operation, although no specific case has appeared in the marine engine material reviewed. For 15-liter displacement high-pressure direct injection (HPDI) truck engines examined in a prior study, normal operation required occasional “dynamic venting,” relating to transient operation (Clark et al., 2017; Delgado & Muncrief, 2015; Speirs et al., 2019). Those methane emissions contributed 9.9 g/kg of fuel, or about 1% fuel loss, to the inventory for those engines. In the absence of detailed LNG marine engine operation and maintenance information, any factors assigned to this cause would need to be addressed in future studies.

Valve overlap (part of exhaust slip)

Some of the losses of methane found in the engine exhaust might be due to valve overlap, where the engine exhaust and intake valves are open at the same time (Joss, 2017). Valve overlap is more common in diesel engines because only intake air can be lost during the overlap period. Overlap is desirable for optimal gas exchange and permits the valve durations to be extended. With fixed valve timing, its benefits and deficits vary with engine speed. However, if the fuel and air mixture is prepared in the intake manifold, then late exhaust valve closure can lead to fuel flowing directly to the exhaust (Stone & Ball, 2004). Marine engines are turbocharged, and Nieman, Morris, Miwa, and Denton (2019) observed that the intake manifold pressure can sometimes be higher than the pressure in the exhaust manifold, accentuating loss. Dual fuel engines adapted from fuel oil engines would require adjustment of valve timing to address this loss. Note that late model engines with variable valve timing (e.g., Rolls-

Royce, 2018) presumably would be configured to avoid this loss completely. HPDF engines, where fuel is not present in the intake, would avoid this loss. Where there is timing control over natural gas port injectors, introduction of the natural gas can be delayed relative to intake valve opening to avoid blow-through (Wärtsilä, 2009).

Concealed gas (part of exhaust slip)

For engines fueled with natural gas at low pressure, there is a fuel-air mixture present during at least part of the compression stroke, and it is present throughout the cylinder volume. If the gaseous fuel is introduced with air from the manifold, it is present throughout the intake and compression strokes. Some of the fuel-air mixture enters crevices or contained spaces in the engine (Joss, 2017; Wagemakers & Leermakers, 2012). A prime example is the space between the piston crown and cylinder wall, which is above the top ring of the cylinder at the top land crevice. The head gasket area also offers crevices. These zones are protected from the combustion process in the bulk of the cylinder, and the methane in these areas remains unburned. Toward the end of the expansion stroke, it emerges from the crevices into the bulk gas, and much of it is discharged in the exhaust. These examples are some the largest cases of methane losses (Konigsson, 2014). Nieman et al. (2019) observed that this top land is potentially larger in diesel engines that may be adopted for dual-fuel operation. Nieman et al. (2019) also observed that it is best to prevent fuel from getting trapped in these areas in the first place, which can be done by reducing the crevice volume or by directly injecting the gas. A second methane storage mechanism exists; in this method, some of the gas is absorbed into the oil film on the cylinder wall during compression, protected from oxidation, and then desorbed in time to be expelled subsequently in the exhaust stroke (Murillo Hernandez, 2015). Both crevice and absorption methane slip would appear with methane from other sources of loss and are characterized as part of the total exhaust loss, discussed below.

Inefficiency of combustion (part of exhaust slip)

Combustion of a fairly homogenous lean mixture of gas and air proceeds with a flame that moves from the ignition source—that is, burning diesel, a rich burning gas mix from prechamber holes or a flame kernel from a spark plug—through the bulk of the gas in the cylinder. Laminar flame speeds are slow, and so charge movement and turbulent flame propagation are desirable. However, Joss (2017) presented unstable flame propagation caused by turbulence as a cause for poor combustion at high engine speed, and this may be interpreted as high piston speed for long stroke, low- and medium-speed marine engines. Broadly, if the charge motion in the cylinder is not optimized for the combustion, the flame front may not reach some stray pockets of gas; these then fail to burn, particularly at very high lambda values. Jensen, Schramm, and Morgen (1999), working with a small bore engine, showed that the fraction of unburned gas passing through the engine rose as the mixture became leaner beyond a lambda of 1.25, and was also affected by gas composition. Tan, Dagaut, Cathonnet, and Boettner (1994) showed that the presence of ethane and propane assisted with methane oxidation, and stressed both the effect of LNG composition and the difference between using boil-off gas and forced LNG evaporation. Poor combustion may also occur close to the cylinder wall, in a “quench zone” associated with cooling by heat transfer to the wall. While partial combustion of the gas to form CO detracts from engine efficiency, it also serves to reduce methane slip. Overall, poor combustion efficiency of the gas would appear as methane slip along with methane from other sources of loss and is characterized as part of the total exhaust loss, discussed below.

Open crankcase emissions

Additional methane loss can occur from crankcase emissions, which are not included in the exhaust stream unless intentionally fed into the exhaust. Piston rings do not seal completely against the cylinder wall. Gases that pass by the rings, termed blow-by, enter the crankcase, and must be vented. Some air and fuel may also reach the crankcase via valve stem clearances and return lubricating oil passages. Tatli and Clark (2009) presented data on the flow from crankcases of diesel truck engines of 5.9 to 14.6 liter displacement and showed that between 0.22% (for a recently rebuilt engine) and 1.49% of the working gas was lost past the rings. Blow-by in production spark-ignited engines is typically about 1% of the intake flow (Stone & Ball, 2004). Delprete, Selmani, and Bisha (2019) related blow-by to ring design, and this permits the scaling of data to larger engine sizes.

For decades, automobile engine crankcases have been closed, meaning that the crankcase gas is returned to the engine intake. Closing crankcases has not been favored on diesel engines because the oil in the blow-by flow fouls turbochargers, and this would also apply to turbocharged gas engines. Separation of the oil mist also proves to be difficult. Caterpillar (2015) provided practical information on closing marine diesel and natural gas engines. The Caterpillar 3516C IMO II marine diesel engine includes a closed crankcase design. Caterpillar subsidiary Progress Rail has announced dual fuel IMO Tier III marine engines, suited to tug applications, with a closed crankcase system.

In natural gas engines, the blow-by gas generally carries the same methane concentration as is supplied in the intake air. If the crankcase is vented to the atmosphere, this implies a methane slip of about 1%, regardless of the air/fuel ratio in the cylinder. Dieselnet cites sources that predict the blow-by volume flow in terms of engine power output. Values range from *Blow-by [dm3/s] = rated power [kW]/180* for a new engine to *Blow-by [dm3/s] = rated power [kW]/60* for a worn engine. For an average condition engine with an air/fuel ratio of 30, these values would translate to a methane slip of about 1g/kWh.

In a U.S. pump-to-wheels methane study (Clark et al., 2017), 9- and 12-liter stoichiometric spark-ignited engines were characterized for both exhaust and crankcase emissions. The engines had open crankcase vents, although similar engines were sold with closed crankcase systems in Europe and in the United States in subsequent years. The 9-liter engines, equipped with a three-way exhaust catalyst, emitted at 5.55 g/kg from the tailpipe and at 9.90 g/kg from the crankcase vent. The 12-liter engines emitted at 2.45 g/kg from the tailpipe and 10.19 g/kg from the crankcase vent. Johnson et al. (2015) measured both exhaust and crankcase methane emissions from four-stroke lean burn G3512, G3612, and G3516 Caterpillar stationary engines driving natural gas compressors. For a total of six engines, the crankcase fugitive methane was 4% to 22% of the engine exhaust methane emissions.

Brunnet et al. (2018) acknowledged methane in the crankcase while discussing oil mist explosions in marine engines: “The increasing use of LNG fueled ships leads to an accumulation of unburned methane in the crankcase or below the piston, depending on 4-stroke or 2-stroke engines, respectively” (p. 282). The oil mist arises mostly from high velocity blow-by gas stripping oil from the cylinder wall. Wärtsilä (2007) presented oil mist separation for diesel-powered cruise ships. However, the objective of such technology is not necessarily to close the crankcase, but to remove oil from the stream and return the oil to the crankcase, still venting the stream to atmosphere. Both open-vent and closed-vent demister systems are in the marketplace (UT99, 2019). Lofholm, Pettersson, and Vestergard (2009), of Wärtsilä, reported that for gas engines, the separator can provide closed crankcase operation, with the stream returned to the turbocharger intake.

For large two-stroke engines employing a crosshead design, the underside of the piston does not discharge to the crankcase, but rather to the intake chest that feeds the intake ports. The intake chest is isolated from the crankcase by a seal, and low leakage would be anticipated past that seal. In this way, these engines would re-ingest any blow-by, and methane slip from the crankcase should be insignificant relative to other sources. If four-stroke gas engines (either spark-ignited or dual fuel) without a crosshead design are used with high-pressure gas injection in the future, far less gas would be anticipated in the area of the rings, and methane slip due to crankcase venting would be substantially reduced.

Closing the crankcase and returning the unburned gas to the engine intake would recapture about 1% of the LNG used to fuel the engine and contribute to raising the efficiency of the engine. UT99 (2019) found that the efficiency of cogeneration gas engines rises by 0.7% as a result of closing the vent, and this implies 0.7% blow-by of methane.

The U.S. Environmental Protection Agency (EPA) and the European Union have recently moved to control crankcase emissions from stationary engines. The EPA rule includes regulation of 200 to 500 horsepower spark-ignited engines. Increasing regulation and increasing commercial offerings with closed crankcase systems suggest that there will be wide adoption of closed vents in the future. However, in the absence of enforced retrofits and noting the longevity of marine engines, it is likely that both open and closed crankcase systems will be in service in marine applications.

A crankcase emissions contribution needs to be incorporated selectively as an emissions factor. It is also important to undertake an assessment of the fraction of engines that both vent to the atmosphere and use technology that causes high methane levels in the crankcase. Where there is a crankcase vent that discharges to the atmosphere from any low-pressure LNG engine, the Caterpillar (2015) estimators and an assumption of 0.75% blow-by suggest a methane loss factor of 1 g/kWh. At present, there is no inventory to determine the fraction of marine LNG engines having closed crankcases. About 37% of merchant ships are 5 to 14 years old, and these represent 54% of the tonnage; this attests to a fairly slow replacement rate (Equasis, 2017). Because the closed crankcase technology is not the historical norm, it is reasonable to apply the open crankcase emissions factor to a portion of low-pressure LNG engines, excluding slow-speed engines, for purposes of a near-future HtWa fleet estimation. We incorporate crankcase emissions in our “high leakage” scenario.

Appendix B. Methane slip emission factors

In this appendix, we explain our methane slip emission factor assumptions. The discussion is organized by engine technology.

Lean burn spark-ignited engines

We suggest a central value of 4.1 gCH_4/kWh for LBSI engines. While we excluded this engine from our analysis because it has few international shipping or cruise ship applications, LBSI engines are being used for smaller ships. We therefore provide some information on this technology here, in case it is beneficial to the reader.

LBSI engines use a single fuel, natural gas, and a four-stroke cycle. The gas is sufficiently lean that a prechamber with a rich spark-ignited mixture is used to provide a high-energy ignition source for the gas in the bulk of the cylinder. The gas jets from the prechamber also assist with mixing and completeness of the combustion in the cylinder. Very lean operation supports low NO_x in the exhaust, without need for aftertreatment. Rolls-Royce Power Systems (Rolls-Royce/Bergen), Mitsubishi, and Caterpillar manufacture marine engines working on this principle. Wärtsilä already manufactures lean burn prechamber spark-ignited engines for stationary use and will offer a marine engine in this LBSI segment starting in 2021.

Stenersen and Thonstad (2017) and Ushakov, Stenersen, and Einang (2019) presented the latest data on methane slip and find a weighted 4.4 g/kWh on the water compared with a manufacturer reported 2.8 g/kWh on the test bed, for an average of 4.1 g/kWh for the E2 and E3 test cycles.

It is reasonable to consider whether other data sources approximate or otherwise differ from the suggested 4.1 g/kWh value, other than reported data that are too old to reflect recent technology. However, in some cases, the precise engine load associated with the emissions factor is not reported. Rolls-Royce (2012) presented values of 3 g/kWh at full load, and 5 g/kWh at 25% load, and these are in reasonable harmony. Corbett et al. (2015), using multiple sources, presented 5 g/kWh in their Table 3. Stenersen and Thonstad (2017) also presented manufacturer data, with various Rolls-Royce engines having slip of 4.2 to 5.5 g/kWh and with a Mitsubishi engine emitting 3 and 3.6 g/kWh at two different lambda values. Winebrake, Corbett, Umar, and Yuska (2019) used a value of 4.66 g/kWh. Verbeek, Kadijk, van Mensch, Wulffers, van den Beemt, and Fraga (2011) suggested a factor of 3.9 g/kWh, but expressed concern that it could be as high as 13 g/kWh at low loads. Speirs et al. (2019) plotted data from several sources and showed an average of 26 g/kg, supporting the 4.1 g/kWh value.

From two manufacturer surveys, Thinkstep (2019) presented a value of 2 g/kWh for LBSI, which is substantially below the values presented above. In June 2019, Dr. Elizabeth Lindstad of SINTEF provided a commentary (Lindstad, 2019) critical of the low emissions factor used in the Thinkstep report, and there was a response from Thinkstep that defends the number of 2 g/kWh that was supplied in response to surveys. Precise definition and choice of engine loads when determining emissions factors has contributed further to the disagreement. Data available for the E2 or E3 cycles emphasize high load (weighted average of 68.5%), and LBSI emissions generally rise substantially as load is reduced. Long-haul shipping using LBSI technology may meet or exceed the average load for the E2 or E3 cycles, but ferries and tugs may emit at higher brake-specific levels.

High-speed, lean burn spark-ignited truck engines average about 4 g/kWh upon unit conversion, in line with the Stenersen and Thonstad (2017) LBSI value. The Thinkstep (2019) value for high-speed spark-ignited engines was 3.25 g/kWh.

Without a preponderance of other sources disputing the Stenersen and Thonstad (2017) and Ushakov et al. (2019) value, methane E2 and E3 emissions of 4.1 g/kWh are supported for LBSI.

LBSI engine brake specific emissions levels vary with load. Table B1 shows the ratio of emissions for 25% and 50% load to 90% load, estimated from graphs of Ushakov et al. (2019) and Rolls-Royce (2012). As discussed for LBSI medium-speed engines below, an engine that sees low average-to-peak load ratios in service will emit at a higher brake-specific level than an engine that is operated near full load, or weighted toward high loads, as for the E2 and E3 cycles.

Table B1. Ratios of part load to high load emissions for eight LBSI engines. The data of Ushakov et al. (2019) were estimated from plots in their paper.

Emissions Ratio	50%/90%	25%/90%
Ushakov 1	1.7	3.3
Ushakov 3	0.8	0.7
Ushakov 4	0.8	3.5
Ushakov 5	2.1	4.6
Ushakov 8	1.8	8.7
Ushakov 9	1.2	1.3
Ushakov 10	1.0	1.0
Ushakov Average	1.3	3.3
Rolls-Royce (2012)	1.3	1.7
Average of 8	**1.3**	**3.1**

Low-pressure dual-fuel (LPDF) engines, medium-speed, four-stroke

We suggest a central value of 5.5 gCH_4/kWh for medium-speed, four-stroke LPDF engines.

Medium-speed, four-stroke LPDF engines use a very lean mixture of air and natural gas with a small amount of MGO pilot fuel. The lean mixture reduces NO_x formation and helps avoid engine knock. Compression must be sufficiently high to provide the temperature to ignite the MGO, which has an auto-ignition temperature far below that of the natural gas mixture.

Minimizing pilot injection lowers NO_x emissions but leaves methane unburned, especially at part load. At very low loads, methane slip is high unless the engine controls switch to diesel-only operation below a specified torque output. There is, therefore, a compromise between assuring low methane slip and providing high LNG substitution at light loads.

Wärtsilä offers two designs for four-stroke engines burning gas and diesel. First, there are engines recommended for marine use. They are designated “DF” for dual fuel. Examples include the W20DF, W34DF, and W50DF. These employ the low-pressure gas introduction described in this section. Second, there are Wärtsilä four-stroke engines designated as “GD” for gas-diesel that employ high-pressure gas injection and are designated for stationary and offshore platform use, and not for marine applications. However, Ushakov et al. (2019) counted this technology as available for marine use. These HPDF medium-speed engines include the W32GD and W46GD four-stroke engines. The “DF” engines run either on diesel alone, or on low-pressure gas with a diesel pilot that provides about 1% of the energy. The “GD” engines are designed to run on a range of gas and diesel mixtures, or on diesel alone.

Several medium-speed LPDF four-stroke engines may be used with electric drive to propel a large ship, providing a similar level of power to that of a single slow-speed engine. Substantial data are available for LPDF medium-speed engines. As with LBSI, the Thinkstep (2019) factor of 3.84 g/kWh was lower—about 55% of the value—than the Stenersen and Thonstad (2017) and Ushakov et al. (2019) value of 6.9 g/kWh. LPDF emissions are likely to be affected by a NO_x-versus-methane tradeoff, at a time when the IMO has tightened NO_x regulations without methane regulations in place. Ushakov et al. observed that "it is quite often that engines appear to be 'overtuned' resulting in very low nitrogen oxides emission, far below the limit set by the standards" (p. 1319). This overtuning, involving leaner mixtures, would contribute to combustion slip. In some cases, engines may be capable of emitting low NO_x or low methane, but not both simultaneously.

Wärtsilä has stated that its W20 DF engine met 6 g/kWh Stage V (2020) European standards on the E3 test cycle. Data provided to Bengtsson, Andersson, and Fridell (2011) by Wärtsilä showed 3.6 g/kWh total hydro carbons (THC), but the load is unknown. However, as reported by Stenersen and Thonstad (2017), Wärtsilä presented E2 cycle averaged values of 3.82, 3.57, and 3.54 g/kWh with increasing bore size for LPDF engines.

The detailed test data of Sommer et al. (2019) suggested that the emissions from the two LPDF engines that they tested exceeded the 7.3 g/kWh value. From the graph of the data, the cycle average would be about 9 g/kWh. On the other hand, the data gathered by Anderson et al. (2015) suggested a factor not much above 2 g/kWh, with 1g/kWh at high power loading. Anderson et al. (2015) themselves estimated an averaged cycle emissions value by applying the E3 and E2 factors of 0.2, 0.5, 0.15, and 0.15 to engine loads of 90%, 72%, 40%, and 29%, respectively and calculated 2.4 g/kWh for THC, which implies 2 g/kWh for methane.

Corbett et al. (2015) used the same value, 4.4 g/kWh, for LPDF and LBSI. Thomson, Corbett, and Winebrake (2015) and Winebrake et al. (2019) presented values so low for LPDF that it is supposed that some HPDF data may be included in averaging, and these values were not considered for comparative purposes. Speirs et al. (2019) plotted data from several sources, showing an average of 42 g/kg; depending on engine fuel efficiency, this supports a value in the range 6 to 6.5 g/kWh.

Determining a single representative factor for the LPDF engines is difficult, and there is strong evidence that they vary widely in use, have responded to NO_x regulations (Speirs et al., 2019), or represent engines of different generations and manufacturers. The split between the real-world measurements of Sommer et al. (2019) and Anderson et al. (2015) is wide, but averages to about 7 g/kWh. There is, however, an argument that LBSI and LPDF should yield similar slip, at least at high load, since only the ignition source differs.

Methane slip from LPDF engines is evidently highly dependent on load. Ushakov et al. (2019) have plotted brake-specific emissions against load for seven LPDF engines. Additional data at different loads are available from Anderson et al. (2015) and Sommer et al. (2019), and from Nielsen and Stenersen (2010) and MacQueen (2011), as plotted by Sommer et al. (2019). With a best effort, data were read from graphs, except the data for Anderson et al. (2015), which were obtained by linear interpolation and extrapolation of published data. The Nielsen and Stenersen (2010) and the MacQueen (2011) data were presented by Sommer et al. (2019) in units of g/MJ fuel, so that increased slip at light load would not include reduced engine efficiency and would underestimate a ratio based on brake-specific units. All other data used to compute ratios were in brake-specific units of g/kWh.

The individual engine data of Ushakov et al. (2019) average to a value of 1.7 for the ratio of emissions at 50% load/90% load and average to 4.0 for 25% load/90% load, as shown in Table B2. Two of the engines of Ushakov et al. (2019) showed lower brake specific emissions at 50% load than 90% load.

Table B2. Ratios of part-load to high-load emissions for 11 LPDF engines. Data for 10 of the entries were estimated from data on plots, and must be considered approximate.

Emissions Ratio	Basis	50%/90%	25%/90%
Ushakov 1	kWh	0.6	1.1
Ushakov 2	kWh	0.8	1.3
Ushakov 3	kWh	3.8	5.7
Ushakov 5	kWh	1.6	3.5
Ushakov 6	kWh	1.8	6.8
Ushakov 7	kWh	1.6	4.3
Ushakov 8	kWh	1.8	5.5
Ushakov Average	kWh	1.7	4.0
Anderson et al.	kWh	2.8	8.1
Sommer et al.	kWh	3.0	8.6
Nielsen/Stenersen	MJ fuel	1.6	2.3
MacQueen	MJ fuel	1.1	3.6
Average of 11	**mixed**	**1.9**	**4.6**

The Sommer et al. (2019) data were presented in units of g/kWh in the paper, and in g/MJ fuel in the supplemental material. The differences in the 25%/90% and 50%/90% ratios differed in the following way: 3.0 and 8.6 on a g/kWh basis, and 2.4 and 6.4 on a g/MJ fuel basis. This shows the added influence of the reduced fuel economy in the brake-specific emissions ratios.

Sommer et al. (2019) measured two engines that were very similar. If Sommer et al. (2019) data are weighted twice, the averages for the table above are 2.0 and 4.9.

Ushakov et al. (2019) provided average values for the seven engines on their plot for each load percentage, and they were read to the nearest 0.5 g/kWh as 4.5 g/kWh (100%), 5.5 (75%), 7.0 (50%), and 16.5 (25%). This yielded ratios of part-load emissions to full-load emissions of 1, 1.22, 1.56, and 3.67. If the E2 or E3 weighting values are considered, the emissions implied for these seven engines would be 6.0 g/kWh, or 1.33 times the 100% load value. This differs from the 6.9 g/kWh presented by Ushakov et al. (2019), due to different averaging approaches.

In summary, the Thinkstep (2019), Bengtsson et al. (2011), and Anderson et al. (2015) data all support a value below 4 g/kWh, and the similarity to LBSI engines suggests a value of 4.1 g/kWh. In contrast, Sommer et al. (2019) and the SINTEF (Lindstad, 2019) data (particularly manufacturer measurements) support values that are far higher. We suggest using an average of the 4.1 g/kWh LBSI factor and the 6.9 g/kWh LPDF factor. This yields a factor representative of an E2 or E3 cycle of 5.5 g/kWh, which is also similar to the value of 5.3 g/kWh for the two ships measured on the water by SINTEF. However, it is certain from reported data that the slip of LPDF engines can vary by a factor of at least three.

Low-pressure dual-fuel (LPDF) engines, slow-speed, two-stroke

We suggest a central value of 2.5 gCH_4/kWh for slow-speed, two-stroke LPDF engines.

Slow-speed, two-stroke, turbocharged, crosshead LPDF engines mix the gas and air early in the cycle stroke and use a diesel pilot injection to ignite the gas. Only 1% to 2% of the energy is delivered by the pilot fuel. Scavenging is via exhaust valves in the head, and intake ports through the cylinder walls. Winterthur Gas & Diesel (WinGD) and Wärtsilä offer engines working on this principle. These may be termed an Otto dual fuel, because the pilot injection acts as a spark plug to initiate the flame front in the gas. Gas is injected through the cylinder walls above the moving piston crown partway through the compression stroke, after the exhaust valves have closed, and is then further compressed with the air before being ignited by the diesel. The gas mixture must be sufficiently lean to avoid auto-ignition.

Few data are available for large, direct drive LPDF engines. The weighted cycle data for the WinGD manufacturer data in the SINTEF report (Lindstad, 2019) yield a factor of 3.2 g/kWh. The Thinkstep report (2019) presented 2.1g/kWh. WinGD (2018) presented a factor of 1.6 to 2.4 g/kWh for methane at 80% of THC and showed the rise of slip from 1.9 g/kWh at full load to 3.2 g/kWh at 25% load for their 50cm bore engine. Motorship (2017) presented a 3 to 4 g/kWh range for a 72 cm bore engine, and CIMAC (2016) reported a 4 to 5 g/kWh value. The slow-speed LPDF showed some variation with load. The 50%/100% reported by SINTEF (Lindstad, 2019) was 1.14, and the 25%/100% was 1.31.

In the absence of additional test data, we suggest a value of 2.5 g/kWh for slow-speed, two-stroke LPDF engines.

High-pressure dual-fuel (HPDF) engines, slow-speed, two-stroke

We suggest a central value of 0.2 gCH_4/kWh for slow-speed, two-stroke HPDF engines.

Slow-speed, two-stroke, turbocharged, crosshead HPDF engines employ a sophisticated high-pressure injection system for the gas, and also inject a small quantity of pilot fuel. These are also termed Diesel-cycle dual fuel engines, because both fuels are injected at high pressure near top dead center and because no combustion can occur prior to the dual injection. They are manufactured by MAN and are offered with either exhaust gas recirculation or selective catalytic reduction systems to control NO_x emissions. These slow-speed two-stroke engines share some commonality in combustion with the high-speed four-stroke high-pressure, direct injection, heavy-duty, over-the-road engines sold by Volvo and Westport and with the Wärtsilä gas-diesel (GD) engines in stationary engine applications.

MAN report a slip for their engines that is 0.2 g/kWh. The SINTEF report (Lindstad, 2019) presented the methane emissions as near zero. Huan, Hongjun, Wei, and Guoqiang (2019) echoed the 0.2 g/kWh value. Thinkstep (2019) presented 1 g/kg, which translates to about 0.14 g/kWh. CIMAC (2016) reported 0.3 to 0.4 g/kWh. Variation of the value with load or engine bore is unknown. Speirs et al. (2019) observed that HPDF two-stroke engines “have no associated measurements of their methane emissions other than from the manufacturers” (p. 53) and present the 0.2 g/kWh value.

Steam turbines

We suggest a central value of 0.04 gCH_4/kWh for steam turbines, but even though it is used today, we exclude this technology from our analysis because it has limited future applications for international shipping and is an older and less efficient technology compared with other LNG engines.

Methane loss is due to leaks or incomplete combustion in the boiler. Power plant data, which would include leaks, suggests 0.2 to 0.3 g/kg (Hanjy et al., 2019). For small boilers, the data of Merrin and Francisco (2019) were far below 0.1 g/kg. Though there is a wide spread, these data suggest a typical value of 0.04 g/kWh for the combination of an LNG boiler and steam turbine. Co-firing with fuel oil would reduce the brake-specific loss because less methane would be supplied to the turbine.

LNG carrier tankers have long used steam turbines because, despite their inefficiency compared with other marine engines, they allow ships to use their cargo as a fuel (Fernández, Gómez, M., Gómez, J., & Insua, 2017). When ships transport LNG, some of it evaporates. This “boil-off gas” builds pressure in the cargo tank that needs to be relieved. One way is to vent the methane into the atmosphere, but this is harmful to the climate and can create a fire and safety hazard on deck. Another way is to re-liquefy the gas into a liquid, but that requires massive amounts of energy that could instead be used for propulsion. Indeed, most LNG carriers have historically burned boil-off gas in steam turbines. But nowadays ships have other options to use LNG, including marine diesel engines that are more efficient and consume less LNG.

Gas turbines

We suggest a central value of 0.06 gCH_4/kWh for gas turbines. We investigated gas turbines but we do not include them in our analysis because they are not suited for international shipping or for most cruise ship applications.

Gas turbines are used for high-speed ships such as ferries and naval ships. They are much less efficient than other marine engines, but they generate a large amount of power that can propel a ship quickly through the water. They are not suited for slower speed freight and passenger transportation.

The Thinkstep (2019) report presented a value of 0.08 g/kWh for a gas turbine alone, and 0.05 g/kWh for a combined cycle system. General Electric (GE) characterizes its COGES system as having zero methane. Siemens (2016) also suggest zero slip.

We should note that another option is to burn fuel directly in a gas turbine, recover waste heat with a steam turbine, and use both to power generators and electrically driven propellers. Fernández et al. (2017) presented the Rolls-Royce and GE designs for these systems. Data suggest that these systems may be very efficient. GE (2016) presented a high efficiency for their latest technology 605 MW electric power plant. In 2016, the combined cycle plant in Bouchain, France, achieved a reported efficiency of 62%. Marine units, constrained in power and size, would not achieve such high efficiency, but this indicates a current upper limit for gas turbines coupled to steam turbines. However, we are not aware of any combined-cycle applications for marine at this time.