Methane Emissions from Natural Gas Bunkering Operations in the Marine Sector: A Total Fuel Cycle Approach

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Abstract

This research evaluates emissions associated with the use of liquefied natural gas (LNG) for marine transportation. In particular, this research focuses on the scope and scale of *methane slip* and *methane leakage* during dockside fuel bunkering and use. The research explores how LNG vessels perform on a net greenhouse gas (GHG) basis vis-à-vis conventional fuels under various bunkering leakage and slip assumptions.

Using best available data, this study applies a total fuel cycle analysis methodology using the latest version of the Total Energy and Emissions Analysis in Marine Systems (TEAMS) model to evaluate "well-to-hull" emissions for vessel operations. TEAMS allows emissions analysis along the entire fuel pathway, including extraction, processing, distribution, and use of natural gas fuels in vessels. Until this project, all available total fuel cycle models treat generically the port-based, fuel transfer, and shipboard processes for natural gas fuels. This work advances the state of knowledge for these critical stages of fuel cycle processes. The work also directly informs maritime stakeholders about ways to manage, mitigate, or minimize potential releases of greenhouse gases related to bunkering operations for natural gas fuels.

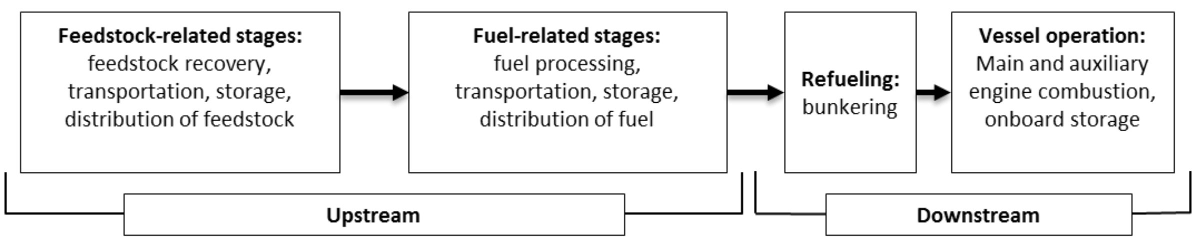
In addition to a comprehensive literature review on port-based and shipboard methane leakage and slip in natural gas fuel delivery and storage systems, this work analyzes a variety of possible conditions that include: (1) types of marine engines used; (2) types of bunkering available; (3) types of storage and boil-off recovery systems; and, (4) types of LNG production used. Results focus on methane leakage and slip and report these emissions in the context of GHG emissions using carbon dioxide (CO_2) equivalents. The results show that LNG fuels used in Diesel cycle (compression ignition) natural gas engines offer GHG emissions benefits compared to conventional fuels in most cases, although methane leakage and slip can diminish those benefits considerably. In contrast, the results indicate that LNG fuels used in lean-burning, Otto cycle (spark ignition) natural gas engines offer little to no benefits compared to conventional fuels. Results from this work will better inform projects and policies aimed at improving the efficiency of fueling and reducing methane losses and emissions from the use of natural gas in marine transportation systems.

1 Introduction

This research focuses on the use of natural gas fuel (specifically liquefied natural gas, or LNG) in the maritime sector, and how methane (CH_4) emissions from such use impact overall greenhouse gas (GHG) emissions. In particular, this research focuses on the scope and scale of methane slip and leakage during fuel bunkering and fuel use.

This research is timely and important. The marine transportation sector is actively considering approaches to reduce emissions from vessels. One approach is to replace conventional petroleum based fuels (residual oil and distillates) with LNG. The shift to LNG has the potential to reduce emissions of criteria pollutants significantly at the vessel stack (end-use). However, emissions that occur in the production and delivery of LNG must be accounted for, as shown in Figure 1. One emissions product of particular concern is CH_4 that is emitted either through: (1) "methane leakage" during fuel production, storage, transportation, and the specific process of refueling (or "bunkering"); and, (2) "methane slip" or unburned methane emissions released during vessel operation (via fuel combustion in the engine).

Figure 1. Components of a total fuel cycle analysis for marine vessels.



While methane slip has been accounted for in prior life-cycle models, this work updates that previous work, as well as provides specific attention to leakage during bunkering. This study leverages insights from existing literature and research efforts, including the work on the Total Energy and Emissions Analysis for Marine Systems (TEAMS) model. The TEAMS model allows analysts to account for these upstream and downstream emissions in various ways. Through this research, a new version of TEAMS that is compatible with the 2014 Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model was developed and applied to evaluate total fuel cycle emissions from several LNG and conventional fuel cases.

The cases use data derived from literature on LNG storage, refueling, and use, discussed in Section 2. TEAMS now has the flexibility to incorporate a variety of user-defined processes, inputs, and emissions factors to address a wide variety of LNG vessel bunkering operations and use. While results are consistent with prior published work using TEAMS, the explicit presentation of inputs defined in this report can become a resource for future application of TEAMS and demonstrates that TEAMS will be flexible if and when better inputs emerge.

This research project executed the following objectives:

1. Conduct a comprehensive literature review that characterizes, qualifies, and quantifies (where available) methane leakage and slip in natural gas marine transportation systems (or equivalent systems, depending on data availability). This task is broadly focused on the entire fuel cycle to ensure a clear understanding of: (a) the relative fraction of methane releases that may be attributed to bunkering processes that include dockside and shipboard handling, transfer, and storage; and, (b) the full range of state-of-practice technologies that may be considered in a

maritime context. This literature review summarizes a set of data that is of different units (e.g., %, grams/BTU, grams/kwh, etc.). Emissions factors are normalized to common units and summarize the literature in a way that allows for comparisons across engine types, fuel systems, and well-defined fuel cycle stages.

2. Employ the results of our findings to characterize handling, transfer, and storage emissions rates. This task updates TEAMS to better enable scenario-specific inputs for maritime operations involving natural gas (at dockside, during transfer, and shipboard). This involved a new release of TEAMS that ensured code compliance with GREET and improved the functionality and versatility of the software.

3. Conduct a quantitative Total Fuel Cycle Analysis (TFCA) using the TEAMS model that would employ data found in Task 1 to improve the characterization of dockside and shipboard handling, transfer, and storage of natural gas fuels, as well as emissions released during vessel operation. Results compare the TEAMS analysis to previous analyses of natural gas fuels and to conventional fuels. This TEAMS analysis demonstrates the scale of the leakage or slip effect vis-à-vis different fuel cycle stages. This latter set of analysis enables policymakers and technology system designers to target efforts on the stages of the fuel cycle that are most problematic from a leakage/slip standpoint.

4. Consider case studies recently produced to develop an initial feasibility framework for considering the context-specific implications of our findings. For example, this work reexamines with bunkering leakage the downstream portions of West Coast scenarios from previous work that did not include bunkering leakage (Thomson et al., 2015). The updated case models the implications of alternative dockside, transfer, and shipboard designs/controls on methane emissions compared to those reported in previous case studies. Additionally, marine fuel price trends in a West Coast (LA/LB) bunker market allow estimation of the economic value of natural gas leakage that can be avoided, recovered, or reduced over a long-term period. This provides additional information important to understanding the issues requiring further focused study as efforts continue to bring LNG in maritime application.

2 Characterization of Downstream Methane Leakage

2.1 Environmental Policy Motivates LNG Consideration

The International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted by the IMO in 1973 to address the issue of pollution emitted from ships entering the marine environment (International Maritime Organization, 2002). MARPOL has been amended several times as new information about the causes, effects, and extent of marine pollution has been discovered. Annex VI was first adopted in 1997 to address air pollution, specifically SO_x and NO_x (International Maritime Organization, 2008). Subsequent changes have decreased the allowed emissions globally and assigned areas designated as ECAs with even stricter emissions requirements (International Maritime Organization, 2002, 2008). As marine fuels tend to have high sulfur content, these stricter requirements have led to exploration of different fuels – such as natural gas – for marine transportation.

The literature is clear that natural gas fuels can significantly reduce criteria pollutants from vessel operations; however, the advantages from a GHG emissions perspective remain uncertain (Thomson et al., 2015). For example, LNG fuel production pathways can be energy intensive (Comer et al., 2010; Corbett and Winebrake, 2008; Meyer et al., 2011; Winebrake et al., 2006, 2007; Winebrake and Meyer, 2008), and the leakage of CH_4 that accompanies natural gas extraction and distribution has important GHG impacts. In addition, methane emissions from burning natural gas in marine engines (i.e., "slip") can also have a negative GHG impact. Since the US is concerned with both criteria pollutants and GHG emissions, decision makers find it important to look at the life-cycle emissions generated by natural gas fuels compared to traditional marine bunkers.

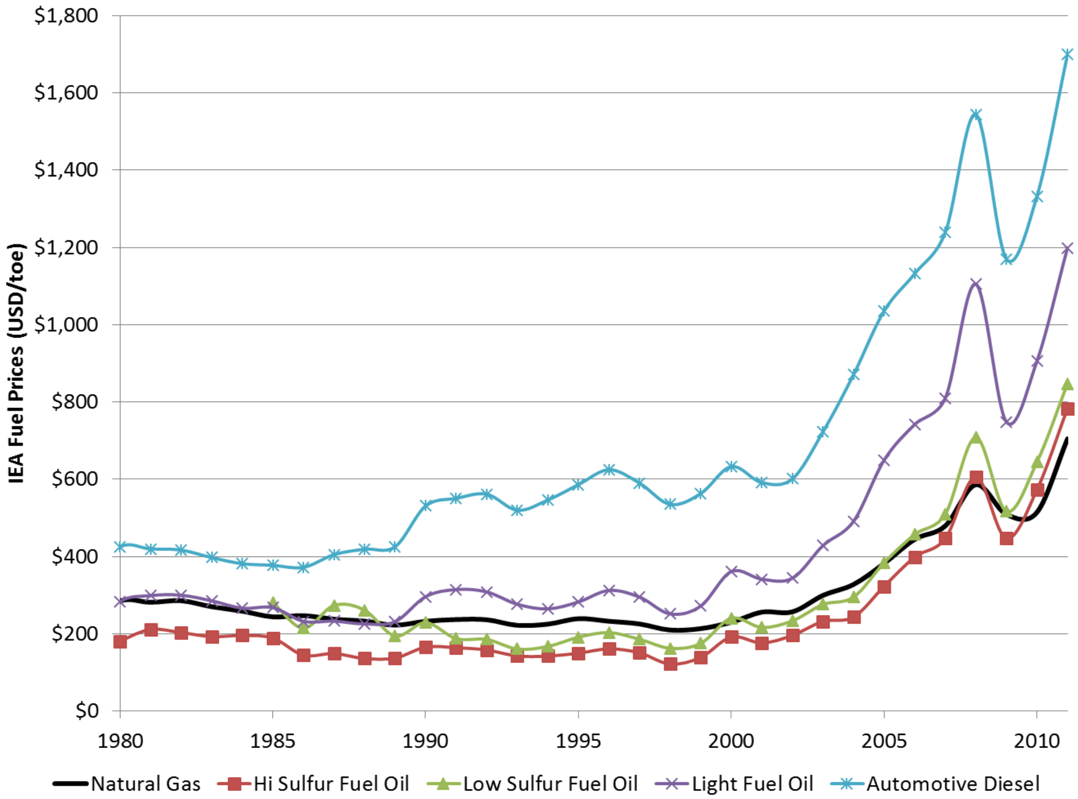
2.2 Consideration of Natural Gas Fuels for Marine Vessels

The emissions signature of natural gas meets all current, pending, and proposed standards for marine vessel operations, and the current price differential favoring natural gas suggests an economic advantage may exist (Thomson et al., 2015). Figure 2 illustrates that natural gas pricing may be advantageous on a price bases both globally and specifically in North America (IEA, 2012). Recently, the shipping industry has joined other sectors in considering the merits of gaseous fuels as a feasible, economical, and low-emitting alternative to traditional petroleum fuels. For these reasons, natural gas is emerging as an attractive fuel, with many newly constructed vessels powered either by natural gas exclusively or by a combination of conventional diesel and natural gas (Pospiech, 2014; Thomson et al., 2015). The emergence of market-ready reciprocating internal combustion engines capable of natural gas and/or dual fuel operation in maritime service makes studies such as this one more important for industry leaders and policy decision makers. Multiple firms are building or are planning to build vessels using these engines, making this research extremely relevant to current investment decisions (Andersen et al., 2013; Rolls-Royce, 2012; Wartsila, 2014).

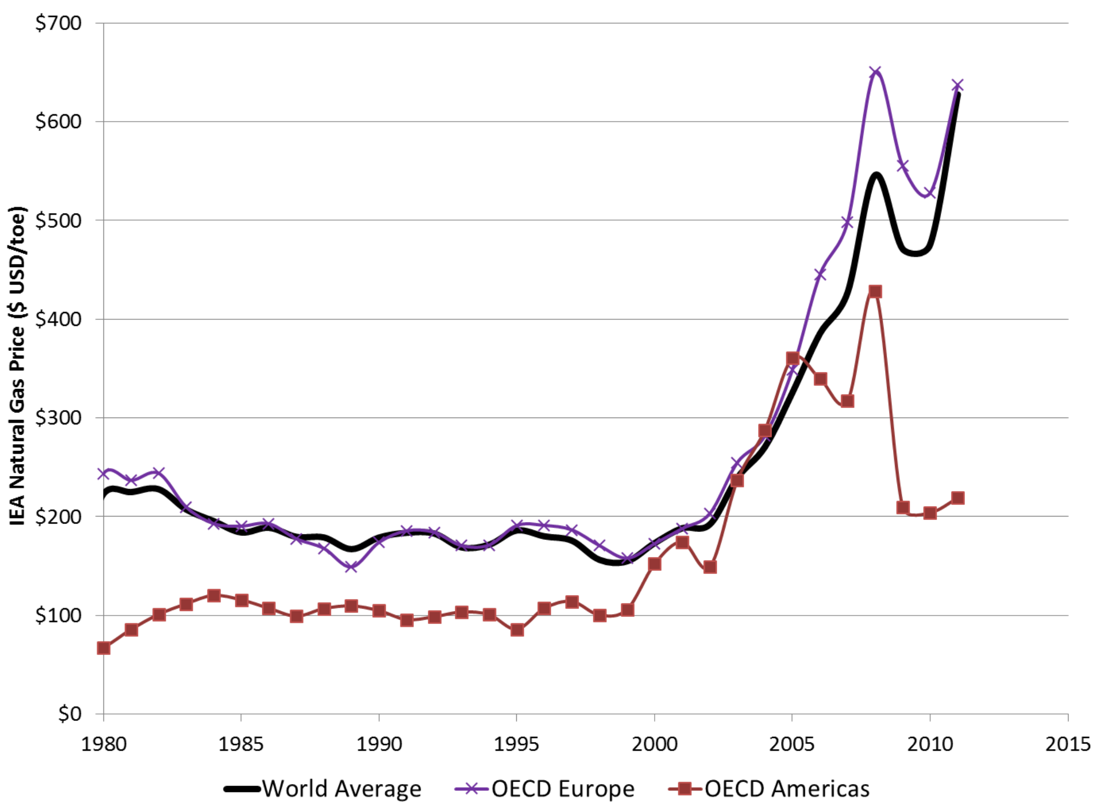
Of course, existence of the technology is not the only thing considered when deciding whether or not to switch to alternative fuels. Operators are also looking at cost and technical feasibility issues, including:

- the ability to operate within and beyond emission control areas, without the need for aftertreatment of exhaust gases for criteria pollutants;
- the price differentials for natural gas versus other marine fuels, including residual heavy fuel oil; the existence of infrastructure networks for obtaining natural gas fuel; and,
- the financing of natural gas vessels in fleet modernization/replacement strategies.

Figure 2 Natural gas fuel prices by fuel type a) compared with other fuel types, and b) compared regionally for the US and Europe (IEA, 2012).



a)



b)

Regarding the second point above, recent trends in the prices of crude oil and natural gas are making natural gas a more attractive marine fuel, as shown in Figure 2. In addition, natural gas infrastructure is growing (Fullenbaum et al., 2013), making it more plausible to fuel ships with natural gas in the future.

However, increased use of natural gas in the marine sector may negatively affect a third important factor: climate change. Complementing the IMO's concerns about criteria pollutants such as SO_x, NO_x, and PM_{10}, new research regarding GHG emissions from vessel operations has stimulated efforts to reduce GHG emissions from international shipping. Currently, international shipping is responsible for ~2–3% of total CO_2 emissions globally, and the IMO adopted mandatory measures to reduce GHGs in 2011 (Bazari and Longva, 2011; Smith et al., 2014). Whether increased natural gas use in the marine sector will increase GHG emissions globally is an open question that this study helps answer. Answering this question requires consideration of methane leakage and emissions along the entire fuel production, delivery, and use pathway (Brynolf et al., 2014b; Lowell et al., 2013; Meyer et al., 2011) . When upstream emissions are considered, advantages from a GHG emissions perspective remain uncertain, because natural gas fuel production pathways involve methane leakage during natural gas extraction and distribution, which has important GHG impacts (AEsoy et al., 2011; Arteconi et al., 2010; Bengtsson et al., 2011; Bengtsson et al., 2014; Brinkman et al., 2005; Brynolf et al., 2014a; Choi and Song, 2014; Elgowainy et al., 2009; Huo et al., 2008; Jayaram et al., 2010; Korakianitis et al., 2011; Lowell et al., 2013; Shen et al., 2012; TIAX et al., 2007; Yazdanie et al., 2014) .

2.3 LNG Bunkering Methane Leakage

LNG bunkering of a marine vessel may take place in a variety of ways, but four approaches stand out:

(1) Truck to Ship – fuel is pumped from a tanker truck into the ship, for small volumes in the range of 50-100 m^3;

(2) Ship to Ship – fuel is pumped from a bunker vessel or barge into the ship, for volumes in the range of 200-10,000 m^3;

(3) Terminal to Ship – fuel is pumped from land production or storage facilities into the ship, for volumes in the range of 100-10,000 m^3; and,

(4) Portable Tanks – modular (full) tanks are swapped for empty ones[1] (American Bureau of Shipping, 2015; DNV GL, 2014). Each of these transfer processes can occur using either a hose or a loading arm (Arnet, 2014), and some may involve refrigerated piping/hoses using liquid nitrogen to minimize evaporated methane during transfer (Arnet, 2014). Technical details and the pros/cons on each of these approaches can be found in a 2014 MARAD report on this topic (DNV GL, 2014).

In all these bunkering scenarios, there is the opportunity for CH_4 to leak through various components of the bunkering system. The most comprehensive study to date on LNG leakage from maritime bunkering operations emerges from Lowell, et al. (2013) based on work for the International Coalition for Clean Transportation (ICCT). That study identifies a range of leakage rates due to bunkering (measured in gCO_2e/MJ)[2] as shown in Table 1 and supplemented with additional information from Marintek (Lowell et al., 2013; Nielsen and Stenersen, 2010). These leakage rates vary widely and can occur from "(1) losses

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[1] As noted by DNV GL (2014) in a report for MARAD, a 40-foot (ISO-scale) portable tank has a fuel capacity of ~13,000 gallons of LNG.

[2] Units are grams of CO_2 equivalents per mega-joule. Converting all emissions species to CO_2 equivalents accounts for the different global warming potential of different pollutants.

due to heat absorption and venting from storage tanks over time; (2) venting of displaced vapor when filling a storage tank; (3) LNG liquid and vapor purged from hoses and lines after fueling a vessel; and (4) flash losses created from precooling lines and storage tanks or from transferring LNG from a high-pressure to a low-pressure tank" (Lowell et al., 2013). Flash losses were not measured in the ICCT report due to the difficulty in quantifying these losses; however, these flash losses are expected to be insignificant in the pathways described.

Leakage rates vary according to whether the LNG fueling is close to the supply (production or import), whether it is part of a centralized bunkering activity or at a remote site, and whether there is long-term storage of LNG. ICCT leakage assumptions are provided in Table 1, drawn from the report appendix tables. The ICCT leakage assumptions resulted in estimated leakage values during bunkering (reproduced in this report, Table 2). The bunkering configuration with the greatest leakage, per ICCT, included bunkering at a location with distributed fueling and storage. These values establish the basis to conduct scenario analyses in this report. Table 2 also demonstrates the different units in which leakage values are reported, as well as a column that converts these values to a common unit corresponding to TEAMS input values.

The American Bureau of Shipping (ABS) adopts a risk assessment framework in considering LNG leakage during bunkering. Similar to the ICCT report, ABS identifies four initiating events that are risk drivers for LNG bunkering operations and identifies common causes for each event (American Bureau of Shipping, 2015). These initiating events include: (1) leaks from LNG pumps, pipes, hoses, or tanks; (2) inadvertent disconnection of hoses; (3) overfilling or over-pressuring vessel fuel tanks; and, (4) external impact. The report also identifies 22 prevention and mitigation safeguards that can help minimize the frequency and volume of bunkering leaks.

A research study conducted by the Norwegian University of Science and Technology developed a risk-based approach to compute the methane leakage during bunkering, reported in total mass released (kg) (Arnet, 2014). These were calculated in two ways: (1) assuming the natural gas fuel in a component is lost, called "static release"; and, (2) assuming that the bunkering process is not shut down immediately and natural gas is "pushed" through the system breach, called "dynamic release." The estimated release during an event is the sum of the static release and the dynamic release of natural gas. Arnet (2014) also computes the risk, or frequency of bunkering release events. Most release conditions computed result in frequencies on the order of 10 in a million or less. Therefore, when considering a single trip with a single vessel bunkering, as in this study, the frequency-weighted release volumes are smaller than the routine leakage rates suggested by the ICCT study. Therefore, we don't adjust the ICCT values for additional risk-based releases, but consider this to be a useful step when considering leakage at a LNG bunkering facility that may fuel hundreds or thousands of vessels in a year.

Table 1. Leakage processes and assumptions based on the ICCT report (Lowell et al., 2013).

Bunkering Conditions	ICCT leakage assumptions		
		Current	**Best practice (according to ICCT)**
LNG fueling close to supply (at import or production facility)	Vapor displaced [% of LNG fill mass]	0.22%	BOG recovery system captures methane
	Recovery rate [%]	95%	
LNG storage	Boil off rate [%/day]	0.15%	Flaring with 95% efficiency
	Duration [days]	4	
	Recovery rate [%]	0%	
LNG tank filling at centralized bunker site	Vapor displaced [% of LNG fill mass]	0.13%	Flaring with 95% efficiency
	Vapor vented {%]	100%	
LNG fueling at a remote location	Vapor displaced [% of LNG fill mass]	0.22%	Flaring with 95% efficiency
	Vapor vented {%]	100%	

Table 2. Methane emissions related to LNG bunkering in the maritime sector.

		Reported Emissions			Emissions in TEAMS Units	
	%	**gCH_4/mmBtu**	**gCO_2e/MJ[a]**	**gCH_4/ ton LNG[b]**	**gCH_4/ mmBtu**	**Source**
Boil Off Rate	0.13				**N/A[c]**	ICCT
	0.15				**N/A[c]**	ICCT
Total From Fueling		2.0			**2.0**	ICCT
		40.8			**40.8**	ICCT
		176.3			**176.3**	ICCT
Leakage from Bunkering		Best practice	0.0		**0.0**	ICCT
			0.2		**8.5**	ICCT
			0.3		**12.7**	ICCT
			0.5		**21.1**	ICCT
		Current practice	1.1		**46.5**	ICCT
			4.3		**181.6**	ICCT
			4.5		**190.1**	ICCT
Offshore Vessel Emissions				40.0	**0.8**	Marintek
				44.0	**0.8**	Marintek
				60.9	**1.2**	Marintek
				80.0	**1.5**	Marintek
				100.5	**1.9**	Marintek

[a] To convert to TEAMS units, values were divided by 25 to convert to CO_2e (1g CH_4 = 25 CO_2e) based on 100 year global warming potential (GWP) assumption and ten multiplied by 1055.87 (1mmBTU = 1055.87 MJ) to convert MJ to mmBTU;
[b] To convert to TEAMS units, value was divided by 52.66 (1 ton LNG = 52.66 mmBTU) to convert from tons to mmBTU units;
[c] This value is reported as a percentage in TEAMS so no conversion is necessary.

2.4 LNG Engine Methane Slip

In addition to bunkering leakages, concerns about methane “slip” – defined here as methane that escapes the combustion chamber as an unburned hydrocarbon – have arisen in the industry. This methane slip is a function of the type of LNG engine in use. For marine engine applications considered in this report, the natural gas fueled engine designs considered are: (1) lean burn spark-ignited engines operating on the Otto Cycle; (2) Diesel dual fuel (DDF) compression-ignited engines, operating like a lean burn engine on the Otto Cycle but with Diesel injection to ignite the methane/air mixture; and (3) Diesel injected compression ignited engines, operating with natural gas on the Diesel Cycle. Each of these is described in more detail below:

> **Lean burn natural gas engines** can achieve lower downstream CO_2 emissions levels than petroleum-based Diesel engines at similar air-fuel ratios, at very similar thermal efficiency under lean conditions (Cho and He, 2007). The engines can also operate on a much leaner fuel-air mixture and operate at higher compression ratios using advanced spark timing (Korakianitis et al., 2011).
>
> **Diesel dual fuel (DDF) engine designs** operating with natural gas fuel typically use “a port injected “premixed” air/methane mixture which is ignited by the Diesel injection and burns with a flame propagation (like the Otto combustion)” (Broman et al., 2010).
>
> **High-pressure natural gas injection Diesel cycle engine** uses directly injected (DI) methane which burns with diffusion controlled combustion (like the Diesel combustion) (Broman et al., 2010). This engine design is “based on a high pressure gas injection principle with pilot fuel ignition. With this principle the diesel combustion process can be fully utilised and thereby the same high thermal efficiency as for the heavy fuel oil burning two-stroke engines can be obtained.” (Juliussen et al., 2011)

In addition to methane slip, there are other emissions differences between traditionally fueled diesel marine engines and natural gas fueled marine engines. These are summarized in Table 3 for two primary GHGs (CH_4, and N_2O), and for three criteria pollutants (NOx, PM_{10}, and NMVOCs). Fuel cycle emissions for CO_2 are computed in TEAMS based on energy density and heating values consistent with the GREET model inputs for upstream emissions, from first principles; key inputs for these are presented in Table 4.

Table 3. Typical engine emissions factors (reported in g/kWhout, g/hp-hrout, and g/mmBTUin).

Engine Type	Units	Methane slip (CH_4)	Nitrous oxide (N_2O)	Oxides of nitrogen (NOx)	Particulate matter (PM_{10})	Non-methane volatile organic compounds (NMVOC)
Lean-burn Otto cycle engine	g/kWh_{out}	5	0.015	2	0.04	0.19
	$g/hp\text{-}hr_{out}$	**3.7**	**0.011**	1.5	0.03	0.14
	$g/mmBTU_{in}$	660	2	264	5	25
Dual-fuel gas engine (gas mode)	g/kWh_{out}	5	0.015	2	0.1	0.19
	$g/hp\text{-}hr_{out}$	3.7	0.011	1.5	0.07	0.14
	$g/mmBTU_{in}$	660	2	264	13	25
Diesel cycle gas engine	g/kWh_{out}	0.693	0.015	12	0.1	0.5
	$g/hp\text{-}hr_{out}$	**0.517**	**0.011**	8.9	0.07	0.37
	$g/mmBTU_{in}$	91.4	2	1583	13	66
Low-sulfur petroleum Diesel engine	g/kWh_{out}	0.034	0.015	14	0.44	0.7
	$g/hp\text{-}hr_{out}$	**0.025**	**0.011**	10.4	0.33	0.52
	$g/mmBTU_{in}$	4.5	2	1846	58	92
High-sulfur petroleum Diesel engine	g/kWh_{out}	0.034	0.015	14	0.44	0.7
	$g/hp\text{-}hr_{out}$	**0.025**	**0.011**	10.4	0.33	0.52
	$g/mmBTU_{in}$	4.5	2	1846	58	92

NOTE: Values in bold and shading are used as model inputs for TEAMS analyses of downstream GHGs. All conversions from or gEF/kWh_{out} $gEF/hp\text{-}hr_{out}$ to $gEF/mmBTU_{in}$ use an engine thermal efficiency of 45 and a conversion factor of 3412 BTU/kWh. Sources: These values represent the authors' review of various sources, with greater reliance upon documents in the following order: i) peer-reviewed or conference publications; ii) official engine manufacturer reports or specifications; and iii) presentations made by industry technical and/or marketing representatives. (Aabo, 2014; Juliussen et al., 2011; Jun et al., 2002; Kristensen, 2012; Kunz et al., 2013; Nielsen and Stenersen, 2010; Pospiech, 2014)

Table 4. Example input values related to fuel specifications; used in TEAMS to calculate energy use, carbon dioxide (CO_2), and sulfur oxide (SO_X) emissions.

Fuel	Heating Value (Btu/gal)		Density	C ratio	S ratio
	LHV	HHV	grams/gal	(% by wt)	(ppm by wt)
Liquid Fuels:					
U.S. conventional on road diesel	128,450	137,380	3,167	86.5%	200
Diesel for non-road engines	128,450	137,380	3,167	86.5%	163
Low-sulfur on-road diesel	129,488	138,490	3,206	87.1%	11
Low-sulfur marine distillate fuel	128,450	137,380	3,167	86.5%	1,000
Residual oil	140,353	150,110	3,752	86.8%	5,000
Bunker residual fuel	140,353	150,110	3,752	86.8%	28,000
Gaseous Fuels (at 32F and 1atm):	**Btu/ft3**	**Btu/ft3**	**gms/ft3**		
Natural gas	983	1,089	22.0	72.4%	6

NOTE: Shaded rows indicate those values used for the case study in this report.

Methane slip engine emissions are related to poor combustion of methane under very lean methane/air mixtures, variations in flame propagation dynamics, and "blow-by" of unburned methane during cylinder valve operations (Broman et al., 2010). However, for compression-ignited (CI) LNG engines (where small amounts of diesel fuel are used to ignite the natural gas in the combustion chamber using compression ignition principles), the methane slip is much less. Some reports document older gas engine emissions of methane to be significantly higher than reported for state of the art engines currently marketed by manufacturers (Nielsen and Stenersen, 2010), and there is evidence that recent design innovations are reducing methane slip from Otto-cycle and dual fuel engines. Nonetheless, methane slip remains higher for Otto cycle engines than for Diesel cycle gas engines.

The ICCT study estimated a nominal methane exhaust rate between 2.2. and 4.6 percent of fuel used. This is consistent with the emission factors reported in Table 3, as illustrated in Table 5. If the engine specific fuel consumption is considered to be equivalent to 175-206 g/kWh (similar fuel consumption as reported by other studies) (Corbett and Koehler, 2004; Nielsen and Stenersen, 2010), then methane slip emissions range from ~0.3% for large Diesel cycle engines to ~1.5% - 2.5% for newer design dual fuel and Otto cycle gas engines to ~4% - 9% for older natural gas engine designs. The methane percent loss estimates estimated by Lowell et al (2013) reflect methane slip rates between 4-8 g/kWh.

Table 5. Cross table illustrating methane slip as a percent of fuel consumption for natural gas engines.

	Specific fuel consumption (g/kWh_{out})		
Methane slip (g/kWh_{out})	**175**	**195**	**206**
0.69	0.40%	0.36%	0.34%
3.00	1.71%	1.54%	1.46%
4.00	2.29%	2.05%	1.94%
5.00	2.86%	2.56%	2.43%
8.00	4.57%	4.10%	3.88%
15.00	8.57%	7.69%	7.28%

The differences in complete combustion of methane rich gaseous fuels and traditional liquid petroleum fuels is well understood in engineering literature. As explained by Cho and He (2007):

> "Homogeneous lean burn mixtures result in lower flame propagation, occurrence of misfire, low mixture distribution quality in multi-cylinder engines and high unburned HC emissions in the exhaust. … The lower exhaust temperatures increase the difficulties in methane oxidation and result in low THC conversion efficiency. … Furthermore, HC emissions from natural gas engines are mainly composed of methane. … However, methane is the most difficult hydrocarbon to be oxidized" (Cho and He, 2007).

While natural gas engines generally produce lower emissions of CO and non-methane hydrocarbons compared to normal gasoline engines, unburned methane can account for about 90% of the unburned hydrocarbons that escape combustion in the cylinders (Korakianitis et al., 2011). In fact, as stated by Korakianitis et al. (2011):

> "Part-load unburned HC emissions of dual-fuel engines are significantly higher than in normal diesel engines, … with concentrations of the order of 6000 ppm, compared with significantly less than 100 ppm in conventional diesel operation. … The lean-burn strategy generally resolves emissions issues, but unburnt methane emissions remain relatively high" (Korakianitis et al., 2011).

Some manufacturers, such as Rolls-Royce, claim to have lean-burn 4-stroke gas engines with methane slip estimates ~3-4 g/kWh; and some recent tests of direct gas injection engines operated as a conventional diesel engine show slip reductions that are "20-40 times lower in comparison to the methane slip recorded for the most modern, state-of-the-art, dual-fuel engines" (Pospiech, 2014). Other publicly available engineering research reflects this understanding (Eswara et al.; Kristensen et al., 2004). These combustion and emissions studies explain the large differences in methane emissions factors among different gas engine technologies in Table 3.

With regard to other pollutants, gas engines produce less particulate matter (PM) than Diesel engines, because natural gas does not contain aromatic compounds such as benzene and contains fewer dissolved impurities (Cho and He, 2007). Gas engines using Diesel fuel pilot ignition produce more PM, a result of the formation of particles at the heterogeneous flame front where Diesel charge air is combusting. It is normal to observe ~30% of the total fuel energy supplied by the pilot fuel in smaller bore, higher-speed engines (Korakianitis et al., 2011); however, larger bore, medium-speed engines can operate on less Diesel pilot charge, reported to be as little as 8% (92% natural gas) at full load for some engines (http://www.marinelink.com/article/maritime-standards/dual-fuel-technology-468). Wartsila reports that its lean burn, low pressure, dual-fuel technology utilizes between 1% and 5% of total energy in Diesel fuel pilot ignition, depending upon engine size and load (Wartsila, 2014, 2015). Generally lower NOx emissions are produced, mainly because of Otto cycle combustion conditions, namely as pressure and temperature, do not provide the same conditions for rapid oxidation rates of ambient nitrogen in the mixing air; however, natural gas engines in a Diesel cycle can produce higher NOx than a true spark-ignited engine because higher temperatures and pressures increase the reaction rates for oxidizing nitrogen (Korakianitis et al., 2011).

3 Methodology

3.1 Total Fuel Cycle Modeling and the TEAMS Model Update

Total fuel cycle analysis calculates the total emissions profile associated with the use of a given fuel in a vessel by considering emissions along the entire "fuel cycle." This fuel cycle includes the following stages (see Fig. 1):

- **Upstream Stages**:
    - *Feedstock stage* – encompassing the extraction of the raw material through delivery to the refinery; and,
    - *Fuel processing stage* – encompassing the delivery of a fuel from the refinery to the vessel, including bunkering.
- **Downstream Stages**:
    - *Bunkering stage*[3] – encompassing the fueling (i.e., "bunkering") of vessels in a variety of ways; and,
    - *Operation stage* – encompassing the use of the fuel in the vessel itself, in both main and auxiliary engines.[4]

[3] This report is the first to explicitly call out "bunkering stage" as a component of the total fuel cycle for marine fuel/vessels. In previous TFCA work, it has been unclear whether bunkering is considered part of "upstream" or "downstream" stages. We incorporate bunkering into the "downstream" stage of the TFCA, but we distinguish bunkering from vessel operation to allow for comprehensive analysis of different bunkering leakage assumptions.
[4] The operation stage includes both fuel burned in the combustion chamber and fuel that is emitted as unburned after the combustion process (i.e., methane slip).

Fuel cycle analyses were first published in the life-cycle analysis literature as a subset of product life-cycle quantification, and mainly aimed at economic or carbon metrics (DeLuchi, 1991; Manne et al., 1979). TFCA became a specialized and unique type of LCA as alternative fuels were considered for both air quality and carbon emissions (Schlamadinger and Marland, 1996; TIAX and Pont, 2007; TIAX et al., 2007), and as dedicated models focused on current and alternative pathways for transportation fuel (Wang, 2002; Winebrake et al., 2001). TFCA became even more critical with the emergence of Low-Carbon Fuel Standards regulation and recognition of the importance of land use change (LUC) and emerging extraction methods (e.g., fracking).

A major element of this research was to develop a new version of the TEAMS model which could be fully integrated as a 'plug-in' into the most recent GREET model release. The GREET model was developed approximately twenty years ago by Argonne National Laboratory (ANL). GREET allows researchers to examine the well-to-wheels emissions for light duty vehicles operating on a wide variety of alternative fuels and fuel pathways. GREET has been widely used in TFCA (Elgowainy, Gaines, & Wang, 2009; Huo, Wang, Bloyd, & Putsche, 2008; Meyer, Green, Corbett, Mas, & Winebrake, 2011; Wang, 2002; Winebrake et al., 2001; M. Wu, Wu, & Wang, 2006).

TEAMS, on the other hand, was developed with support from MARAD to assist TFCA modeling in the marine sector. TEAMS has been used in previous evaluations by these authors for MARAD (Corbett and Winebrake, 2008; Winebrake et al., 2007). The advantages of TEAMS are (1) it offers greater flexibility for modeling the downstream (i.e., end-use) stages of the fuel cycle (i.e., vessel fuel use); and, (2) it allows for the analysis of natural gas as a marine fuel, which GREET does not currently allow. The use of TEAMS together with GREET allows the best of both worlds: comprehensive fuel pathway analysis for upstream fuel production combined with detailed downstream analysis for user-specified vessel characteristics and fuels (Corbett & Winebrake, 2008; Corbett & Winebrake, 2008; Corbett, Thomson, & Winebrake, 2014; Elgowainy, Burnham, Wang, Molburg, & Rousseau, 2009; Elgowainy et al., 2009; Huo, Wu, & Wang, 2009; Huo et al., 2009; Milliken, Joseck, Wang, & Yuzugullu, 2007; Milliken et al., 2007; Thomson, Corbett, & Winebrake, in press; Wang, Wu, Huo, & Liu, 2008; Wang et al., 2008; Winebrake et al., 2001; Winebrake et al., 2001; Winebrake, Corbett, & Meyer, 2007; Winebrake et al., 2007; Y. Wu, Wang, Sharer, & Rousseau, 2006).

For this project, a number of critical changes to TEAMS were implemented to ensure the continued viability of TEAMS as an emissions analysis tool. First, TEAMS code was modified to be compliant with the new framework put forward by ANL in their GREET 2014 release, so the new TEAMS offers full functionality consistent with previous TEAMS releases, but using the 2014 GREET standards and practices, as well as the updated GREET database of emissions pathways. Updated TEAMS streamlines the process by which a user can generate results into a single, exportable EXCEL worksheet. A user can now rapidly iterate through cases that need to be analyzed, while still maintaining a level of sophistication and control that the TEAMS model has always provided. Most importantly for this scope of work, the modified TEAMS includes the capacity to simulate leakage related to fuel bunkering.

A set of videos has been created that discuss the TEAMS changes and provide users with in depth understanding of how to download and install the new TEAMS. In addition, tutorials are now provided on how to use TEAMs – for example, tutorials are available on (1) customizing ships in TEAMS; (2) modifying existing processes in GREET/TEAMS; and (3) creating new processes and pathways, including those that include leakage in bunkering, among others. Video tutorials are located at: http://rit-lecdm.github.io/TEAMS-Module/. Downloads are available via the tutorial website, with a complete history of TEAMs releases and support files located at: https://github.com/RIT-LECDM/TEAMS-Module/releases.

3.2 Case Study Analysis

This research evaluated the effects of changing the assumptions for bunkering leakage rates on overall emissions of GHGs for LNG usage in the marine sector. The research builds on the case study analysis done by Corbett et al (2014) which examined emissions from 28 different source pathways for LNG. This study focuses on what we called the "West Coast Case" in our previous work Thomson, et al. (2015).

The West Coast Case examines transportation of goods from the Port of Los Angeles/Long Beach to Honolulu, Hawaii. This case provides a good representation of a container vessel operating at two ports that either have or are considering LNG bunkering for maritime transportation.[5] The West Coast Case also provides a well-known route that can be easily characterized, as well as benchmark results from our previous work for comparison purposes.

The vessel and route for the West Coast Case are shown in Table 6. The case represents a container vessel with main engine power of 23,860 kilowatts (kW) and a rated speed of 22 knots. The route occurs over a distance of 2,230 miles and takes 130 hours and 15 minutes to complete. We assume in this case that the vessel is slow-steaming, and the time spent in the slow-steaming mode compared to other operating modes is shown in Table 6.

For this research, we use the data from Table 3 as emissions factor model inputs for TEAMS analyses of downstream GHGs. Specifically, we perform four TEAMS analyses for this case study: two gas-fueled engines i) lean-burn Otto cycle engine; ii) Diesel cycle gas engine; and two petroleum-fueled engines iv) low-sulfur petroleum Diesel engine; and v) high-sulfur petroleum Diesel engine.

[5] The use of LNG at the Port of LA/LB has long been recognized; see http://www.bizjournals.com/pacific/news/2014/04/07/hawaii-gas-starts-shipping-liquefied-natural-gas.html for information about Hawaii's movement towards LNG.

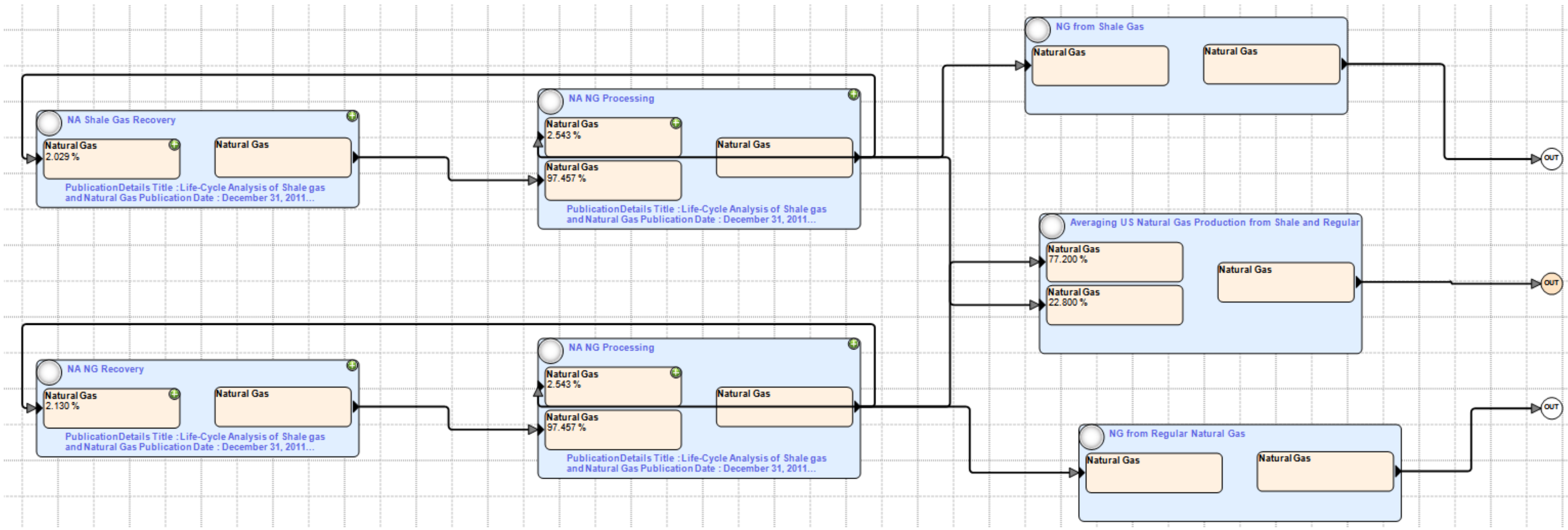
Table 6. Vessel and route characteristics for the West Coast Case used in this study.

Vessel Characteristic	Value
Vessel Type	Container
Average DWT	32,000
Rated Power (kW and HP)	23,860 kW 31,996 HP
Distance (miles)	2,230
Rated Speed (knots)	22
Time for one-way trip (HH:MM)	130:15
Engine Efficiency (%)	45%
Time Spent in Each Operating Stage as a Percentage of Total Trip Time (%)	
Idle	1.25%
Maneuvering	1.75%
Precautionary	5.00%
Slow Cruise	85.00%
Full Cruise	7.00%

Note: Taken from Table 9 of Corbett et al (2014).

Details of the specific fuel pathway evaluated for our West Coast case study are found in Figure 3 through Figure 7. These figures represent TEAMS LNG default values and are based on US averages of transportation modes and distances from field to port. For example, Figure 2 shows a pipeline distance of 50 miles from field to LNG liquefaction plant; from there, Figures 3, 4 and 5 show assumptions about the movement of this LNG from the plant to the port using barge, rail, and truck, respectively. We assume LNG transported from the plant to a bulk terminal by barge would travel 520 miles, while by rail it would be 800 miles. We then assume transportation from the bulk terminal to the port by truck traveling 30 miles. Users of TEAMS can modify these values to model specific cases (e.g., specific LNG production pathways); however, since the purpose of this work is to explore the impact of bunkering leakages on overall GHG emissions, we use the TEAMS default LNG pathway information for our case study.

Figure 3. Overview of LNG pathway for case study analysis.



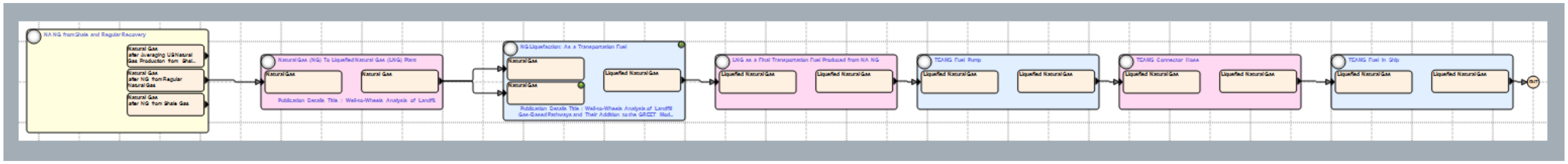


Figure 4. Information on natural gas field to LNG plant for case study from TEAMS.

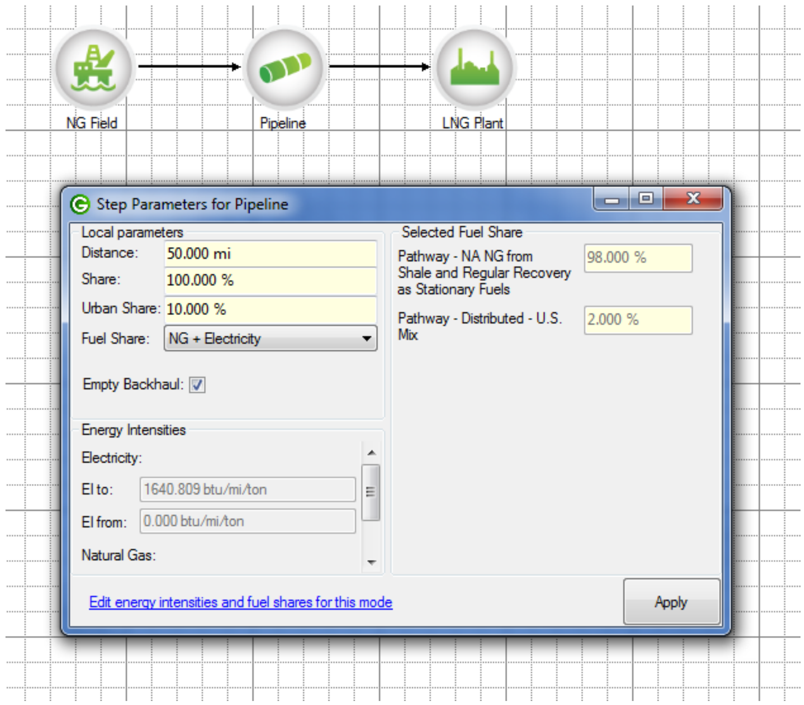


Figure 5. Information on barge transportation from LNG plant to bulk terminal for case study from TEAMS.

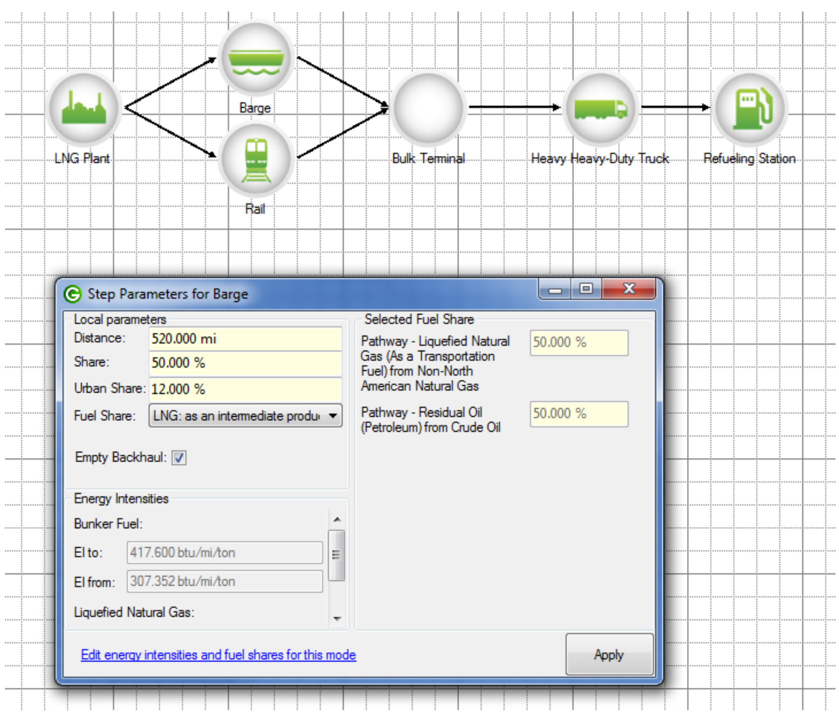


Figure 6. Information on rail transportation from LNG plant to terminal for case study from TEAMS.

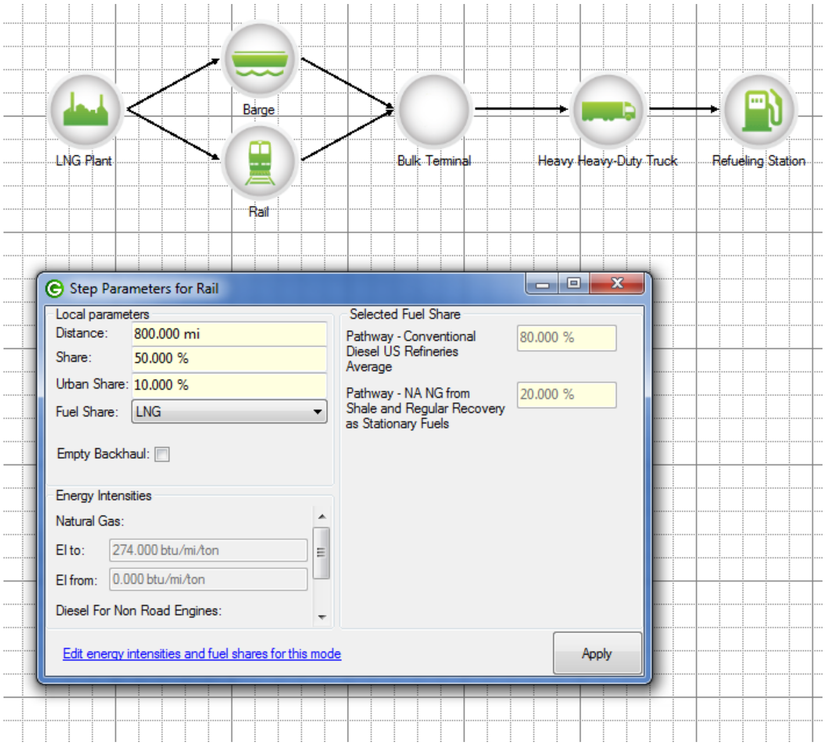
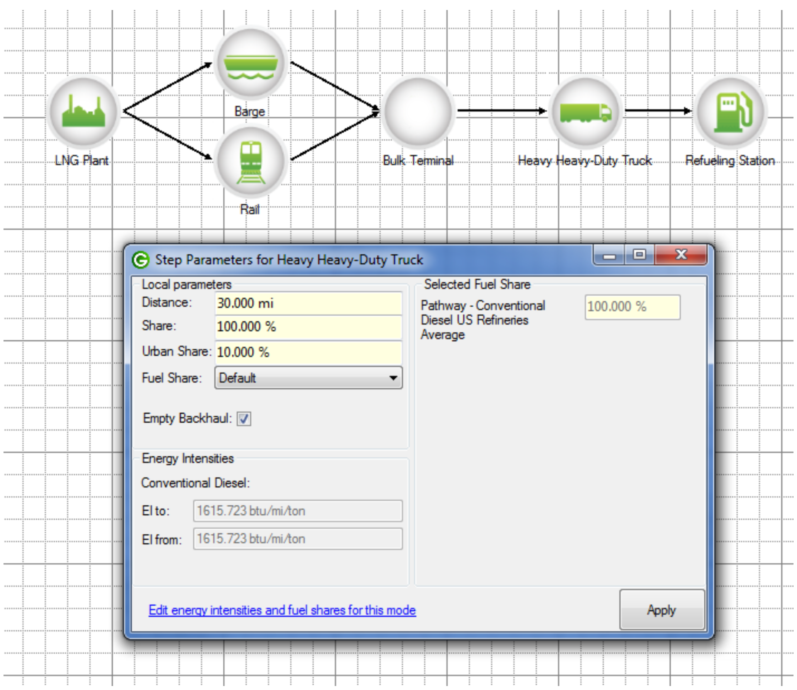


Figure 7. Information on truck transportation from bulk terminal to port for case study from TEAMS.



The key question explored in this research is: What is the role of CH_4 leakage and slip on overall (TFCA) greenhouse gas emissions for the marine sector? To answer this question, TEAMS was revised to allow for users to input bunkering leakage factors. Figure 7 depicts a bunkering process, generically shown as “refueling station ➔ connector ➔ ship.” For simplicity, TEAMS represents the connection process as a single node (“connector”) that captures all leakage associated with the bunkering process; however, users could add multiple nodes in this process to reflect multiple connections for more complex bunkering operations. This was not necessary for this case study, since the resolution of the CH_4 leakage data available did not allow for distinctions in the types of potential connections that are possible.

Data from Lowell et al (2013) (“Leakage from Bunkering” in Table 1), show that CH_4 leakage from bunkering operations may range from 0.0 g CH_4/mmBtu (no leakage) to 190.1 g CH_4/mmBtu (maximum leakage in Table 1) after converting to TEAMS units. Our goal was to apply these leakage rates to the West Coast Case to determine what impact different leakage values would have on overall TFCA greenhouse gas results. If the bunkering leakage rates had little impact on overall emissions, then bunkering as a major source of greenhouse gas emissions would be discounted; however, if the bunkering leakage rates had a significant impact on overall emissions, then bunkering operations should be considered very carefully as the US expands LNG bunkering operations at ports.

We applied a range of Lowell et al (2013) values to the bunkering process for our West Coast case. We evaluated the following scenarios: (1) no bunkering emissions; (2) 12.7 gCH_4/mmBtu (~0.065%) bunkering leakage; (3) 46.5 gCH_4/mmBtu (~0.24%) bunkering leakage; and (4) 190.1 gCH_4/mmBtu (~1.0%) bunkering leakage. We also ran a fifth case using low sulfur diesel fuel for comparison purposes. Our leakage fractions were implemented in TEAMS by modifying new processes related to the bunkering of fuels as described above and shown in Figure 8. We also used default values for emissions factors and GWP found in TEAMS as shown in Table 3 and Table 7.

Figure 8. Depiction of how bunkering leakage can be added under the new TEAMS model.

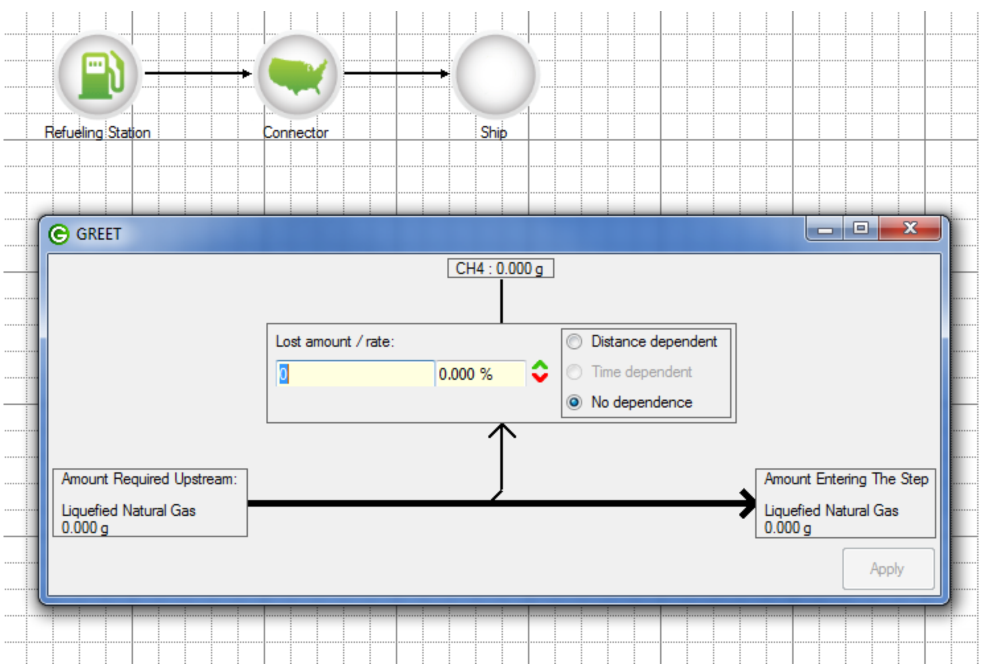


Table 7. Global Warming Potential (GWP_{100}) inputs for emissions calculations.

Greenhouse Gas	GWP used (100 year)
Carbon dioxide (CO_2)	1
Methane (CH_4)	30
Nitrous Oxide (N_2O)	296

3.3 Economic Analysis

To measure the economic value of bunkering losses, TEAMS was used to determine the total amount of methane leakage for each of our leakage scenarios. This leakage represents "lost fuel" – that is, fuel that has been purchased by the vessel operator, but which does not make it into the ship. The value of this fuel is determined by multiplying the total amount of fuel lost (mmBTU) by the average price of natural gas in $/mmBTU (EIA, 2015). We use 32 cents/kg as the delivered LNG price for this study. This represents the 2012 price for natural gas vehicle fuel in California.[6] FERC's estimated LNG landed prices for October 2015 ranged from $2.20 to $6.71 per MMBtu in North America, which corresponds to a price of 12 cents/kg to 35 cents/kg.[7]

4 Results

Table 8, Table 9, and Table 10 show the energy use and emissions of methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and total greenhouse gases (GHG) for various scenarios studied. In each table, the emissions related to bunkering leakage and slip are explicitly identified. Table 8 provides the results for the LNG compression ignition engine under four different assumptions about bunkering leakage and using slip emissions factors as reported above. Table 9 presents similar results for two conventional diesel fuels: low sulfur diesel (i.e., ECA compliant fuel at 1000 ppm per Table 4) and bunker residual fuel oil. Finally, Table 10 provides results for the LNG spark ignition engine, where methane slip is determined to be much higher than in compression ignition systems.

The results for each of the LNG configurations are also shown in Figure 9 and Figure 10, which compare the LNG results with conventional fuel results. Lastly, Figure 11 depicts the total GHG emissions (in CO_2eq/trip) for all scenarios. The percentage emissions reductions (or increases) for each scenario are shown in Table 11.

The results indicate that there is potential for LNG to provide GHG emissions reductions, even when routine bunkering leakage is accounted for. However, these emissions benefits are only apparent for compression ignition LNG engines. As shown in Table 11, compression ignition LNG systems have the potential to reduce GHG emissions between 6-15% compared to low-sulfur diesel as reported in CO_2 equivalent (CO_2eq) emissions using global warming potentials shown in Table 7. That is, even with a bunkering leakage of 1%, the LNG system still shows net GHG benefits compared to diesel. Such is not the case for LNG systems that rely on spark ignited engines. In those systems, the results indicate *increases* in GHG emissions from 5-13%, depending on bunkering leakage assumptions.

[6] California natural gas prices are published by the U.S. Energy Information Administration and can be downloaded at http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_sca_a.htm.

[7] For more information on FERC landed LNG prices, see: https://www.ferc.gov/market-oversight/mkt-gas/overview/ngas-ovr-lng-wld-pr-est.pdf.

Thus, two key findings related to the use of LNG in the marine sector emerge from this work:

1. *First, the type of LNG engine employed is a critically important determinant for GHG emissions reductions. This work shows that compression ignition LNG systems will provide total fuel cycle GHG emissions benefits compared to low sulfur and residual oil systems; however spark ignition LNG systems will not.*

2. *Second, routine bunkering leakages can have an important impact on overall GHG emissions no matter whether LNG is used in a compression ignition engine or a spark ignition engine. This impact is due to the high volume of natural gas throughput and the high global warming potential of methane.*

Other observations from the tables can also be extracted. For example, in LNG cases where bunkering leakages occur, the emissions of CH_4 from bunkering can make up a significant portion of the overall upstream (extraction and production) emissions. For example, in our low leakage scenario (12.7 gCH_4/MMBTU) for the compression ignition LNG engine (Table 8) CH_4 emissions from bunkering only make up about 2% of upstream GHG emissions. In contrast, in our high leakage scenario (190.1 gCH_4/mmBTU), CH_4 emissions from bunkering make up more than 30% of upstream GHG emissions. Clearly, leakage of CH_4 from bunkering operations is important for reducing the GHG impact of LNG systems.

Regarding costs, Table 12 shows the estimated increased costs due to bunkering losses based on a natural gas price of 32 cents/MMBtu. Based on the amount of CH_4 that is released through the bunkering process, we calculate the cost per trip ~$830 for the 1% leakage case. Of course, this result will vary considerably based on the volatility of LNG prices.

Table 8 Emissions results for LNG compression ignition (CI) engine under various bunkering leakage assumptions; values reported in kilograms per trip.

LNG without bunkering leakages, main engine only					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	-	-	11,762	14,128
CH_4 (kg)	2,408	-	1,075	-	3,483
CO_2 (kg)	147,819	-	-	574,575	722,394
N_2O (kg)	1	-	-	23	24
GHG (kg CO_2eq)	220,266	-	32,250	581,383	833,899
LNG with bunkering leakage, main engine only, 12.7 gCH_4/mmBtu (~0.065%)					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	9	-	11,762	14,137
CH_4 (kg)	2,408	168	1,075	-	3,651
CO_2 (kg)	147,819	97	-	574,575	722,491
N_2O (kg)	1	0	-	23	24
GHG (kg CO_2eq)	220,266	5,146	32,250	581,383	839,045
LNG with bunkering leakage, main engine only, 46.5 gCH_4/mmBtu (~0.24%)					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	34	-	11,762	14,162
CH_4 (kg)	2,408	620	1,075	-	4,103
CO_2 (kg)	147,819	356	-	574,575	722,750
N_2O (kg)	1	0	-	23	24
GHG (kg CO_2eq)	220,266	18,965	32,250	581,383	852,865
LNG with bunkering leakage, main engine only, 190.1 gCH_4/mmBtu (~1%)					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	143	-	11,762	14,271
CH_4 (kg)	2,408	2,604	1,075	-	6,087
CO_2 (kg)	147,819	1,493	-	574,575	723,887
N_2O (kg)	1	0	-	23	24
GHG (kg CO_2eq)	220,266	79,625	32,250	581,383	913,524

Table 9 Emissions results for low sulfur diesel and residual fuel oil; values reported in kilograms per trip.

Low Sulfur Diesel from Crude, main engine only					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	1,399	-	-	11,762	13,161
CH_4 (kg)	1,660	-	52	-	1,712
CO_2 (kg)	159,144	-	-	761,539	920,683
N_2O (kg)	2	-	-	23	25
GHG (kg CO_2eq)	209,498	-	1,560	768,317	979,375
Residual Oil from Crude, main engine only					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	719	-	-	11,762	12,481
CH_4 (kg)	1,551	-	52	-	1,603
CO_2 (kg)	117,988	-	-	819,411	937,399
N_2O (kg)	2	-	-	23	24
GHG (kg CO_2eq)	164,962	-	1,560	826,189	992,711

Table 10 Emissions results for LNG spark ignition (SI) engine under various bunkering leakage assumptions; values reported in kilograms per trip.

LNG without bunkering leakages, main engine only					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	-	-	11,762	14,128
CH_4 (kg)	2,408	-	7,697	-	10,105
CO_2 (kg)	147,819	-	-	574,575	722,394
N_2O (kg)	1	-	-	23	24
GHG (kg CO_2eq)	220,266	-	230,910	581,383	1,032,559
LNG with bunkering leakage, main engine only, 12.7 gCH_4/mmBtu (~0.065%)					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	9	-	11,762	14,137
CH_4 (kg)	2,408	168	7,697	-	10,273
CO_2 (kg)	147,819	97	-	574,575	722,491
N_2O (kg)	1	0	-	23	24
GHG (kg CO_2eq)	220,266	5,146	230,910	581,383	1,037,705
LNG with bunkering leakage, main engine only, 46.5 gCH_4/mmBtu (~0.24%)					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	34	-	11,762	14,162
CH_4 (kg)	2,408	620	7,697	-	10,725
CO_2 (kg)	147,819	356	-	574,575	722,750
N_2O (kg)	1	0	-	23	24
GHG (kg CO_2eq)	220,266	18,965	230,910	581,383	1,051,525
LNG with bunkering leakage, main engine only, 190.1 gCH_4/mmBtu (~1%)					
	Upstream	Bunkering	Slip	Operating	Total
Total Energy (mmBtu)	2,366	143	-	11,762	14,271
CH_4 (kg)	2,408	2,604	7,697	-	12,709
CO_2 (kg)	147,819	1,493	-	574,575	723,887
N_2O (kg)	1	0	-	23	24
GHG (kg CO_2eq)	220,266	79,625	230,910	581,383	1,112,184

Figure 9. GHG emissions results of case analysis for compression ignition LNG engine showing impact of bunkering leakage and slip on overall GHG performance compared to low sulfur diesel and residual fuel oil.

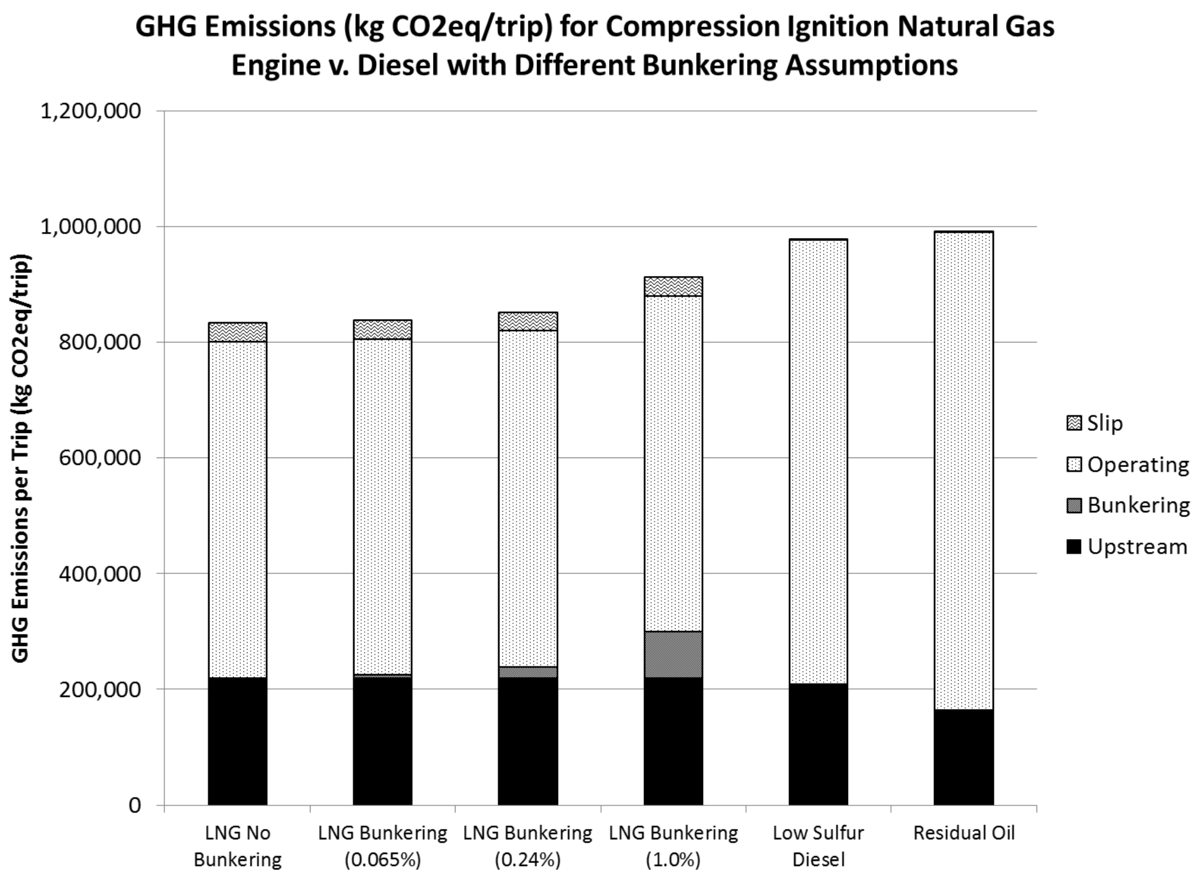


Figure 10. GHG emissions results of case analysis for spark ignition LNG engine showing impact of bunkering leakage and slip on overall GHG performance compared to low sulfur diesel and residual fuel oil.

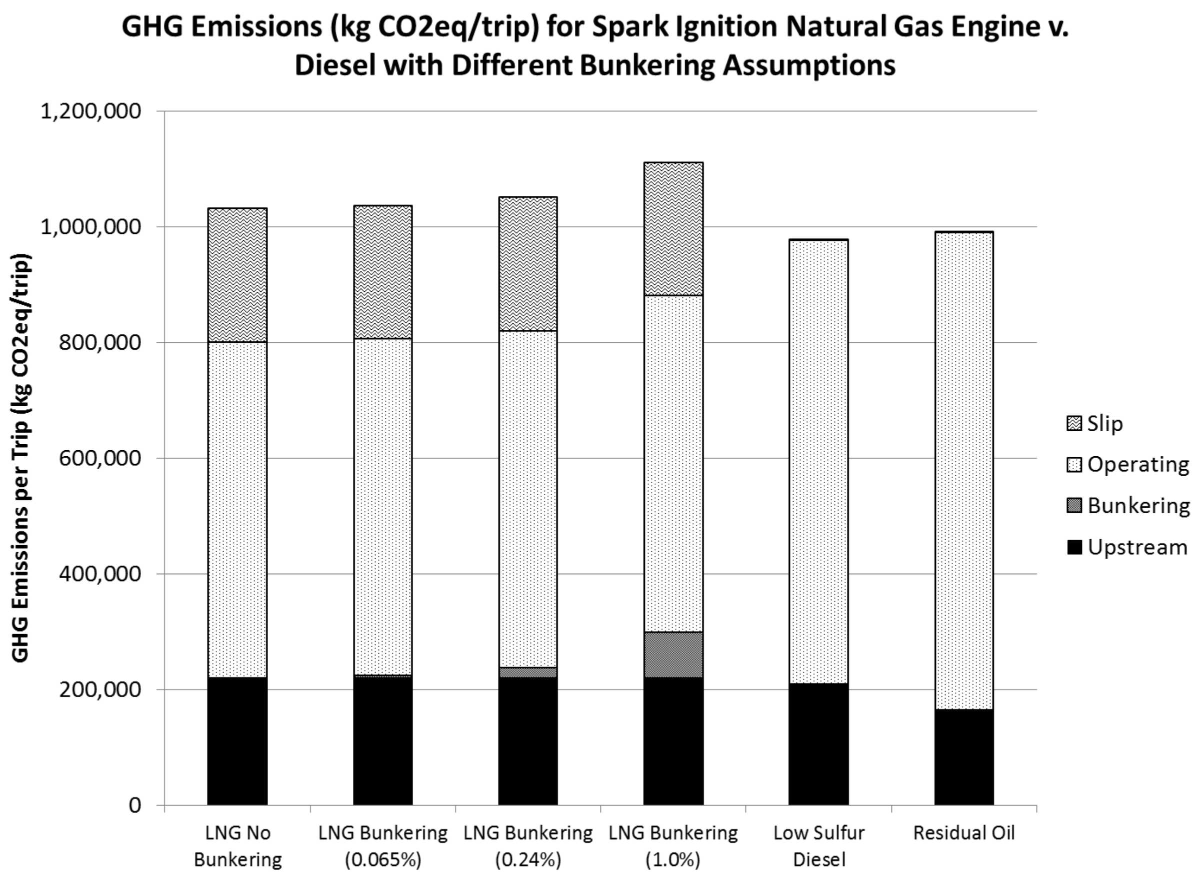


Figure 11. Total GHG emissions results of case analysis comparing compression ignition LNG, spark ignition LNG, low sulfur diesel, and residual fuel oil across various bunkering leakage assumption.

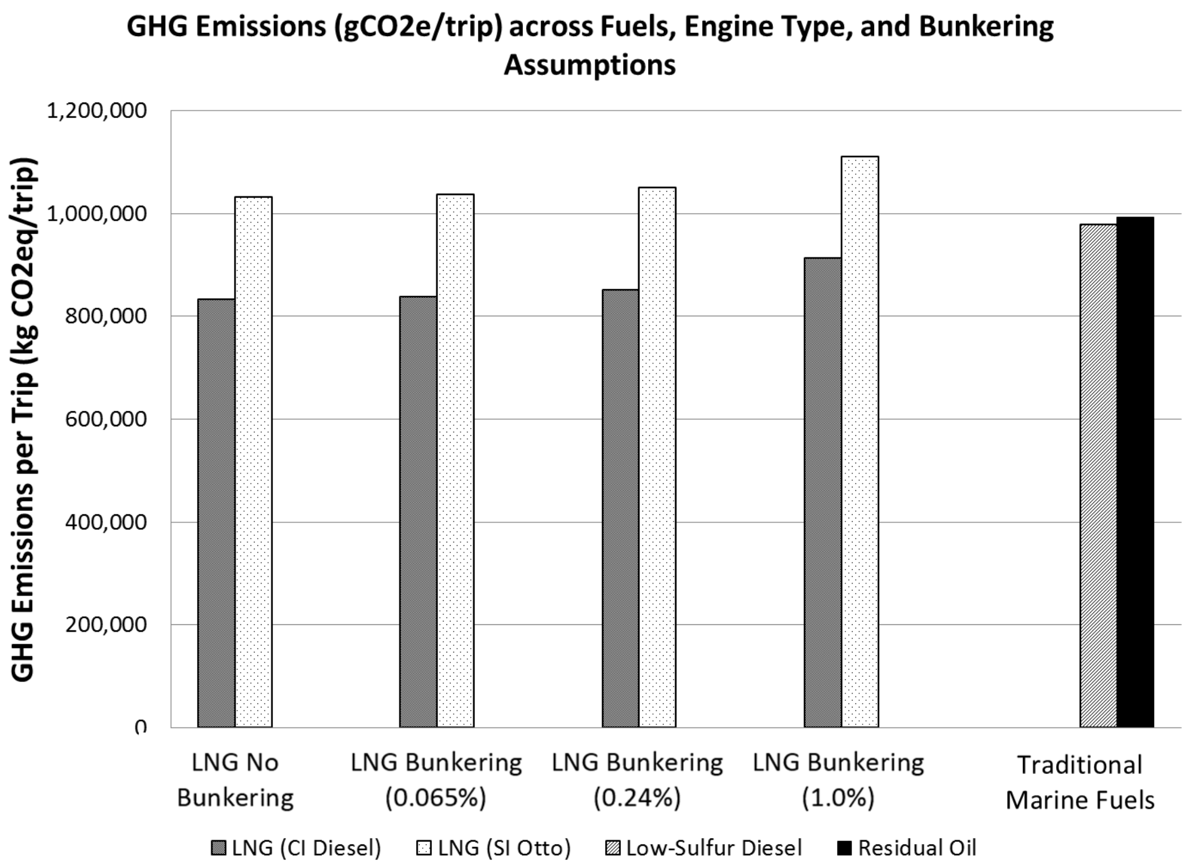


Table 11 Total fuel cycle greenhouse gas emissions results of each scenario as compared to low sulfur diesel fuel.

	LNG w/ Compression Ignition Engine	LNG w/ Spark Ignition Engine	Low Sulfur Diesel	Residual Fuel Oil
LNG No Bunkering	-14.9%	+5.4%	-	+1.4%
LNG Bunkering (0.065%)	-14.3%	+6.0%	-	+1.4%
LNG Bunkering (0.24%)	-12.9%	+7.4%	-	+1.4%
LNG Bunkering (1.0%)	-6.7%	+13.6%	-	+1.4%

Table 12 Costs due to bunkering leakages.

	Fuel Lost per Trip (kg CH_4/trip)	Total Cost per trip ($/trip)
LNG No Bunkering	-	$0
LNG Bunkering (0.065%)	168	$54
LNG Bunkering (0.24%)	620	$198
LNG Bunkering (1.0%)	2,604	$830

Note: Table uses a natural gas market price of $0.32/kg$CH_4$ as described in the text.

5 Conclusions

The primary research question we investigated in this study was: How does methane leakage and methane slip affect net GHG impacts for LNG fueled marine vessels using a total fuel cycle analysis approach. This research complements previous work related to TFCA analysis of LNG systems, including the development of modeling tools (such as TEAMS).

There are two key findings that emerge from this research. The first is that methane slip is a very important factor that can determine whether LNG systems will lead to GHG emissions reduction or increases compared to conventional fuels. In the case of compression ignited LNG systems, methane slip is well controlled, and this research shows clear GHG emissions advantages compared to conventional fuel (even when routine bunkering leakage assumptions are loosened). However, in the case of spark ignited LNG systems, methane slip is more significant, and can actually negate the advantages of the LNG system. In the spark ignited cases, emissions from the LNG system were higher even in cases where no bunkering leakages were assumed.

The second important finding is that routine bunkering leakages can have a disproportionate impact on overall GHG emissions due to the high volume of natural gas throughput and the high global warming potential of methane. This research shows that even small bunkering leakages can have significant effects. For example, a ~1% leakage of methane in bunkering operations led to a ~10% increase in net GHG emissions. In the compression ignition engine, this 1% bunkering leakage cut the net GHG emissions advantages of LNG from -14.9% benefit down to a -6.7% benefit compared to low-sulfur diesel fuel. What is important to note is that leakage reductions in frequently recurring bunkering processes have substantial benefits on total fuel cycle GHG impacts; moreover, there exist several places in the bunkering process where leakage can be reduced and these require additional research and/or testing to improve upon the available literature. Although the economic value of this loss may not be significant (based on natural gas prices modeled), the environmental opportunity costs are important.

The results discussed in this study evaluate best available data from the literature. Additional testing and analysis are required to fully characterize methane leakage during bunkering by type of bunkering configuration, as well as to evaluate methane slip during vessel operations. This is an area that remains an important source of uncertainty in terms of life-cycle releases of methane. Although there are not enough data in the literature to characterize specific types of bunkering operations (e.g., ship-to-ship v. truck-to-ship), we believe our results can be applied generically to a whole set of bunkering approaches. Leakage issues from any bunkering operation should be carefully considered in infrastructure planning and operational purposes and leakage emission rates need further testing under actual bunkering procedures.

Significant advances to the TEAMS model, which now has full integration with the latest version of GREET, will make possible the integration of new leakage data, in particular information specific to the bunkering configuration(s). With the new TEAMS model, researchers can specifically "build" and evaluate vessel bunkering processes. Emissions rates during bunkering processes that may be estimated or measured can now be considered explicitly in total fuel cycle analyses. We believe TEAMS will continue to be an important tool for evaluating new leakage data as it emerges for specific bunkering operations. We also believe that TEAMS can inform maritime stakeholders where important innovations or improved bunkering operations can minimize potential releases of natural gas pollutants and GHGs. For future work, we suggest integrating total warming potential (TWP) functionality into TEAMS.

Last, we identify non-routine or chronic leakage as important areas of potential leakage meriting future research. This study examined leakage from normal operations, that is to say, this study did not characterize non-routine or *chronic* leakage. Additionally, there is also the possibility of episodic, unplanned releases due to equipment failure or operator error, essentially *acute* leakage incidents; on an annual basis, a few of these incidents could increase the net GHG impact of natural gas as a marine fuel. The chances of these leakages occurring can be estimated from the safety literature (Arnet, 2014; DNV, 2013) and the impacts assessed, and we recommend focused study using TEAMS in a stochastic or probabilistic context to evaluate the long-run GHG emissions.

6 References

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