Options for Reducing Methane Emissions from New and Existing LNG-Fueled Ships

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1. Introduction

Liquefied natural gas (LNG) is growing as a marine fuel choice due to its ability to meet regulated emission limits. However, natural gas is still a fossil-fuel with an environmental footprint and concerns over high fugitive methane emissions, a more potent greenhouse gas (GHG) than carbon dioxide (CO_2). This report provides an overview of the technology choices and operational measures for reducing methane emissions from ships operating on liquefied natural gas. The applicability of these measures is evaluated for their emissions reduction, readiness, costs, and other factors through review of literature. Moreover, the existing and proposed policies and regulations and their relevance to the uptake of LNG is reviewed. An examination of research studies, industry reports, expert opinions, and additional literature provides a clearer understanding of the impact of LNG on maritime sector emissions.

This report provides important background information on the types of LNG engines being used on board ships, available methane control technologies and operational measures, and comparative emissions profiles associated with LNG operations. Furthermore, this report provides an up-to-date discussion of the current regulatory landscape at national, regional, and international levels.

2. Background

Methane is a potent greenhouse gas that has contributed to 30% of observed global warming to date (International Energy Agency, 2022). Global shipping is estimated to contribute to about 3.1% of annual global carbon dioxide and approximately 2.8% of annual GHGs (Smith et al., 2015). LNG is emerging as an alternative fuel to conventional bunkers, as it emits lower criteria air pollutants (SO_x and NO_x), and less carbon dioxide. Consumption of liquefied natural gas (LNG) by international shipping increased by around 28-29% from 2012 to 2018, per the Fourth IMO Greenhouse Gas Study (GHG4), and methane emissions increased 2.5x from 59,100 metric tons (MT) in 2012 to 148,000 MT CH_4 in 2018.

LNG is composed primarily of methane. In LNG engines, uncombusted methane can escape in the exhaust gasses, referred to as methane slip. Methane slip rates around 3.8% were measured on-board a new “efficient" LNG dual-fuel engine (low-pressure dual fuel two-stroke engine), which has significant implications for the climate, as well as emissions monitoring and reporting (Balcombe et al., 2022). Furthermore, fugitive emissions from the fuel system and uncombusted boil-off gas contribute further warming potential, with boil-off rates around 0.1% of cargo/fuel per day (Wärtsilä, n.d.-a). Due to these issues, the viability of LNG as a low carbon fuel has been called into question (European Federation for Transport and Environment, 2022; Pavlenko et al., 2020; Swanson et al., 2020).

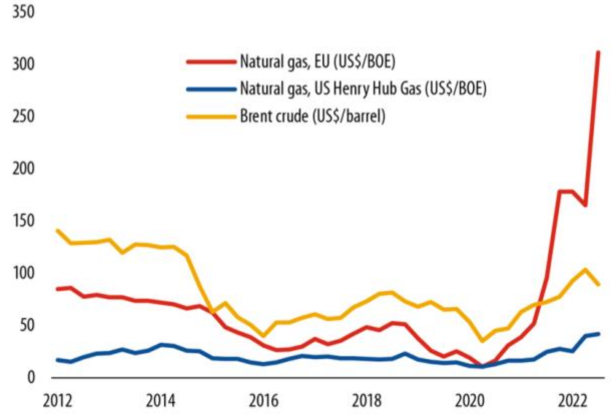
IMO GHG regulations do not currently directly address engine or fuel system emissions of methane from ships, though emissions of methane are rising. In 2022, 51% of newbuild vessel orders (by tonnage) were LNG dual-fueled, corresponding to 397 orders and 36.4 million gross tonnes (Gordon, 2023). In 2021, the US Department of Energy spent 35 million USD funding twelve projects to reduce methane emissions, with a large focus on addressing methane slip in natural gas engines (The U.S. Department of Energy, 2021). While efforts are underway to reduce methane emissions from ships, later discussed in Emission Abatement Practices and Technology, the scale of the issue is significant, and the regulatory landscape is unclear.

2.1. Uptake of LNG vessels

LNG has a lower carbon-to-hydrogen ratio, is virtually sulfur free, and has a lower nitrogen content than conventional fuels, resulting in less carbon dioxide, as well as, lower sulfur oxides (SO_x) and nitrogen oxides (NO_x) formation at combustion (Sharafian et al., 2019). Uptake of LNG is driven, in part, by compliance with the implementation of MARPOL sulfur emission control areas (ECAs or SECAs), inside which ocean-going vessels (OGVs) must use fuels with a sulfur content no greater than 0.1% S by mass, or use equivalent control technologies. The North American, Baltic, and North Sea ECAs went into full effect (0.1% S) in January 2015 (Urdahl, 2023). As LNG contains little to no sulfur, SO_x emissions from LNG powered vessels are typically negligible and in compliance with MARPOL VI regulations. In 2020, the IMO set a global limit of sulfur in maritime fuels of 0.50% S (from 3.50%) (International Maritime Organization, 2019). Prior to the development of SECAs under the IMO, some of the Baltic states implemented their own regulations. Between 1998 and 2014 Sweden implemented a system of differentiated fairway dues for SO_x based on the vessel's environmental performance. In 2008 Norway imposed a levy on NOx emissions operating in its waters (2023 rates of 24.46 NOK/kgNOx equivalent to 2.31 USD/kgNOx) (The Norwegian Tax Administration, 2023). Additionally, the Energy Efficiency Design Index (EEDI) has set minimum efficiency requirements for new vessels and ratings, with a sole focus on reducing the CO_2 intensity of newly built ships.

In 2019, there were only 10 coastal ports offering LNG bunkering, with another 15 in development (Parfomak et al., 2019). The relatively low price of LNG as a marine fuel coupled with regulations made it an attractive solution for some vessel owners and for some ports to offer LNG-based incentives to attract their business. The majority of LNG has been sold under long-term contracts, with prices tightly coupled with crude oil (Stoppard, 2015). In 2008, oil prices were at an all-time high but following the global financial crisis, prices shot downward and LNG prices fell in turn (Ross, 2022). Prices began to rise, but experienced a more pronounced low throughout the global COVID-19 pandemic, further benefiting the shipping industry as it experienced a boom of business, making more money in three years than in the last six-decades of business (Milne, 2023). Although, current trends in fuel costs and business may disrupt this. The presence of long-term contracts linking LNG prices to crude oil prices creates a disadvantage for future LNG investment when these prices are high and volatile. Alternatively, such disadvantages for LNG can be advantageous for investments in renewable energies that support greener fuels. The cost of renewable energies have been stable or decreasing over time, complemented by their highly predictable operating costs over time, thus their uptake will likely result in a greater ability to stabilize long-term energy costs compared to fossil fuels (Lieberman & Doherty, 2008). Vessel owners must consider the long-term cost effect of investments in fuel, infrastructure, or exhaust technologies to reduce emissions.

International Monetary Fund 2022: "European gas hit hardest" (chart 1)



Sources: IMF PCPS; US Bureau of Labor Statistics; and IMF staff calculations.
Note: The consumer price index is rebased as 2021=100. BOE = barrel of oil equivalent.

(Pescatori & Stuermer, 2022)

2.2. Climate Concerns

Assessing the environmental impact of LNG in a broader context of GHGs may indicate that it is a poor choice, due to its higher methane emissions compared to conventional marine fuels. In one study, switching a marine low pressure dual fuel four-stroke engine from diesel fuel to LNG showed that particulate matter (PM), black carbon (BC), nitric oxides (NOx), and carbon dioxide (CO_2) were reduced by about 93%, 97%, 92%, and 18%, respectively; however, formaldehyde (HCHO), carbon monoxide (CO) and methane (CH_4) increased greatly, including 11.5 g/kWh of methane, which is approximately 7.4% methane slip (Peng et al., 2020). The emissions of unburned methane are referred to as methane slip or grouped into unburned hydrocarbons (UHCs), for which this GHG source has only recently received attention.

The methane emissions of the shipping industry increased by approximately 150% from 2012-2018, partially attributed to increased consumption of LNG and the increase in the use of dual-fuel machinery that has higher specific exhaust emissions of methane (Faber et al., 2020). The global warming potential (GWP) allows a comparison of GHGs continued impact on the environment, in reference to CO_2, with values often reported in CO_2 equivalent emissions (CO_2e). Methane has a shorter lifetime in the atmosphere, as such its 100-year GWP of 29.8 (IPCC) is less than its 20-year GWP of 82.5 (IPCC). The GWP also accounts for indirect effects, such as methane's role as a precursor to ozone. GWPs are periodically updated to align with the latest scientific understanding, however it is relevant to note that studies employing older GWPs for emissions weighting may pose challenges for making meaningful comparisons (Table 1). For example, UNFCCC guidelines require the use of the GWP values from the IPCC's Fifth Assessment Report and data collected by EPA's Greenhouse Gas Reporting Program continues to use GWP values from IPCC's Fourth Assessment Report. (Myhre et al., 2013; United Nations Climate Change, n.d.; United States Environmental Protection Agency, 2023).

Table 1: IPCC Global Warming Potential Ranges

	Scale	Low	High	Recent GWP
IPCC	20-year CH_4	**56** (1995)	**86** (2014)	**82.5** (2021)
	100-year CH_4	**21** (1995)	**34** (2014)	**29.8** (2021)

3. LNG Engines and Emissions

LNG can be used in internal combustion engines, with relatively minor modification to those using conventional fuels. The basic mechanical components are quite similar, including cylinders, pistons, crankshafts, etc. Though, the CAPEX for a turnkey project to retrofit a two-stroke LNG engine totals $30.3 million USD (SEA-LNG, 2022a). The retrofit primarily focuses on adjustments to the start of combustion, air-fuel ratio, injectors, or other mechanical components for enhanced combustion efficiency. Moreover, vessels switching to LNG will require new infrastructure for cryogenic storage and fuel delivery.

3.1. Note on dual fuel

Dual fuel engines (DF) are capable of running on multiple fuel sources. Dual fuel in the marine industry typically refers to an engine designed to run on either fuel oil or gas, particularly LNG. Other dual fuel engines are now on the market, including those that are designed to use methanol. In the future, dual-fuel ammonia engines are expected. DF engines operate on a primary (main) fuel, as well as a secondary (pilot) fuel. The majority of DF engines use diesel or another energy-dense fuel as a pilot to initiate combustion when running the engine on gas fuel.

3.2. Description of common LNG engine types

Modern two- or four-stroke diesel engines can be run either with an air-fuel mixture Otto-cycle or direct fuel injection diesel-cycle mode. Pure gas engines, i.e. non-dual-fuel engines, are lean-burn gas internal combustion engines (ICE) that operate solely on the Otto-cycle. Switchable dual-fuel (DF) engines entered the market in the late 1990s as four-stroke engines, and two-stroke dual-fuel engines followed in 2010 (Ohashi, 2015). The investment costs of a dual-fuel engine are estimated to be $229,000 (USD) greater than a conventional diesel engine, but with reduced operating costs (Bui et al., 2022). At the end of year 2016, 120 "gas-fueled" vessels were in operation, from which approximately 41% had four-stroke lean-burn spark ignited engines (LBSI 4-S), 47% had four-stroke low-pressure dual fuel (LPDF 4-S), 3% two-stroke low-pressure dual fuel (LPDF 2-S), and 8% used two-stroke high-pressure dual fuel (HPDF 2-S) (Stenersen & Thonstad, 2017). Greater than 50% of these LNG fueled ships were operating in Norwegian waters. By 2021, 614 LNG-fueled vessels were in operation, from which approximately 57% had LPDF 4-S and 26% LPDF 2-S (Kuittinen et al., 2023).

Engine preference is highly influenced by the operational parameters of the vessel. Comparatively, low-speed two-strokes (HPDF) are typical for container ships traveling at a constant engine load for a long distance whereas ferries or cruise ships choose a medium-speed four-stroke (LPDF or LBSI) for operating near the coast and more constantly changing engine load. LBSI engines are at a disadvantage in the shipping industry, with preference to the fuel flexibility of dual-fuel engines. Although container and cargo ships represented only 1.3% of LNG use as a maritime fuel reported to the IMO data collection system for 2021 (Marine Environment Protection Committee, 2022). The small population of cargo ships utilizing LNG as a maritime fuel contributes to the limited representation of HPDF 2-S, low-speed engines within the current LNG engine landscape. There is no obvious decision on which marine engine is best across the board, but vessel owners can weigh the advantages and disadvantages, with additional consideration of compatible technologies and their costs.

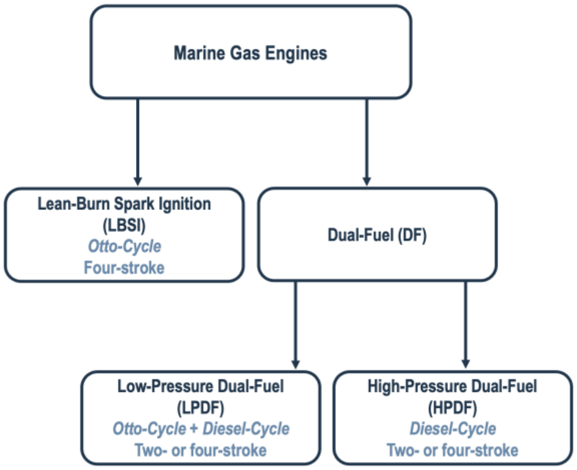


Figure 1: Marine Gas Engines (EERA)

3.2.1. 2-Stroke and 4-stroke

The base mechanics of two- and four-stroke engines are the same for both high- and low- pressure engines and both engines use the combustion cycle to produce energy. During combustion, the piston moves within a cylinder, up- and downwards. As the piston moves downwards, it captures air and fuel, then as it travels to the top an exhaust valve opens to expel the exhaust. The thermal energy of combustion increases the pressure to drive the piston generating the power output, through what is referred to as a "power stroke". The difference between 2- and 4-stroke engines comes from the number of stages to complete one power stroke. A four-stroke engine's crankshaft rotates for two revolutions to complete the four piston strokes of intake, compression, power, and exhaust. Whereas, the two-stroke engine eliminates the intake and exhaust strokes in a four-stroke cycle. Two-strokes combine more functions into one movement to compress the air-fuel mixture into the combustion chamber and simultaneously draw a fresh air-fuel mixture into the crankcase. For large ocean-going vessels, two-stroke engines are common across the industry due to their ability to burn low-grade fuel oil, their higher power-to-weight ratios, and lower maintenance needs than four-stroke (Wankhede, 2021). However, as emissions standards tighten, lower power four-stroke engines have preferable exhaust emissions (for regulated pollutants, such as NOx), take up less space and weight, and have lower costs of installation (Wärtsilä, 2018).

3.2.2. High-pressure (Diesel-cycle)

High-pressure diesel-cycle, aka "compression-ignition", engine systems inject fuel into the cylinders at high pressures, from 350-900 bar. Heat is generated in the charge air during compression which ignites the fuel when it enters the combustion chamber. The piston moves to increase volume during the burn to hold the pressure constant. Due to the high pressure, a double-walled supply system is used with leak fuel detection and alarms. High-pressure fuel injection systems are efficient due to their lower fuel consumption and reduced methane emissions. Low-pressure Otto-cycle engines have an inherently higher methane slip than high-pressure diesel-cycle (Sachgau, 2022). This can be attributed to the gas fuel being immediately burned as it is injected into the high-pressure engine, reducing methane slip (Stenersen & Thonstad, 2017). In contrast, there is a trade-off for higher NOx emissions of diesel-cycle engines. Diesel-cycle engines inject natural gas directly into the combustion chamber at high pressure, rather than pre-mix LNG with air as in lean-burn.

However, unlike traditional diesel engines, an ignition source or pilot fuel is required (Jääskeläinen, 2020). High-pressure diesel engines, both two- and four-stroke, have higher compression ratios, temperature, and pressure leading to a more complete combustion. Diesel-cycle engines have been the choice for large vessel applications, optimized for the specific needs of marine propulsion and power generation, with regard to conventional marine fuels.

3.2.3. High-pressure 2-Stroke (HPDF 2-S)

Modern two-stroke diesel engines have a simple and compact design, high power-to-weight ratio, and often lower NOx emissions than four-stroke engines (Chavan & Sewatkar, 2019). Historically, the simple design of these engines made them reliable to maintain but came with poor fuel economy and high carbon dioxide emissions. Modern marine HPDF 2-S performance standards are close to that of a diesel-only engine while providing concrete environmental benefits in terms of carbon dioxide emissions, when operating on natural gas (Hountalas et al., 2023). They were largely replaced by four-stroke engines in non-marine sectors (i.e. automobiles, aircrafts, power generation). The reliability, low maintenance, and ability to burn low-grade fuel oils has led to their continued use in ocean-going vessels (Wankhede, 2021). Past models of two-stroke engines are being replaced with direction injection and fuel injected two-stroke engines which consume less fuel for more power (Sachgau, 2022).

3.2.4. High-pressure 4-Stroke (HPDF 4-S)

Four-stroke diesel-cycle marine engines are the least common choice for ocean-going vessels, and have not been used for ship propulsion to date (Krivopolianskii et al., 2019; Stenersen & Thonstad, 2017). HPDF 4-S engines are the least efficient engines at point-of-use for OGVs, as its engineering was targeted for improvements in the automotive industry. Thus, HPDF 4-S engines are not represented in the current market for use in OGVs (Alturki, 2017). Modern four-stroke engine manufacturers promote their reliability and flexibility over two-stroke options. Wärtsilä reports that its four-stroke engines can maintain service speeds (>11 km/h), if it encounters failure, allowing maintenance overhauls while the ship is in operation or preventing stranding. In contrast, a two-stroke engine would be out of operation entirely (Wärtsilä, 2018). Direct injection technology to make diesel-cycle engines more efficient is not a cost-competitive solution for four-stroke engines (MAN Energy Solutions, n.d.).

3.2.5. Low-Pressure (Otto-cycle)

Low-pressure (Otto-cycle) engines offer simpler designs at a somewhat lower investment cost. The Otto-cycle uses constant volume combustion of an air-fuel mixture, with a much lower combustion ratio compared to diesel-cycle engines. Otto-cycle combustion results in a sudden jump in pressure while the volume remains essentially constant. Whereas, diesel-cycle has a heat transfer at a constant pressure (auto-ignition due to compression). The Otto-cycle has a limited power output compared to diesel-cycle and an increased risk of misfire (MAN Energy Solutions, 2022). Conversely, lower peak temperatures and constant volumes increase efficiency and produce less NOx emissions, as well as optimize the injection timing and avoid knocking in the engine.

Otto-cycle gas combustion is characterized by a trade-off between methane slip and NOx emissions, with higher methane slip than Diesel-cycle engines (Sachgau, 2022). In LPDF engines, a lean-burn Otto principle is utilized in combination with the diesel-cycle, also referred to as a mixed cycle engine. The lean-burn Otto principle is fueled by a premixed air-gas mixture in the combustion chamber. The "lean" mixture of air and gas in the cylinder has more air than is needed for complete combustion, further reducing peak temperature and pressures. Dual-fuel mixed cycle engines are ignited by a substantial diesel pilot representing more than ~15% of the total fuel energy, although pilot fuel can be as low as 1% at high engine loads (Jääskeläinen, 2020; Win GD, 2020). This differs from lean-burn spark ignition engines which use a spark plug or a diesel micro-pilot (<5%) for ignition (Jääskeläinen, 2020).

3.2.6. Low-pressure 2-Stroke (LPDF 2-S)

The experience with dual fuel and gas engines has been greater for four-stroke than two-stroke engines. Aforementioned, the LPDF 2-S engines represent only 3% of the current LNG fleet. However, LPDF 2-S engines have gained some popularity in the LNG market; Four of the thirteen LNG carriers commissioned in 2017 were set to be built with LPDF 2-S engines. This can be attributed to improvements in fuel consumption, a lower capital cost, and marketing the propulsion system in consideration of overall performance rather than just that of the main engine (Riviera Newsletters, 2018). These LPDF engines meet NOx limits in emission control areas (ECAs) without the need for the vessel to be fitted with exhaust after treatment equipment (Riviera Newsletters, 2018). However, high methane emissions require exhaust gas treatments when considering low-GHG measures to meet climate targets. Engine load has a greater effect on methane slip for LDPF 4-S engines than for the LPDF 2-S, with low loads showing the highest slip (Balcombe et al., 2022).

3.2.7. Low-Pressure 4-Stroke (LPDF 4-S)

In the last ten years, improvements in Otto-cycle engine technology have reduced methane slip by 50% in four-stroke engines (MAN Energy Solutions, n.d.). For dual-fuel mixed cycle engines, the diesel-cycle complies with the Tier II limits, whereas Tier III limits are met when the engine operated in the otto-cycle. LPDF 4-S engines can achieve up to 85% reduced NOx, 20-25% reduced CO_2, and nearly eliminate particulate matter emissions when operated in gas mode with LNG compared to its diesel mode operation (Stoumpos et al., 2018). Four-stroke lean burn dual-fuel engines ignited by a small (<5% fuel energy) diesel micro-pilot share more in common with lean burn SI engines than they do with dual-fuel engines using a much larger diesel pilot (>15% fuel energy) (Jääskeläinen, 2020). In contrast, pilot injection is significantly more important for engine performance showing direct proportionality between the amount of energy supplied by pilot injection and NOx emissions (Krivopolianskii et al., 2019).

3.2.8. Lean Burn Spark Ignition (LBSI 4-S)

On a four-stroke LBSI engine, the Otto-cycle mixes gas and air before the charge enters the cylinder, called premixed combustion or referred to by its air-fuel ratio. The relatively homogenous mixture ignites with a spark plug. In LBSI engines, combustion duration is the factor that most affects thermal efficiency to reduce NOx and unburned hydrocarbons (UHCs) (Khoa & Lim, 2022). Paired after treatment of LBSI engines with an oxidation catalyst has made great progress in laboratory testing, with a 70% methane slip reduction. The first pilot installation on board a vessel will start in 2023 (Sachgau, 2022).

Table 2: Comparison of Marine Engine Characteristics

Engine Type	Fuel Cycles	Pilot Fuel?	Power Stroke	Power Range	Thermal Efficiency	NOx emissions	Methane, GWP_{100}
Lean-burn spark ignited	Otto	No, spark plug ignition	Four-Stroke	Medium- and High-speed 0.5 - 8 MW	High	Tier III	~10% total WtW GHGs
Low-Pressure DF	Otto & Diesel	Yes	Four-Stroke	Medium-speed 1 - 18 MW	High at high load, poor at low load	Tier III	~17% total WtW GHGs
			Two-Stroke	Low-speed 5 - 63 MW	High at high load, poor at low load	Tier III	~11% total WtW GHGs
High-Pressure DF	Diesel	Yes	Two-Stroke	Low-speed > 2.5 MW	High	Tier II	<1% total WtW GHGs

(Schuller et al., 2021; Ushakov et al., 2019)

3.3. Engine Emissions

Most marine engine manufacturers report that their modern LBSI and LPDF engines satisfy IMO NOx Tier III regulations without additional technologies for exhaust treatment (Eilts, 2018). While HPDF engines have high NOx emissions, above IMO Tier III limits, they have very little methane slip at all operational loads (Nemati et al., 2022). Thus, introducing the engine 'efficiency trade-off' between NOx and UHCs.

Transition to LNG use and DF engines enables vessels to comply with regulations. However, reported emissions often do not consider total efficiency, the full lifecycle emissions of GHGs, and under-regulated species like methane. With IMO regulations set to minimize NOx and SO_x, there has been a trade-off in engine tuning towards lower NOx and SO_x emissions with higher methane slip and carbon monoxide, for which there are no international regulations set. A number of issues remain to be addressed, including unburned hydrocarbons (UHC) from lean-burn gas engines, operational stability for LBSI and Otto-cycle LPDF, and the operation of LBSI engines at low loads.

Challenges remain in regard to UHCs, especially methane with its high global warming potential (GWP) that offsets reduced CO_2 and other GHG emissions. Methane slip is higher for 4-stroke engines than for 2-stroke engines (DNV, n.d.). Two-stroke engines have been common in the maritime industry, and LPDF two-stroke engines are currently the most popular for new ship builds on the orderbook, despite their low presence in the active LNG fleet (Balcombe et al., 2022). The LPDF 2-S engine measured by Balcombe et al. is explained to be one of the most efficient marine gas engines available, while still having a 3.8% rate of methane slip across the main and generator engines. While main engines have been the focal point of emission concerns, it was found that the generator engines produced 60% of total methane emissions whereas the main engines contributed 39% (Balcombe et al., 2022).

Considering downstream stack carbon dioxide emissions without factoring in upstream and fugitive methane emissions from methane slip means that current accounting methods are "reducing GHG savings on paper only" (Lindstad & Rialland, 2020). A comparison of marine engine emissions, weighted by GWP, suggested that only one engine technology, HPDF 2-S, reduced life-cycle GHG emissions when using LNG instead of conventional fuels (Pavlenko et al., 2020). Total hydrocarbons (THC) refer to the measurement of all hydrocarbon compounds, both burned and unburned emissions. UHC specifically refers to the hydrocarbon compounds that have not undergone complete combustion, like methane slip. Addressing THC/UHC and methane emissions, while continuing to meet NOx and SO_x regulations, requires development in engine-level and exhaust after treatment technologies, as well as considering the efficiency of different operational modes, and upstream production pathways. Discovering long-term best practices will not only benefit the environment, but also prepare the industry with technology that can be improved upon rather than scrapped in future regulations.

Table 3: Average Emissions of LNG Vessel Engines Measured in Operation at Sea

g/kWh	NOx	CO	CO_2	THC	CH_4
LBSI (4-stroke)	1.1	1.72	472.4	4.42	4.08
LPDF (4-stroke)	1.90	1.88	444.2	7.29	6.90

*HPDF engines account for just 10% of total LNG consumption today

**LBSI engines include high-speed engines, which in general have lower efficiency

(Stenersen & Thonstad, 2017; Ushakov et al., 2019)

3.3.1. Crankcase Emissions

LPDF marine engines are suspected to leak gasses from the combustion chamber into the engine crankcase, known as blow-by gas. Blow-by gas results from the unstable piston movements in low-pressure engines, with leaks occurring in the space between the piston and the cylinder and/or gaps in the piston rings. It ventilates directly from the crankcase and is not detected in the exhaust gas, thereby measurements need to be made in the crankcase ventilation system and aftertreatments of exhaust gas cannot mitigate these emissions (Winnes et al., 2020).

Previous studies have estimated the blow-by gas to represent 1-2% of methane slip or 1 gCH_4/kWh in marine LPDF engines, based on emissions of non-marine natural gas engines (Johnson et al., 2017; Pavlenko et al., 2020). However, it has also been argued there are no studies to support that marine engines experience blow-by as high as from trucks or other land-use engines (Hult & Winnes, 2020). Using a gas concentration alarm (at 4% vol/vol), one study directly measured emissions from the crankcase of a LNG-fueled vessel with two LPDF 2-S 11530kW main engines, and four LPDF 4-S <4000kW generator engines. The concentration meters did not alarm at any point for any of the vent lines, thus blow-by emissions were assumed to be negligible. Moreover, that total on-board venting and fugitive emissions, including maintenance activities represented only 0.23% of the vessel's methane emissions (Balcombe et al., 2022). Consequently, more research measuring crankcase emissions in a marine context is required to understand their impact and total emissions.

3.3.2. Literature values

Methane slip data from LNG engines is limited and without uniform guidelines for measurement. In some cases, methane emissions are not measured directly but are reported as part of the total measured unburned hydrocarbons. Yet, the percent attributed to methane is reported differently in these studies, with methane expressed to comprise as little as 80% or as much as 97% of total UHCs (Kuittinen et al., 2023). When emissions are reported by the manufacturer or by ship owners, details on the measurement method are often unknown. Additionally, the methane slip is repeatedly reported in different units across studies, or discussed by its CO_2e or in percent-differences that make it difficult to pull together a clear and complete picture.

The Green Ray Project, funded by the European Union, gathered and converted the reported data on methane slip from LNG engines to include measurements of test-bed, on-board, engine manufacturer, and ship owner reported data. The majority of data comes from two- and four-stroke LPDF engines, a minority of LBSI engines, and HPDF engines are only reported on by engine manufacturers. Data was reported in brake specific terms (g/kWh) to explain the rate of emissions by the power produced. The below tables and figures summarize the project's compilation of methane emission data for marine engines.

Table 4: Brake Specific (g CH_4/kWh) TtW Methane Slip of LNG-Fueled Marine Engines, Reports from 2010-2022

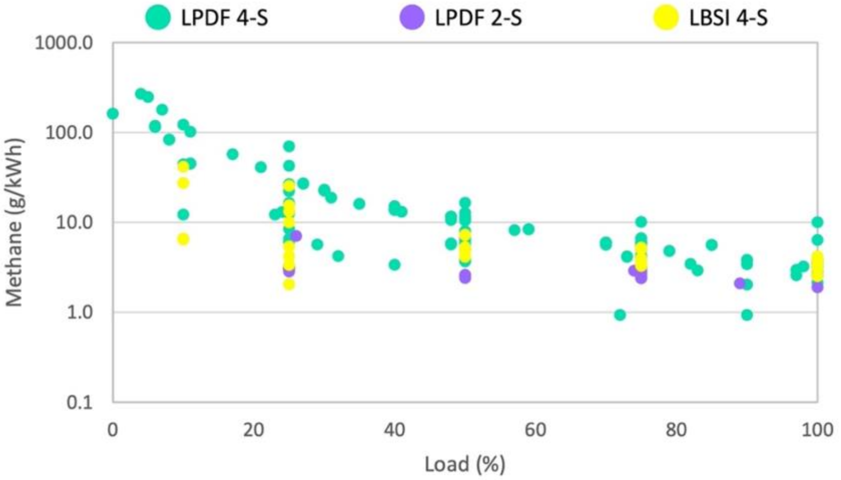
	100% Load	75% Load	50% Load	25% Load	10% Load	E2/E3 Weighted**
LBSI 4-S	2.5-4.2	3.3-5.0	4.1-7.2	N/A	6.4-42.0	2.0-5.5
LPDF 4-S	2.6-10.0	3.1-10.1	2.6-16.7	6.1-70.2	12.2-123.0	2.0-13.5
LPDF 2-S	1.9-2.5	2.4-2.9	2.4-5.1	2.8-7.2	N/A	2.1-3.5
HPDF 2-S*	N/A	N/A	N/A	N/A	N/A	0.2-0.3

*For HPDF engines, no load specific values were found

**The use of E3/E2 test cycle in reporting of methane slip is debated

(Kuittinen et al., 2023)

The Green Ray Project: "Methane emission factors as a function of engine load for all engine types" (p.18)



Green color scale is used for LPDF 4-S engines, purple for LPDF 2-S engines and yellow for LBSI 4-S engines. Note logarithmic scale.

Table 5: Total Number of Engines per Data Source Cited by The Green Ray Project

	Test-bed Study	On-board Study	Manufacturer	Ship Owner	Total
LBSI 4-S	2	6	5	0	13
LPDF 4-S	2	10	5	5	22
LPDF 2-S	0	2	4	6	12
LPDF undefined	5	2	0	0	7
HPDF 2-S	0	0	3	0	3
Total	9	20	17	11	57

(Kuittinen et al., 2023)

3.4. Emission Abatement Practices and Technology

Understanding the sources of GHGs in marine engines using LNG is critical to identifying engine modifications to reduce it. Most modern LBSI and LPDF engines satisfy IMO NOx Tier III standards, whereas the emitted NOx and particulate matter of HPDF are significantly higher. In Norwegian waters, where there is a NOx tax, LBSI engines have been preferred for ferries and 4-stroke LPDF engines for offshore vessels when LNG is the chosen fuel. For these engines, methane slip is of great importance to prevent in order to see long-term environmental benefits of LNG use.

The NOx reduction of LBSI and LPDF with LNG fuel is 75-90% compared to HPDF diesel-cycle operation (Stenersen & Thonstad, 2017). These Otto-cycle, mixed cycle engines have conversely higher unregulated UHC emissions, mainly methane. Use of LNG as an alternative, low-SO_x and NO_x fuel to meet tightening emissions limits, can result in consequential methane emissions (estimated 7-9 g/kWh) (Schramm, 2020; Ushakov et al., 2019). In LBSI engines, improper piston design, as well as crevices and flame quenching were the largest contributors to methane slip. The quenching layer is where the air-fuel premixture does not burn as efficiently in the engines' combustion chamber, typically due to imperfect ratios of the air-fuel mixture or inadequate temperature or pressure conditions. For LPDF engines, high methane emissions were at low operational loads, resulting from a thickening of the quenching layer directly influenced by its air-fuel equivalence ratio.. The low-pressure conditions of a LPDF engine can make it more susceptible to quenching due to inadequate combustion performance at low load. High-pressure engines are less susceptible to quenching, due to their compression ignition-based operation and higher thermal loading. Furthermore, the compression stroke of HPDF engines prevents the possibility of methane slip due to crevice volumes (Grönholm et al., 2021).

Engine- and operational-level modifications have the greatest impact on UHCs for LBSI and LPDF engines, whereas low methane slip from HPDF engines suggest a combination with EGR technology to reduce NOx could comply with IMO limits (Krivopolianskii et al., 2019). Anticipated for the 2024 market, MAN Energy Solutions claims their newest LPDF 4-S engine, designed for LNG carriers and container ships, has 85%

lower methane slip than current industry standards; they attribute this to reduced crevice volumes, improved performance of loads <35%, and unspecified improvements to the combustion process (Burke, 2023).

3.4.1. Operational changes

3.4.1.1. Engine Load

Engine load factor describes power output of the engine as a percentage of its maximum continuous rating (MCR). Low load operations are typically considered to be below 40% of MCR. Low load operations increase incomplete fuel combustion. More trapped fuel is left unburned as the load decreases and wall-quenching is significantly higher (Jensen et al., 2021). Low load operations manifest as higher methane slip for Otto-cycle engines and higher NOx emissions for diesel-cycle engines. For HPDF engines, NOx (g/kWh) under low load is between 65-85% higher than at higher loads of operation (Nemati et al., 2022). Comparison of emissions for LBSI engines at-sea and by the manufacturer show consistent values of slip at medium and high loads, but deviations in data at low loads due to an unsteady nature of combustion from too lean conditions (Ushakov et al., 2019). Various studies found the lowest methane slip at 75-80% load, with approximately half the methane emissions of its combustion conditions during low load operations (Balcombe et al., 2022; Jensen et al., 2021). It is suggested that load dependent variation in methane slip emission factors is suppressed in larger marine engines (Kuittinen et al., 2023). Manufacturers recognize improvements to engine efficiency will require focus on low load performance, however vessel owners can also be cognizant of how they are operating.

3.4.1.2. Operating Mode / Fuel Switching

Dual-fuel mixed cycle engines, such as LPDF, can switch between their Otto- and diesel-cycle operational modes almost instantaneously, for which the operating fuel switches with it. This can allow vessel owners to take advantage of optimal fuel prices as they arise, have a back-up fuel on longer voyages, or switch for fuel efficiency in select operating conditions. Understanding when it's efficient to swap between these modes and fuel sources can be advantageous in improving efficiency. Vessels can operate on a conventional diesel mode where no natural gas is consumed, when deemed beneficial, which may be during low engine loads. The challenge of low load operation is that the Otto-cycle with LNG meets stricter emissions standards, such as those for NOx in ECAs, whereas the diesel-cycle with diesel fuel obtains higher combustion efficiency at these low loads, with consequential NOx emissions (25% MCR). On average, NOx is reduced by 85% and CO_2 by 25% when operating in gas mode compared to diesel. Unfortunately, there is a trade-off for lower NOx, for which the resulting methane slip is greater during Otto-cycle operations (Stoumpos et al., 2018). NOx emissions standards are met during continuous Otto-cycle operation by low-pressure engines, though it may not always be the most fuel-efficient choice or ideal when considering total GHG emissions.

3.4.1.3. Bio- and e-LNG

There are other LNG fuel pathways including liquefied biomethane (bio-LNG) and renewable synthetic methane (e-LNG) that can be used in gas-capable engines. Bio-LNG can be produced from sustainable biomass resources, for which it currently can act as a drop-in fuel, blended with fossil LNG. e-LNG produces hydrogen from electrolysis and combines it with captured CO_2 emissions to synthesize methane to be liquefied. These alternative fuel choices benefit from their ability to be transported, stored, and bunkered in ports using existing LNG infrastructure (SEA-LNG, 2022b). In 2023, MSC Cruises signed contracts to buy e-LNG for its ships beginning in 2026 (Ship & Bunker News Team, 2023). Under advisement of the Kyoto Protocol, bio-LNG would be considered a zero-carbon fuel due to its emissions being measured over the lifecycle, where upstream growth of the feedstock sequesters CO_2 (United Nations, 1997). However, DF engines using green LNG fuels emit the same amount of methane slip as fossil LNG fuels (Comer et al., 2022). Therefore, these fuel pathways can reduce upstream emissions but will not impact the engine emissions discussed without improvements to engine and abatement technologies.

3.4.2. Engine-level technology

Model estimates of methane slip sources in a four-stroke mixed cycle marine engine (LPDF 4-S) running on LNG to be 8.0-10.3g/kWh due to short-circuiting (wiring faults), 5.2-9.0 g/kWh due to crevices-trap (empty engine space), and 1.3-54.1g/kWh due to quenching (cold space where fuels are not completely oxidized) (Jensen et al., 2021). Model predictions of methane slip attributed to wall quenching were suggested to be lower than empirical observations. More than 70% of hydrocarbon emissions were attributed to crevices for Otto-cycle operation (Königsson et al., 2013). The large range of methane slip due to quenching can be attributed to operation at low loads decreasing in-cylinder post-oxidation.

3.4.2.1. Volume Reduction and Pressure Adjustment

One effective engine modification to decrease combustion losses, such as methane slip, is to minimize the empty volume within the various spaces of the combustion chamber. A LPDF engine optimized for low methane slip by improved process control and minimize dead space in combustion chamber by design, can reduce the methane slip to a level of 3.0 – 4.0 gCH_4/kWh (Stenersen & Thonstad, 2017). Reduction in the height and volume of the top land and between the linear distance a piston travels and cylinder head were the most effective engine modifications to reduce methane slip; minimizing the impacts of crevices and quenching on combustion, for both single-injection and dual-fuel engines (Krivopolianskii et al., 2019).

Building on earlier studies that supported minimizing empty volume to reduce methane slip, a combination of an early pilot injection with a volume reduction of the squish region (between the piston crown and cylinder head) improved the thermal efficiency by 7.8% and reduced methane emissions by 49.7% (Park et al., 2022). Reducing methane slip using a low–crevice volume piston is greater under high–load conditions than under low–load conditions (Barba et al., 2017). Additionally, adjusting pressure in the manifolds was shown to improve oxidation and complete combustion. A positive difference between the pressure in the manifolds can triple the emission of unburned hydrocarbons compared to a negative pressure difference (Hiltner et al., 2016). Reducing methane slip due to quenching can also involve using a richer fuel-air mixture (A/F ratio) for more complete combustion; however, this again introduces the NOx-methane trade-off, as the richer mixture will emit more NOx (Stenersen & Thonstad, 2017).

3.4.2.2. Combustion Mode & Start of Direct Fuel Injection (SOI)

Injection timing for both fuels in DF engines (diesel pilot and gas jet) and the injection pressure are important to consider for emissions, since complete combustion depends greatly on the amount of pilot fuel (Latarche, 2021). An early injection mode in a LPDF engine had the highest thermal efficiency of 41.4% (Park et al., 2022). Use of late post-injection diesel can improve the oxidation of UHCs (Königsson et al., 2013). By switching combustion mode from conventional (CDF) to late injection and early injection in a LPDF engine, methane slip is reduced by 12% and 33%, respectively; However, compared to CDF, late and early injection modes produce 417% and 67% more black carbon (Taghi Zarrinkolah & Hosseini, 2023).

Start of Direct Fuel Injection (SOI) can be used effectively to manage methane slip in any combustion mode of a LPDF engine, but the effect is the largest in the early injection mode (Taghi Zarrinkolah & Hosseini, 2023). SOI is the precise moment when the injector begins spraying fuel directly into the combustion chamber, typically measured in degrees of crankshaft rotation. An examination of diesel spray angles (SAs) of 60, 90, 120° revealed that minimum methane slip is obtained when the SA is towards the squish area (between the piston crown and cylinder head), and maximum methane slip is obtained when the SA is towards the piston bowl. Increasing SA from 60 to 90 and 120° results in a 16.4% and 42.5% reduction of methane slip (Taghi Zarrinkolah & Hosseini, 2023).

Modern two-stroke HPDF engines have negligible methane slip levels over the engines' load range (0.2-0.3 gCH_4/kWh) (Sachgau, 2022). SOI technology can reduce its already low methane slip by up to 90%, yet is not considered cost-effective (Sachgau, 2022). With these considerations in mind, a further reduction of methane slip in HPDF engines is possible. HPDF methane slip was significantly impacted by the variation of angle between methane and diesel jets affecting the combustion process and its heat release rate (HRR) with greater emissions at high operational loads (Fink et al., 2018). However, it could address CO and NOx emissions for HPDF engines with reductions of 21% and 31% due to better air–fuel mixing and a higher combustion intensity (Yang et al., 2020). Exhaust after treatment technologies could be implemented to address NOx of HPDF to meet IMO standards and remain competitive with LBSI and LPDF engines.

3.4.2.3. Skip-Firing at Low-Load

Skip-firing refers to a combustion strategy where a portion of the engine's cylinders are intentionally deactivated or "skipped" during certain operating conditions, particularly at low loads at which the lower power output does not require full activation. Skip-firing in a lean-burn engine provides a significant reduction in THC emission and methane slip to overcome high emissions at low loads (Järvi, 2010). By using skip-firing to reduce the excess air ratio in combination with increased specific engine load (using only one cylinder more frequently), the total methane emissions were reduced by up to 33% in a HPDF 4-S engine (Sommer et al., 2019).

A low-load (<20%) Otto-cycle optimization package, using dynamic skip fire (DSF), to deactivate cylinders for increased efficiency reports a 55% reduction of methane slip by the manufacturer for three LPDF engine models (Wärtsilä, n.d.-b). The lower the load, the more cylinders would be deactivated, so that the remaining active cylinders operate at the power of a higher load. Details of the new LPDF engine calibration implementation have not been released by the manufacturer and their baseline comparison is unclear. An independent study attempted to replicate these calibrations and their emissions claims (with comparison of two 2022 LPDF 4-S engines, with and without optimization). It found the new LPDF calibration to reduce methane slip by 24% relative to the baseline; moreover, the methane reduction was sufficient in reducing the total GHG emissions (GWP_{100}=28) in Otto-mode below that of its diesel-mode operation for loads >30%, whereas at low loads the methane slip resulted in greater total GHG emissions than for its diesel-mode operation (Rochussen et al., 2023).

The Green Ray Project: "Effect of cylinder deactivation on methane slip" (p. 20)

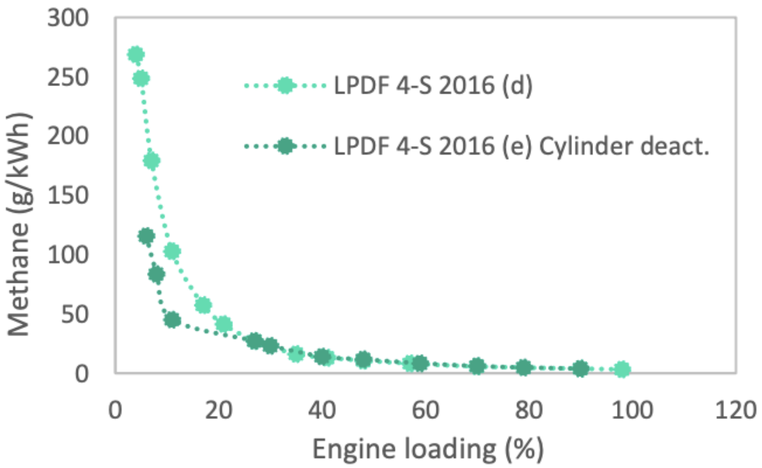


Figure reproduced based on data from the publication of Sommer et al. (2019)

3.4.2.4. Investment in New Engines

A comparison of methane slip from marine engines across different build years, specifically LPDF 4-S engines, showed that emission factors were comparable from vessels 2010 to 2019. However, the newest engines deviated lower with test-bed reported measurements and higher with on-board measurements (Kuittinen et al., 2023). The variation of modern engine methane slip is suspected to originate from operational differences in test-bed and on-board running. It could also be influenced by the different methods of measurement or differences in engine manufacturer technology. However, there are two significant uncertainties about emissions data that The Green Ray Project brings to light. First, that manufacturers are reporting lower numbers with the newest models than observed in true operation. Second, that the comparison is based on vessel-build year rather than the year of engine design, with a recognized possibility of old engine technology being installed on new ships. This is likely to be an influencing factor, based on the average time between keel laid date and built year for vessels more than tripling from 2015-2023 (Van Roy et al., 2023).

Table 6: Methane Slip from Modern (2020-2022) LPDF 4-S LNG-fueled Marine Engines

	100% load	75% load	50% load	25% load	10% load
Test-bed (g/kWh)	2.6-2.9	3.4-4.1	N/A	6.6-13.05	N/A
On-board (g/kWh)	2.0	7.0	17.0	70.0	123.0

(Kuittinen et al., 2023)

Further complicating the issue, for engine emissions measured at sea, engine performance and emission profiles were shown to vary depending on engine type and manufacturer. Additionally, engines were shown to be operating in leaner conditions at sea than in test data presented by the manufacturer, therefore emissions of NOx were lower while UHCs were higher at sea (LSBI 4-S 4.1 gCH_4/kWh, LPDF 4-S 6.9

gCH_4/kWh) than in laboratory testing (LBSI 4-S 2.98 gCH_4/kWh, LPDF 4-S 3.5 gCH_4/kWh) (Stenersen & Thonstad, 2017). Stenersen & Thonstad compared the methane emissions from multiple marine engines based on data gathered from various reporting sources. An older model of a LBSI engine, with modern modifications to reduce methane slip, was considered to be an outlier to the emissions data; Only a slight reduction of methane was observed and considered to not meet current LBSI efficiency (Stenersen & Thonstad, 2017). From this, it can be inferred that engine-level modifications are an emissions solution solely for future investment rather than for vessels in operation. Manufacturers would disagree, offering tailored upgrade packages to reduce methane emissions up to 60%, although the testing methods are not shared to substantiate this (Wärtsilä, n.d.-b). Yet, an independent study found methane slip of the newest 2022 LPDF engine could be reduced by up to 82% at optimal loads through a combination of engine calibration and improved operating strategies (Rochussen et al., 2023). At this time, it is unclear whether it is best practice to retrofit and optimize an engine or to invest in the newest models.

3.4.3. Exhaust after treatment

As discussed in the following sections, exhaust after treatment technologies must overcome challenges converting their respective GHGs when faced with low exhaust temperature and catalyst degradation. HPDF engines require the use of exhaust after treatment technologies to compensate for their high NOx emissions and comply with IMO Tier III standards. The implementation of selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) systems are commonly paired with HPDF engines to mitigate their emissions to meet regulatory requirements. While LNG-fueled LPDF engines may appear advantageous in terms of NO_x standards and the Energy Efficiency Design Index (EEDI), their overall climate impact is not captured due to the exclusion of methane. This regulatory omission fails to fully incentivize the reduction of methane in LPDF engines with the investment costs of exhaust after treatment technologies. These technologies are required for LNG to be competitive for well-to-wake GHGs compared to conventional fuels (MGO, HFO + Scrubber, VLSFO).

A collection of studies investigating GWP20 showed LNG-fueled LPDF 4-S engines increased total GHG emissions when operating with consideration to IMO Tier III standards, which do not necessitate after treatments of exhaust to offset the NOx-CH_4 trade-off at present. Studies of GWP100 found emissions to be largely skewed by the included test-bed measurements, with test-bed results for LNG having a lower WtW than LPDF 4-S engines operating on MGO or VLSFO (Lindstad & Rialland, 2020). This supports The Green Ray Project's findings that test-bed measurements of methane are lower than that of on-board studies (Kuittinen et al., 2023).

3.4.3.1. Exhaust Gas Recirculation (EGR) Technologies

A combination of HPDF engines with EGR technology could comply with IMO Tier III limits, by reducing high NOx emissions and minimal methane slip. This technology is anticipated to be a popular choice in the near future for vessel owners to adapt their present fleet, in consideration of regulations and climate targets (Krivopolianskii et al., 2019). Unfortunately, EGR can increase emissions of carbon monoxide and black carbon, as well as increase wear on the engine, without additional paired technologies to compensate (Jääskeläinen & Khair, 2022). One of the suggested technologies to pair with EGR is a fuel reformer. Fuel reformers help to convert low-grade waste heat, methane slip, or other undesirables from engines into the production of hydrogen. This provides allows the vessel to produce and consume a low-GHG fuel, converted from the waste and harmful emissions of LNG (Qu et al., 2022). Fuel reformers are not new, but their application with LNG-fuel is newly explored.

EGR can reduce NOx and CH_4, but can decrease the thermal efficiency of combustion, whereas a fuel reformer could increase thermal efficiency but raise the NOx emissions; implying that these technologies combined could be advantageous. Applying the two technologies to a large marine low-speed LPDF 2-S engine was shown to improve thermal efficiency, reduce the EEDI index (indicating a more energy-efficient design), and was considered to be practical in application by engineers. NOx emissions continued to meet IMO Tier III standards, thermal efficiency was 2% higher than the base engine, and methane slip was reduced by 20% (Qu et al., 2022). The investment cost to add EGR technology to a low-speed, 48,000 kW engine-power OGV was once estimated to be US $251,058 (ICF International, 2009). However, Maersk reported an investment cost of 50-66 USD/kW-installed power, which would put the cost at $2.16 million (Bunker Index, 2014). A thermo-economic analysis of the combination system and the EEDI calculation showed that the annual fuel cost saved by installing the system on an LNG ship was approximately US $151,726 (based on 600$/ton fuel cost) (Qu et al., 2022). Maersk had two ships retrofitted with EGR prototypes in 2010 and reported the operational costs to be 4-6% of fuel costs, but that the fuel savings offset the initial investment over time (Bunker Index, 2014).

3.4.3.2. Methane Oxidation Catalysts (MOC) and SO_x Traps

LNG has favorable low-sulfur content (>0.004% sulfur) that compliments MOC technology better than high-sulfur fuels. The catalyst to oxidize methane is highly sensitive to sulfur poisoning, even 1 ppm SO_2 was found to inhibit the oxidation of methane (NEPIA, 2019; Ottinger et al., 2015). Thus, the longevity of MOC technology is its biggest challenge as even small amounts of sulfur degrade its efficiency. Moreover, the SO_x content of pilot fuels and lubricating oils contribute to the challenge (Lehtoranta et al., 2021). MOC is a promising exhaust treatment technology paired with LNG ships, with a reported 70% reduction in methane, but more studies are needed regarding regeneration of the catalyst (Sachgau, 2022).

Adding a SO_x trap upstream was shown to protect the efficiency of MOC even under higher sulfur exposure (from 0.5 ppm to 1.5 ppm). Yet regeneration of the catalyst is still vital to its long-term performance, as methane conversion rapidly decreases with time, below 50% efficiency after the first 20 hours. Regeneration recovered efficiency between 60-70% up to 140h, but methane slip was near 2000ppm at 140h and forward (Lehtoranta et al., 2021). Despite methane conversion significantly decreasing within time, there was no change in the performance regarding other reduced emissions (CO, HCHO, ethane, ethylene).

For MOC and carbon capture technologies, temperature of the exhaust plays a significant role. At exhaust temperature of 400°C, MOC methane conversion was negligible (only 2%). However, increased temperature sharply increased methane conversion. At the highest temperature of 550°C, methane conversion was ~70% with a higher exhaust flow, but could be raised up to 80% with a lower exhaust flow, providing more time for the catalytic reactions to occur (Lehtoranta et al., 2021). Engine temperatures can be increased for exhaust gas processing technologies through the reduction of intake air mass and the use of exhaust gas preheating (Zannis et al., 2022). No studies were found regarding consequences of engine wear with prolonged exhaust temperatures in this range. The investment costs of MOC technology were estimated to be US $489,000 with additional annual operating costs of US $120,000/year (6300kW LPDF 4-S). Furthermore, there is an assumed 1% fuel penalty for catalyst operation (Winnes et al., 2020).

3.4.4. Fuel system and tank emissions, boil-off etc.

Natural gas undergoes treatment to improve its quality by removing components that could freeze (e.g. benzene, water, or residual CO_2), could be harmful (e.g. mercury), or could reduce SOx emissions (e.g. Hydrogen-sulfide) and then undergoes liquefaction to become LNG (The LEVON Group, 2015). Double-walled cryogenic systems maintain natural gas in its liquid state by upholding well-insulated conditions (below -162°C). However, insulation is not a perfect practice and some heat will continually seep into the container. LNG vaporization is often due to heat gain from the tank surroundings or from the energy input of the pumping process. Absorbed heat converts amounts of LNG into a vapor that increases the internal pressure of these tanks, and in turn this pressure can further disrupt the cryogenic conditions keeping the remaining fuel in its liquid state. An additional consequence of this vaporization is the reduced fuel quality of LNG, as the most volatile compounds (nitrogen and methane) are lost first in boil-off gas (BOG) (Miana et al., 2016). To relieve this pressure, without emitting methane directly into the atmosphere, the vaporized boil-off must be released from the tank by re-liquifying, consuming, or combusting the fuel. For vessels that are used every day, the pressure can be kept below the venting threshold with steady withdrawal of the natural gas liquid and vapors to power the engines; even so the pressure will build and require other outlets during times of idling or non-use.

Re-liquifying boil-off is often considered to be impractical aboard a ship due to the large space and equipment required, but can mitigate BOG during the early stages of storage and liquefaction. Some LNG carriers have been equipped with reliquefaction plants to collect and condense the vapors and inject the LNG back into the tanks (Lowell et al., 2013). Consuming the BOG as fuel or burning it in a gasification unit can be more practical at sea. Older LNG carriers used BOG to power steam turbine propulsion engines, whereas the majority of vessels built after 2014 used DF engines to burn a mixture of BOG and conventional fuels. At a time where LNG prices were low, BOG allowed carriers to reduce emissions while saving fuel costs. However, high LNG prices discourage carriers from consuming BOG to instead sail on cheaper fuel oil to save on operating costs and receive maximum value cargo sales (Jaganathan & Khasawneh, 2021).

Addressing venting and fugitive emissions from the fuel system and tank could increase the environmental benefit of LNG, in particular, the management of boil-off gas from cryogenic storage. The total volume of LNG vaporized over time can be calculated as boil-off rate (BOR), with a typical loss of 0.15% per day, and new-build LNG carriers projected BOR near 0.1% per day (Wärtsilä, n.d.-a). For smaller tanks, BOR can be as high as 0.25% per day, although they may hold LNG up to 75 days without venting (Chart Industries, 2013). Nevertheless, venting and fugitive emissions contributed less than 0.1% of total GHG emissions and only 0.23% of methane emissions. On the other hand, methane slip contributed to 99% of methane emissions across a round-trip voyage, between the USA and Belgium, and methane slip accounted for 35% of total GHG emissions (GWP100, averaging 40-45% load) (Balcombe et al., 2022). Therefore, it is more meaningful for vessel owners to prioritize reducing methane slip from the engine than from its storage systems.

3.4.5. Upstream Sources of Methane Emissions.

The 2020 U.S. GHG Inventory estimates that the contribution of methane from natural gas operations is approximately 165 million metric tonnes (MMT) in terms of CO_2e; accounting for 25.4% of total methane emissions in the US (United States Environmental Protection Agency, 2022). Consideration of the full life-cycle emissions of LNG introduces well-to-tank (WtT) inefficiencies upstream of the engine to be addressed for long-term GHG planning. However, there is a limited amount of data available for upstream GHG emissions of LNG fuel, particularly for marine transportation. A 2020 study attempting to assess these values, explains "the [WtT] GHG emissions of LNG fuel for marine vessels based on actual fuel consumption has not yet been systematically evaluated" and continues to reiterate, "little data is available on the emissions and energy requirements" of upstream LNG operations. That study estimated the total upstream GHG emissions of LNG for marine transportation to be between 9.8-10.4 gCO_2e/MJ - GWP_{100} based on a look at British Columbia (Manouchehrinia et al., 2020). In contrast, a report on global upstream LNG emissions arrived at 21.5 gCO_2e/MJ - GWP_{100}, evaluating the prior study to be half the global average (Pavlenko et al., 2020).

In the LNG life-cycle, carbon dioxide emissions are primarily associated with steps that use combustion, which occur most often during the "production" timeline. In contrast, methane emissions are associated with venting, leaking, and other fugitive emissions, which occur in storage, pipeline, and fueling distribution systems for which there are fewer sources of combustion (Roman-White et al., 2019). Methane leaks from compressor stations and venting from pneumatic controllers account for most of the emissions from this stage. Total methane emissions have decreased since 1990 due to improved efficiency of distribution, transmission, and storage, however production accounts for approximately 50% of the life-cycle methane emissions in power generation (United States Environmental Protection Agency, 2022). CO_2 emissions from operations have increased due to larger production, for which emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time (United States Environmental Protection Agency, 2022). Emissions can also be attributed to the power supply of upstream LNG technologies, such as during liquefaction. If renewable energies generated the power of a LNG liquefaction plant, the lifecycle GHGs of LNG could be reduced by 5-10% (Al-Douri et al., 2021).

Upstream methane emissions are largely based on inefficiencies in how natural gas is obtained and how it is transported (i.e. time/distance in the pipeline and in storage, due to boil-off) (Thomson et al., 2015). Emission sources include leaks from the well during water injection, gas venting from pneumatically controlled devices, and fugitive emissions from flanges, connectors, open-ended lines, and values. Gathering and boosting and pneumatic controllers in onshore production account for the majority of emissions at this stage. Production emissions also include the combustion of natural gas or other fuels by engines that drive compressors or power supporting equipment (Roman-White et al., 2019; United States Environmental Protection Agency, 2022).

Presently, there are instances that allow vapor recovery units to capture and flare vented gas, for which the combustion converts methane to carbon dioxide. On the other hand, systems exist to capture and recycle the vented gas. Although installation costs can add 50-100% to the initial storage tank cost, the recovered gas can be used in facility operations or sold to profitably reduce methane emissions (United States Environmental Protection Agency, 2006). Newly simulated methods to improve boil-off gas recovery onboard LNG carriers are proposed for zero methane loss without any reduction of turbine outlet pressure of the BOG compressor (Kochunni & Chowdhury, 2020). The simultaneous economic and environmental incentives of these recovery units may increase the likelihood of their adoption.

Engine System CAPEX	**LPDF 2-S** **HPDF 2-S** **$30.05M USD**[1] **$31.24M USD**[2] Based on costs of main and auxiliary engines, labor and yard work, and LNG tanks on a newbuild 14,000 TEU container vessel. Data unavailable for LBSI and LPDF 4-S.

Abatement Type	**Technology or Practice**	**Benefits**	**Limitations**	**Engine Cited**	**CH_4 reduction (max %)**	**CH_4 reduction (min %)**	**CH_4 reduction gCH4/kWh**	**Other Emissions reduced?**	**Investment Cost (USD)**	**Operational Cost**
Operational changes	Engine load (>=75%)	High-impact, low cost Vessel operators can easily adapt Additional performance benefits of higher loads	Not feasible in all real-world situations Less load dependent variation in methane slip for large engines	LPDF 4-S	>50% Based on measured engine load values	0%	68.0 On-board measurement (25→100% load)[3]	CO_2 NOx	0	N/A Engine manufacturer consensus that engines must be loaded to at least 50% MCR during frequent low load operations to prevent operational problems, suggesting there could be long-term cost savings due to reduced

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[1] https://sea-lng.org/wp-content/uploads/2020/04/190123_SEA-LNG_InvestmentCase_DESIGN_FINAL.pdf

[2] https://sea-lng.org/wp-content/uploads/2020/04/190123_SEA-LNG_InvestmentCase_DESIGN_FINAL.pdf

[3] https://greenray-project.eu/wp-content/uploads/2023/04/D1.1_Review_of_methane_slip_from_LNG_engines.pdf

										wear on the engine[4] Although, voyage-level fuel costs could increase.
	Operating mode (Fuel & cycle switching)	DF engines allow easy, instantaneous switch Fuel costs can be advantageous	Diesel-cycle operation on fuel oil to reduce CH_4, may increase other emissions Fuel costs can be prohibitive	LPDF	>99% Limited studies have looked at DF engine emissions operating on its secondary fuel. Low UHCs are typical of diesel fuel.	N/A	N/A	CO	N/A A reduced CAPEX for a LPDF engine. The HPDF gas system CAPEX is ~$1.2M, the LPDF gas system ~$700K[5]	N/A Costs of operation mode are highly dependent on fuel costs, however were estimated to be lower than that of a conventional diesel engine
Engine-level	Volume/ Pressure	Permanent adjustment of engine design by manufacturer for improved emissions	Requires retrofitting for new engine or an entirely new-build vessel	LBSI 4-S, LPDF 4-S	50%[6]	N/A	3.0 – 4.0[7]	UHCs	N/A	N/A

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[4] https://doi.org/10.1007/s00773-020-00760-3

[5] https://sea-lng.org/wp-content/uploads/2020/04/190123_SEA-LNG_InvestmentCase_DESIGN_FINAL.pdf

[6] https://doi.org/10.1016/j.fuel.2021.122015

[7] https://www.nho.no/siteassets/nox-fondet/rapporter/2018/methane-slip-from-gas-engines-mainreport-1492296.pdf

	Combustion	Permanent adjustment of engine design by manufacturer for improved emissions	Requires retrofitting for new engine or an entirely new-build Increased black carbon emissions by up to 67%	LPDF	43%[8]	12%[9]	0.83-2.90 Estimated using 12-42.5% range, based on 6.90 average CH4 emissions of a LPDF 4-S at sea[10]	UHCs, CO, NOx	N/A	N/A
	Skip-firing (deactivating cylinders)	Permanent adjustment of engine design by manufacturer for improved emissions Improves low-load operations Overall efficiency improvements	Requires gas-mode operation Upgrade is ideal for LNG carriers, ferries, or other vessels operating at constant speeds	LPDF 4-S	55%[11] Manufacturer reporting; At low-load less than 20%	N/A	4.26 Estimated with 55% reduction of the manufacturer average E2/E3 weighted cycles of LPDF 4-S[12]	UHCs	N/A	N/A
Exhaust treatment	Exhaust Gas Recirculation	Improve emissions for HPDF and LPDF Combined EGR with fuel reformer is estimated to save >$151K	Decreases thermal efficiency without a fuel reformer Can increase emissions of CO and black carbon	LPDF 2-S	20%[13] Both with and without the fuel reformer	N/A	0.48-1.02 Estimated with 20% reduction based on the 50-75% load	NOx	50-66 USD/kW-installed power[15] Would indicate installation on low-	4-6% of fuel costs Fuel savings are shown to offset the initial

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[8] https://doi.org/10.1016/j.fuel.2022.125775

[9] https://doi.org/10.1016/j.fuel.2022.125775

[10] https://www.nho.no/siteassets/nox-fondet/rapporter/2018/methane-slip-from-gas-engines-mainreport-1492296.pdf

[11] https://www.wartsila.com/services-catalogue/engine-services-4-stroke/ghg-emissions-reduction-upgrades

[12] https://greenray-project.eu/wp-content/uploads/2023/04/D1.1_Review_of_methane_slip_from_LNG_engines.pdf

[13] https://doi.org/10.1016/j.fuel.2022.123747

[15] https://www.bunkerindex.com/news/article.php?article_id=12988

		/yr in fuel costs	Can increase engine wear				range for LPDF 2-S[14]		speed, 48,000kW to cost $2.16M USD	investment over time[16]
	Methane Oxidation Catalyst	Highest reduction potential for CH_4 Low-sulfur content of LNG reduces degradation of MOC catalyst	Negligible conversion at low exhaust temp. Poor performance at low loads Reduced performance in first 20hrs SOx degradation from pilot fuel and lubricating oil Converts CH_4 to CO_2, another GHG High maintenance	Passenger Car Engine — Operation adjusted with an aftermarket engine control unit to reflect exhaust emissions for LPDF 4-S, LNG-fueled[17]	80% at 550°C [18] 650°C is considered max temperature with aluminum pistons before risk of damage to engine[19,20]	>30% at 550°C [21] 2% at 400°C, showing the significance of exhaust temperature	2.07-5.52 Estimated using 30-80% range, based on 6.90 average CH4 emissions of a LPDF 4-S at sea[22]	CO, HCHO, ethane, ethylene	~500K USD[23] or 1-3% of engine cost[24]	~120K USD/yr[25] or 627 USD/kWh [26] Add additional fuel penalty due to catalyst operation

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[14] https://greenray-project.eu/wp-content/uploads/2023/04/D1.1_Review_of_methane_slip_from_LNG_engines.pdf

[16] https://www.bunkerindex.com/news/article.php?article_id=12988

[17] https://www.researchgate.net/publication/305810560_Imitating_emission_matrix_of_large_natural_gas_engine_opens_new_possibilities_for_catalyst_studies_in_engine_laboratory

[18] https://doi.org/10.3390/jmse9020111

[19] https://bartechmarine.com/blog/black-smoke-high-temperatures/

[20] https://www.dieselhub.com/performance/egt.html

[21] https://doi.org/10.3390/jmse9020111

[22] https://www.nho.no/siteassets/nox-fondet/rapporter/2018/methane-slip-from-gas-engines-mainreport-1492296.pdf

[23] https://www.diva-portal.org/smash/get/diva2:1746960/FULLTEXT01.pdf

[24] CIMAC WG 17, 2017. Gas Engine Aftertreatment Systems. CIMAC Position Paper 05/2017. International Council on Combustion Engines.

[25] https://www.diva-portal.org/smash/get/diva2:1746960/FULLTEXT01.pdf

[26] https://www.diva-portal.org/smash/get/diva2:1746960/FULLTEXT01.pdf

4. Policies and Regulations Regarding Methane Emissions from Ships

Governing bodies and organizations have begun to develop and enact policies to monitor, report, and reduce methane emissions from vessels. This section provides an overview of policies and regulations related to methane emissions from ships, including existing and recommended regulations.

4.1. International Maritime Organization

In 2018, The International Maritime Organization (IMO) adopted the initial strategy for the reduction of GHG emissions from ships. The initial ambitions included at least a 40% reduction in carbon intensity by 2030 and an effort to realize a 70% reduction by 2050 relative to 2008 levels, and a 50% reduction in total annual GHG emissions by 2050 relative to 2008 levels (Marine Environment Protection Committee, 2018). However, there are no existing IMO regulations that directly control methane emissions.

4.1.1. MARPOL Annex VI

The IMO outlined a framework to achieve GHG ambitions in amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL). MARPOL Annex VI additionally limits NO_x and SO_x emissions from ships, which are pollutants released in harmful quantities when fuels, such as traditional heavy fuel oil (HFO) are burned. HFO had been the traditional fuel source for large ships due to its low price and energy density, until 2020 when IMO lowered the sulfur content fuel limit from 3.5 percent to 0.5 percent for ships without scrubbers (International Maritime Organization, 2019). HFO typically has a high sulfur content, which makes HFO an unfavorable fuel choice under the MARPOL regulations on NO_x and SO_x emissions (Farshi & Shiralizadeh, 2015). HFO made up 79% of maritime fuel consumption in 2018, and alternative fuel sources are being sought out to reduce NO_x and SO_x emissions, such as Very-low Sulfur Fuel Oil (VLSFO), Ultra-low Sulfur Fuel Oil (ULSFO) and Liquified Natural Gas (LNG) (Faber et al., 2020). LNG accounted for a small proportion of fuel consumption in 2018, the majority of which was related to boil-off gas from LNG carriers (Faber et al., 2020). LNG emits relatively low NO_x and SO_x emissions compared to HFO and other fuels, which makes LNG an attractive option for ships transitioning from HFO (Marine Environment Protection Committee, 2021b). However, LNG is associated with high amounts of methane slip, and future methane emissions regulations may steer shipowners away from LNG as a primary fuel source.

In 2011, the Energy Efficiency Design Index (EEDI) was introduced in MARPOL Annex VI, which sets efficiency requirements for new ships. EEDI requires new ships (built in 2013 and beyond) of 400 gross tons and above to be constructed with a greater emphasis on energy efficiency (International Maritime Organization, n.d.). EEDI aims at reducing CO_2 emissions through technological efficiency requirements. EEDI was expanded in 2021 with the Energy Efficiency Existing Ship Index (EEXI), which came into effect in 2023. EEXI includes updated regulations for efficiency requirements on existing ships, which compel existing ships to meet carbon intensity standards through engine upgrades and other technological enhancements (Marine Environment Protection Committee, 2021a). IMO requires the Ship Energy Efficiency Management Plan (SEEMP) which provides tools that ship operators can use to improve energy efficiency, including speed management, switching to alternative fuels, and maintenance practices. Though they address overall efficiency and aim to reduce carbon intensity, EEDI, EEXI, and SEEMP do not consider methane emissions or methane slip, which impact total GHG emissions from operations and energy efficiency (International Maritime Organization, n.d.).

4.1.2. MARPOL Requirements and Methane Slip

While LNG fuels can emit relatively low amounts of NO_x and SO_x, engines burning LNG typically have high amounts of methane slip, which occurs when unburned methane is released into the atmosphere (Sharafian et al., 2019). The MARPOL GHG ambitions and reporting requirements do not consider the methane emissions caused by methane slip. As a result, methane that goes unaccounted for will be released into the atmosphere, further increasing the disparity between GHG emissions targets and the actual amount of GHG emissions. The lack of regulations pertaining to methane slip poses a challenge, especially with the growing adoption of LNG-fueled shipping. The transition to LNG could exacerbate the gap between emissions estimates and actual emissions.

By implementing engine technology requirements and enhanced reporting measures, some challenges with methane slip can be addressed and potentially encourage a transition to more sustainable fuels (Lindstad et al., 2020). Improvements to existing policies may be an effective approach, such as incorporating methane slip into energy efficiency requirements (EEDI/EEXI).

4.2. European Union

The European Union (EU) is a political and economic union of 27 Member States, with governing bodies working to confront global issues such as climate change. Approximately one fifth of the world's vessels (by tonnage) are owned by EU Member States; thus the EU plays an important role in decarbonizing the global maritime sector (European Maritime Safety Agency, 2023). Furthermore, the regulations set by the EU will apply to any ship, of any flag that calls on an EU port. The EU has enacted several policies and regulations aimed at increasing transparency of ship operations and reducing greenhouse gas emissions in the maritime sector, including the Monitoring, Reporting, and Verification system, the Global Methane Pledge, Fit for 55, and FuelEU Maritime.

4.2.1. E.U. Monitoring, Reporting, and Verification

Maritime trade in European nations is regulated in part by the EU. The 2015 EU Monitoring, Reporting, and Verification (MRV) procedure requires ships above 5,000 gross tonnage, excluding certain ships such as military vessels, to calculate and disclose their annual carbon dioxide emissions, fuel consumption, and energy efficiency in a public database. In 2022, EU member states agreed on a proposal that requires oil, gas, and coal companies to measure, report, and verify methane emissions. The 2024 MRV reporting requirements will include the emissions of methane and nitrous oxides, through required monitoring plans.

The monitoring requirements for methane and nitrous oxide emissions will likely closely resemble the existing methods for monitoring carbon dioxide, which include monitoring requirements for emissions, distance traveled, fuel consumption, and other parameters on a per voyage basis, aggregated to annual totals. Carbon dioxide monitoring plans must maintain a list of emissions sources, indicate the procedure for measuring fuel consumption, and identify emissions factors for all relevant fuel types. The existing carbon dioxide regulations also require the publication of emissions and energy efficiency data on individual ships (Erbach, 2020).

Beginning in 2024, ship operators will be responsible for administering a monitoring plan for all ships above 5,000 gross tonnage that includes methane and nitrous oxide emission in the scope of regulation. The monitoring plan will need to be assessed by an accredited EU MRV verifier. General cargo ships below 5,000 gross tonnage, but above 400 gross tonnage will additionally fall under this regulation beginning in 2025 (European Parliament & Council of the European Union, 2023).

4.2.2. Global Methane Pledge

The EU and the United States launched the Global Methane Pledge (GMP) at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 26). Over one hundred countries have joined the GMP, committing to a collective goal of at least a 30% reduction in global methane emissions from 2020 levels by 2030 (Climate & Clean Air Coalition, 2021, 2023). The pledge is non-binding and individual countries do not have country-specific targets.

The GMP highlights the potential for major reductions in methane emissions from upstream and downstream maritime operations. While the GMP draws attention to the potential emissions reductions from the energy sector, it has implications for many industries, including the maritime industry. The emphasis on reducing collective methane emissions may result in the establishment of maritime-specific methane emissions targets, accompanied by expanded monitoring and reporting requirements. However, no country has demonstrated progress towards achieving the goals of the GMP (Climate & Clean Air Coalition, 2021).

4.2.3. Fit for 55

In 2022, the EU Fit for 55 plan was established with the goal of reducing GHG emissions by at least 55 percent by 2030 compared to 1990 levels, working toward the EU's primary goal of reaching climate neutrality by 2050. The Fit for 55 plan is a broad approach to decarbonizing many sectors and includes a cap-and-trade system, reductions in emissions, carbon dioxide emissions standards for vehicles, reductions in the energy sector, and transitions to greener fuels in maritime and aviation transport (Council of the European Union, 2023). The EU has introduced a specific goal of reducing the greenhouse gas intensity of energy used onboard ships by up to 80% by 2050 through a transition to greener fuels in its FuelEU Maritime legislation (discussed in the next section).

The EU also has a cap-and-trade program, the Emissions Trading System (ETS), which could incentivize a transition to cleaner fuels. A provisional agreement has been reached which would include maritime emissions in ETS. If officially adopted, the inclusion of maritime emissions in ETS will go into effect in 2024, and it will be the first explicit carbon price on maritime emissions (European Commission, 2023). The ETS does not currently include methane emissions, but it is set to include methane emissions in 2026 for ships greater than 5,000 gross tonnage. A decision on whether ships between 400 and 5,000 gross tonnage will be included in the ETS is to be reached by the end of 2026. Emissions are charged on a Tank-to-Wake basis (Erbach & Foukalová, 2023).

4.2.4. FuelEU Maritime

The EU FuelEU Maritime initiative, which is part of the Fit for 55 plan, aims to accelerate a transition to renewable and low-carbon fuels through the reduction of GHG intensity of ships' energy. FuelEU GHG intensity reduction targets are outlined by the following schedule: 2% from 2025, 6% from 2030, 14.5% from 2035, 31% from 2040, 62% from 2045, and 80% from 2050. GHG intensity reductions will be compared to a reference value of 91.16 gCO_2e/MJ (European Parliament, 2023). FuelEU differs from EU ETS in that it considers a well-to-wake approach to assessing a fuel's emissions factor. FuelEU well-to-wake emissions are calculated in two separate parts, well-to-tank and tank-to-wake, then combined.

The initiative includes the release of carbon dioxide, methane, and nitrous oxide in its definition of 'greenhouse gas emissions,' and defines 'zero-emission technology' as a "technology that does not imply, when used to provide energy, the release of the following greenhouse gasses and air pollutants into the atmosphere by ships: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur oxide (SO_x), nitrogen oxide (NO_x) and particulate matter (PM)." GHGs are calculated and reported as CO_2e (GWP100).

FuelEU will include methane slip in the CO_2e methodology starting in 2025, which is calculated as a percentage of the mass of fuel used by the engine. The FuelEU methane slip factors for vessels using fuels such as LNG are 0.2% for HPDF, 1.7% for LPDF 2-S, 3.1% for LPDF 4-S, and 2.32% for LBSI. These values are calculated at 50% of the engine load (European Commission, 2021). The inclusion of methane slip in FuelEU will help account for carbon emissions currently overlooked at the EU level, resulting from the growing usage of LNG as ship fuel.

5. Proposed Measures for Regulating and Reporting Methane Emissions

5.1. Proposed Regulations

While there are currently few regulations specifically targeting methane emissions from ships set to be enforced and no existing policies related to reducing methane slip, working groups are formulating policies for the future. Documents submitted to the Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG) at the 74th session of the Marine Environment Protection Committee (MEPC), included an approach to "further consider concrete proposals to reduce methane slip and emissions of VOCs" (Healy, 2020). Additionally, amendment proposals to the EU regulation 2019/942 call for regulations to reduce methane emissions in LNG terminals and ships in the energy and petrochemical sectors, and the IMO initial strategy on reduction of GHG emissions considers analyzing measures to address methane emissions in their candidate short term measures for reducing greenhouse gas emissions (Healy, 2020; Sardone & Paulus, 2022). To effectively limit GHG emissions to levels that align with targets set out by the IMO initial strategy on reduction of GHG emissions, the Global Methane Pledge, and other policies and commitments and reduce harmful air pollutants, non-governmental organizations and researchers have suggested strengthening emissions regulations and enacting monitoring and reporting requirements on methane emissions.

Critics of current global policies, such as IMO's EEDI and SEEMP, urge that the shipping industry needs more aggressive regulation on LNG usage and methane emissions (Lindstad et al., 2020; Maersk Mckinney Moller Center for Zero Carbon Shipping, 2022). Based on its hydrogen-to-carbon ratio, LNG fuels result in a 20-30% reduction in carbon dioxide emissions from combustion compared to liquid fossil fuels. While LNG may comply with existing EE[D/X]I fuel consumption requirements and MARPOL Annex VI air pollutant (NO_x and SO_x) regulations, the carbon reduction benefit is likely more than offset due to methane slip (Lindstad & Rialland, 2020). Additionally, total fuel cycle emissions, such as indirect (well-to-tank) emissions, impact GHG emissions from activities and may need to be regulated to properly address total GHG emissions (Maersk Mckinney Moller Center for Zero Carbon Shipping, 2022).

Other suggested policies and regulations include: implementing reporting and on-board monitoring of methane emissions and methane slip; monitoring and regulating the production and distribution chain of the fuel; setting explicit methane emissions reduction targets; encouraging the transition to low-emission fuels and technologies through emissions pricing, quantity control, and subsidies for decarbonization; improving engine technologies and fueling infrastructure to reduce occurrences of methane slip; and assigning penalties for non-compliance of regulations. Methane regulatory and reporting approaches could be modeled after MARPOL Annex VI NO_x and SO_x regulations (Balcombe et al., 2019; Lindstad & Rialland, 2020; Maersk Mckinney Moller Center for Zero Carbon Shipping, 2022).

5.2. U.S. Clean Shipping Act

The U.S. Clean Shipping Act (CSA) was introduced in June 2023 to formulate a plan to eliminate GHG emissions from shipping companies engaged in business with the United States. The CSA intends to mitigate the impacts of shipping on human and environmental health and tackle issues of environmental injustice. The introduction of the CSA aims to empower the Environmental Protection Agency (EPA) with the authority to regulate carbon intensity standards for maritime fuel (CA 42nd District, 2023). The bill includes methane in the list of GHGs.

The CSA amends the Clean Air Act (CAA) to establish carbon intensity standards of fuels used by vessels. The amendments include setting carbon intensity limits and enacting monitoring and reporting requirements. The carbon intensity reductions are as follows: at least 20% from 2027, at least 45% from 2030, at least 80% from 2035, and 100% from 2040 onwards. The carbon intensity reductions are calculated in relation to a baseline of the average carbon intensity of the fuel used by all vessels on covered voyages in calendar year 2024, where 'carbon intensity' means "the quantity of lifecycle greenhouse gas emissions per unit of fuel energy, expressed in grams of carbon dioxide equivalent per megajoule." Lifecycle greenhouse gas emissions include well-to-wake analysis as well as significant indirect emissions, per the CAA. Coverage voyages are described as "any voyage of a vessel for the purpose of transporting passengers or cargo for commercial purposes."

Methods for monitoring emissions will be established and must be consistent, and reporting requirements will be based on existing EU and the IMO reporting schemes. For each calendar year, a vessel must report the carbon intensity and amount of the fuel used for each covered voyage and the total greenhouse gas emissions measured in CO_2e for all covered voyages. The administrator must publish an annual report no later than 6 months after each calendar year that compiles the vessel data reported including explanations of CO_2e of emissions of vessels on covered voyages and the carbon intensity of fuels used by vessels (House of Representatives, 2023).

5.3. Policy Suggestions

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5.4. Reporting

Addressing the lack of transparency in methane slip reporting requires the establishment of solid guidelines. Aforementioned, there is a lack of standardization regarding emission calculations methodologies and units used in methane emission estimates. Manufacturers seldom disclose their methods, and their data can deviate from the findings of independent studies or shipowner reporting, likely due to variations in methods and real-world operating conditions.

Differences in units used to describe methane slip from LNG engines can hinder cross-examination of results. While useful for comparison to a primary GHG, CO_2-equivalency numbers are skewed by the GWP scale selected (i.e. EPA or IPCC) and are subject to change over time (Balcombe et al., 2019; United States Environmental Protection Agency, 2023). Reports regarding abatement practices are often reported in percent reductions, which can distort the effectiveness of the assessment, especially with respect to costs. Furthermore, the majority of after treatment studies focus on LPDF 4-S engines, which is nonindicative of how the technology may work on other engine types. As LPDF 2-S have been a preferred choice for large container fleets choosing LNG, there is extra guesswork for these vessel owners. This cannot be changed by policy, but is a recommendation for future studies to cover more than one engine type. Thus, a considerable policy recommendation would standardize the reporting in g/kWh, with transparent methodology, and leave other units to be supplemental to its discussions.

6. Conclusions

The global growth of LNG as a marine fuel necessitates the mitigation of its consequential methane emissions. Current policies and regulations fail to consider the actual methane emissions associated with the usage of LNG in shipping, which may contribute to the inaccurate labeling of LNG as a low-carbon fuel. With the sector's preference for the LPDF engine, the current state of this engine technology results in significant unburned methane slip into the atmosphere. The management of lifecycle methane emissions from LNG requires urgent focus from manufacturers, regulators, researchers, vessel owners, and maritime stakeholders alike. This report summarized the engines, mitigation strategies, and policies relevant to LNG and its climate concerns.

As vessel owners determine whether or not to choose LNG, they must consider that while it meets present-day emission standards, when used with LPDF engines, the life-cycle GHG emissions are not reduced compared to conventional fuels due to significant methane emissions. Stricter future standards may limit the feasibility of LNG as transition fuel. At the policy level, the addition of methane in GHG emissions calculations and the inclusion of methane slip in reporting requirements will help close the gap between emissions calculations and actual emissions. Fuel choices by ship owners will follow the trend in policy, and shipowners may eventually be steered away from LNG.

Advancements in engine design by the manufacturer to reduce empty volume, improve combustion efficiency, and enhance performance at low loads may not only reduce methane emissions, but also result in fuel cost-savings and improved operational performance. Additional incentives of methane reduction may provide motivation for stakeholders, for which exhaust gas recirculation after treatment technologies demonstrated fuel savings to offset investment costs. However, without political intervention a conflict between environment and economy may deter other technologies and cleaner pathways.

7. References

Al-Douri, A., Alsuhaibani, A. S., Moore, M., Nielsen, R. B., El-Baz, A. A., & El-Halwagi, M. M. (2021). Greenhouse gases emissions in liquified natural gas as a marine fuel: Life cycle analysis and reduction potential. *The Canadian Journal of Chemical Engineering*, *100*(6), 1178–1186. https://doi.org/10.1002/cjce.24268

Alturki, Eng. W. (2017). Four-Stroke and Two-Stroke Marine Engines Comparison and Application. *International Journal of Engineering Research and Applications*, *07*(04), 49–56. https://doi.org/10.9790/9622-0704034956

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, *182*, 72–88. https://doi.org/10.1016/j.enconman.2018.12.080

Balcombe, P., Heggo, D. A., & Harrison, M. (2022). Total Methane and CO2 Emissions from Liquefied Natural Gas Carrier Ships: The First Primary Measurements. *Environmental Science & Technology*, *56*(13), 9632–9640. https://doi.org/10.1021/acs.est.2c01383

Barba, C., Dyckmans, J., Förster, J., & Schnekenburger, T. (2017). Natural gas-Diesel dual fuel for commercial vehicle engines. In J. Liebl & C. Beidl (Eds.), *Internationaler Motorenkongress 2017* (pp. 391–407). Springer Fachmedien. https://doi.org/10.1007/978-3-658-17109-4_23

Bui, K. Q., Perera, L. P., & Emblemsvåg, J. (2022). Life-cycle cost analysis of an innovative marine dual-fuel engine under uncertainties. *Journal of Cleaner Production*, *380*, 134847. https://doi.org/10.1016/j.jclepro.2022.134847

Bunker Index. (2014). Maersk ships approach 3,500 hours of EGR operation. *Bunker Index*. https://www.bunkerindex.com/news/article.php?article_id=12988

Burke, J. (2023, June 7). MAN's new auxiliary engine 'slashes' methane slip. *Diesel & Gas Turbine Worldwide*. https://www.dieselgasturbine.com/news/man-s-new-auxiliary-engine-slashes-methane-slip/8029504.article

CA 42nd District. (2023, June 8). *Congressman Robert Garcia Introduces the 'Clean Shipping Act' to Address Port Pollution and Champion Environmental Justice for Local Port Communities*. Congressman Robert Garcia Press Releases. http://robertgarcia.house.gov/media/press-releases/congressman-robert-garcia-introduces-clean-shipping-act-address-port-pollution

Chart Industries. (2013). *LNG ISO Intermodal Containers*. Chart Inc. https://files.chartindustries.com/14732510_LNG_ISO.pdf

Chavan, Y., & Sewatkar, C. (2019). *Two Stroke Gasoline Direct Injection Strategy Optimization Using 1D and 3D Analysis Tool* (SAE Technical Paper No. 2019-26–0311). SAE International. https://doi.org/10.4271/2019-26-0311

Climate & Clean Air Coalition. (2021). *Global Methane Pledge*. https://www.ccacoalition.org/en/resources/global-methane-pledge

Climate & Clean Air Coalition. (2023). *Fast action on methane to keep a 1.5°C future within reach*. Global Methane Pledge. https://www.globalmethanepledge.org/

Comer, B., O'Malley, J., Osipova, L., & Pavlenko, N. (2022). *Comparing the future demand for, supply of, and life-cycle emissions from bio, synthetic, and fossil LNG marine fuels in the European Union*. International Council on Clean Transportation. https://theicct.org/publication/lng-marine-fuel-sep22/

Council of the European Union. (2023, June 2). *Fit for 55*. European Green Deal. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

DNV. (n.d.). *LNG as marine fuel: Environmental performance*. DNV, Why LNG as Fuel. Retrieved July 12, 2023, from https://www.dnv.com/maritime/insights/topics/lng-as-marine-fuel/environmental-performance.html

Eilts, P. (2018). LNG as Future Fuel Option. *MTZ Industrial*, *8*(1), 66. https://doi.org/10.1007/s40353-018-0004-y

Erbach, G. (2020). *Monitoring, reporting and verification of CO2 emissions from maritime transport* (Briefing PE 642.224). European Parliamentary Research Service.

https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/642224/EPRS_BRI(2019)642224_EN.pdf

Erbach, G., & Foukalová, N. (2023). *Review of the EU ETS* (Briefing PE 698.890). European Parliamentary Research Service. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698890/EPRS_BRI(2022)698890_EN.pdf

European Commission. (2021). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC* (COM/2021/562 final, Document 52021PC0562). European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0562

European Commission. (2023). *Inclusion of maritime emissions in EU Emissions Trading System (ETS).* Reducing Emissions from the Shipping Sector. https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en

European Federation for Transport and Environment. (2022, April 13). Methane escaping from 'green' gas-powered ships fuelling climate crisis—Investigation. *Transport & Environment*. https://www.transportenvironment.org/discover/methane-escaping-from-green-gas-powered-ships-fuelling-climate-crisis-investigation/

European Maritime Safety Agency. (2023). *The EU Maritime Profile. Section 2: The maritime cluster in the EU*. European Union. https://www.emsa.europa.eu/eumaritimeprofile/section-2-the-eu-maritime-cluster.html

European Parliament. (2023, March 23). *Fit for 55: Deal on new EU rules for cleaner maritime fuels*. https://www.europarl.europa.eu/news/en/press-room/20230320IPR77909/fit-for-55-deal-on-new-eu-rules-for-cleaner-maritime-fuels

European Parliament, & Council of the European Union. (2023). *Regulation (EU) 2023 / Of the European Parliament and of the Council ... Amending Regulation (EU) 2015/757* (2021/0211(COD)-MRV). European Union. https://doi.org/10.5040/9781782258674

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauserhof, E., Schim van der Loeff, W., Smith, T., Zhang, Y., Kosaka, H., Adachi, M., Bonello, J. M., Galbraith, C., Gong, Z., Hirata, K., Hummels, D., Kleijn, A., Lee, D. S., Liu, Y., … Xing, H. (2020). *Fourth Greenhouse Gas Study 2020* (Full Report IV). International Maritime Organization. https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

Farshi, A., & Shiralizadeh, P. (2015). Sulfur Reduction of Heavy Fuel Oil by Oxidative Desulfurization (ODS) Method. *Petroleum & Coal*, *57*(3), 295–302.

Fink, G., Jud, M., & Sattelmayer, T. (2018). Influence of the Spatial and Temporal Interaction Between Diesel Pilot and Directly Injected Natural Gas Jet on Ignition and Combustion Characteristics. *Journal of Engineering for Gas Turbines and Power*, *140*(10), 102811.

Gordon, S. (2023, January 16). Green Technology Tracker: January 2023. *Clarksons Research*. https://insights.clarksons.net/green-technology-tracker-january-2023/

Grönholm, T., Mäkelä, T., Hatakka, J., Jalkanen, J.-P., Kuula, J., Laurila, T., Laakso, L., & Kukkonen, J. (2021). Evaluation of Methane Emissions Originating from LNG Ships Based on the Measurements at a Remote Marine Station. *Environmental Science & Technology*, *55*(20), 13677–13686. https://doi.org/10.1021/acs.est.1c03293

Healy, S. (2020). *Greenhouse gas emissions from shipping: Waiting for concrete progress at IMO level* (Briefing PE 652.754). Policy Department for Economic, Scientific and Quality of Life Policies. https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/652754/IPOL_BRI(2020)652754_EN.pdf

Hiltner, J., Loetz, A., & Fiveland, S. (2016). *Unburned hydrocarbon emissions from lean burn natural gas engines sources and solutions.* CIMAC Congress.

Hountalas, T. D., Founti, M., & Zannis, T. C. (2023). Experimental Investigation to Assess the Performance Characteristics of a Marine Two-Stroke Dual Fuel Engine under Diesel and Natural Gas Mode. *Energies*, *16*(8). https://doi.org/10.3390/en16083551

House of Representatives. (2023). *118th Congrees 1st Session to amend the Clean Air Act to provide for the establishment of standards to limit the carbon intensity of the fuel used by certain vessels, and for other purposes* (No. 117H8336). US House of Representatives. https://robertgarcia.house.gov/sites/evo-subsites/robertgarcia.house.gov/files/evo-media-document/garcro_029_xml.pdf

Hult, C., & Winnes, H. (2020). *Emission factors for methane engines on vehicles and ships, with a focus on methane emissions* (8). Swedish Environmental Research Institute. https://www.diva-portal.org/smash/get/diva2:1601009/FULLTEXT01.pdf

ICF International. (2009). *Costs of Emission Reduction Technologies for Category 3 Marine Engines* (EPA-420-R-09-008). The U.S. Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100GPCR.PDF?Dockey=P100GPCR.PDF

International Energy Agency. (2022). *Global Methane Tracker 2022, Methane and climate change*. https://www.iea.org/reports/global-methane-tracker-2022/methane-and-climate-change

International Maritime Organization. (n.d.). *Improving the energy efficiency of ships*. Retrieved July 12, 2023, from https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx

International Maritime Organization. (2019, December 20). IMO 2020—Cleaner shipping for cleaner air, Global limit on sulphur in ships' fuel oil reduced from 01 January 2020. *International Maritime Organization*. https://www.imo.org/en/MediaCentre/PressBriefings/pages/34-IMO-2020-sulphur-limit-.aspx

Jääskeläinen, H. (2020). Natural Gas Engines. *DieselNet*. https://dieselnet.com/tech/engine_natural-gas.php

Jääskeläinen, H., & Khair, M. K. (2022). Exhaust Gas Recirculation. *DieselNet*. https://dieselnet.com/tech/engine_egr.php

Jaganathan, J., & Khasawneh, R. (2021, September 3). UPDATE 1-Off the boil: LNG tankers burn more oil as gas prices soar. *Reuters*. https://www.reuters.com/article/global-tankers-lng-idUSL1N2Q50U0

Järvi, A. (2010). *Methane slip reduction in Wärtsilä lean burn gas engines.* CIMAC Congress.

Jensen, M. V., Cordtz, R. F., & Schramm, J. (2021). Numerical analysis of methane slip source distribution in a four-stroke dual-fuel marine engine. *Journal of Marine Science and Technology*, *26*(2), 606–617. https://doi.org/10.1007/s00773-020-00760-3

Johnson, D. R., Heltzel, R., Nix, A. C., Clark, N., & Darzi, M. (2017). Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development. *Applied Energy*, *206*, 739–750. https://doi.org/10.1016/j.apenergy.2017.08.234

Khoa, N. X., & Lim, O. (2022). Influence of Combustion Duration on the Performance and Emission Characteristics of a Spark-Ignition Engine Fueled with Pure Methanol and Ethanol. *ACS Omega*, *7*(17), 14505–14515. https://doi.org/10.1021/acsomega.1c05759

Kochunni, S. K., & Chowdhury, K. (2020). Zero methane loss in reliquefaction of boil-off gas in liquefied natural gas carrier ships by using packed bed distillation in reverse Brayton system. *Journal of Cleaner Production*, *260*, 121037. https://doi.org/10.1016/j.jclepro.2020.121037

Königsson, F., Kuyper, J., Stalhammar, P., & Angstrom, H.-E. (2013). The Influence of Crevices on Hydrocarbon Emissions from a Diesel-Methane Dual Fuel Engine. *SAE International Journal of Engines*, *6*(2), 751–765. https://doi.org/10.4271/2013-01-0848

Krivopolianskii, V., Valberg, I., Stenersen, D., Ushakov, S., & Æsøy, V. (2019). Control of the combustion process and emission formation in marine gas engines. *Journal of Marine Science and Technology*, *24*(2), 593–611. https://doi.org/10.1007/s00773-018-0556-0

Kuittinen, N., Heikkilä, M., & Lehtoranta, K. (2023). *Review of Methane Slip from LNG Engines* (HORIZON-CL5-2021-D5-01-12; D1.1 New Generation Marine Engines and Retrofit Solitions to Achieve Methane Abatement Flexibility). The GREEN RAY Project. https://greenray-project.eu/wp-content/uploads/2023/04/D1.1_Review_of_methane_slip_from_LNG_engines.pdf

Latarche, M. (2021). Chapter Three—Dual-fuel and gas engines. In *Pounder's Marine Diesel Engines and Gas Turbines (Tenth Edition)* (pp. 59–86). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-08-102748-6.00003-7

Lehtoranta, K., Koponen, P., Vesala, H., Kallinen, K., & Maunula, T. (2021). Performance and Regeneration of Methane Oxidation Catalyst for LNG Ships. *Journal of Marine Science and Engineering*, *9*(2), 111.

Lieberman, D., & Doherty, S. (2008). *Renewable Energy as a Hedge Against Fuel Price Fluctuation: How to Capture the Benefits* [Background paper]. Commission for Environmental Cooperation. http://www.cec.org/files/documents/publications/2360-renewable-energy-hedge-against-fuel-price-fluctuation-en.pdf

Lindstad, E., Eskeland, G. S., Rialland, A., & Valland, A. (2020). Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel. *Sustainability*, *12*(21), Article 21. https://doi.org/10.3390/su12218793

Lindstad, E., & Rialland, A. (2020). LNG and Cruise Ships, an Easy Way to Fulfil Regulations—Versus the Need for Reducing GHG Emissions. *Sustainability*, *12*(5), Article 5. https://doi.org/10.3390/su12052080

Lowell, D., Wang, H., & Lutsey, N. (2013). *Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping* [White Paper]. International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2021/06/ICCTwhitepaper_MarineLNG_130513.pdf

Maersk Mckinney Moller Center for Zero Carbon Shipping. (2022). *Reducing methane emissions onboard vessels: An overview of methane emission sources and levels onboard vessels and the technologies, solutions, and regulatory drivers that can help reduce them* (Part Two; Onboard Vessel Solutions). Maersk Mckinney Moller Center. https://cms.zerocarbonshipping.com/media/uploads/publications/Reducing-methane-emissions-onboard-vessels.pdf

MAN Energy Solutions. (n.d.). LNG for the maritime energy transition. *MAN Energy Solutions*. Retrieved July 10, 2023, from https://www.man-es.com/marine/strategic-expertise/future-fuels/lng

MAN Energy Solutions. (2022). *ME-GA - The latest dual-fuel MAN B&W two-stroke engine*. MAN Energy Solutions.

Manouchehrinia, B., Dong, Z., & Gulliver, T. A. (2020). Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada. *Energy Reports*, *6*, 802–812. https://doi.org/10.1016/j.egyr.2020.03.016

Marine Environment Protection Committee. (2018). *Initial IMO Strategy on Reduction of GHG Emissions From*

Ships (Annex 11, MEPC 72/17/Add.1). International Maritime Organization. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Resolution%20MEPC.304%2872%29_E.pdf

Marine Environment Protection Committee. (2021a). *2021 Guidelines on Survey and Certification of the Attained Energy Efficiency Existing Ship Index (EEXI)* (Annex 8, MEPC 76/15/Add.2). International Maritime Organization. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.334(76).pdf

Marine Environment Protection Committee. (2021b). *Resolution MEPC.328(76). Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto* (Annex 1, MEPC 76/15/Add.1). International Maritime Organization. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.328(76).pdf

Marine Environment Protection Committee. (2022). *Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2021)* (IMO Data Collection System (DCS) MEPC 79/6/1). International Maritime Organization. https://www.imo.org/en/OurWork/Environment/Pages/Data-Collection-System.aspx

Miana, M., Legorburo, R., Díez, D., & Hwang, Y. H. (2016). Calculation of Boil-Off Rate of Liquefied Natural Gas in Mark III tanks of ship carriers by numerical analysis. *Applied Thermal Engineering*, *93*, 279–296. https://doi.org/10.1016/j.applthermaleng.2015.09.112

Milne, R. (2023, May 4). Maersk warns of 'radically changed' world as profits tumble. *Financial Times*. https://www.ft.com/content/c9808a10-a9d9-45ee-ac80-3da93172f290

Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J. F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., & Zhang, H. (2013). *Global Warming Potential Values*. Greenhouse Gas Protocol.

https://ww2.arb.ca.gov/sites/default/files/2018-06/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

Nemati, A., Ong, J. C., Pang, K. M., Mayer, S., & Walther, J. H. (2022). A numerical study of the influence of pilot fuel injection timing on combustion and emission formation under two-stroke dual-fuel marine engine-like conditions. *Fuel*, *312*, 122651. https://doi.org/10.1016/j.fuel.2021.122651

NEPIA. (2019). *LNG as a marine fuel*. NorthStandard. https://www.nepia.com/publications/lng-as-a-marine-fuel/

Ohashi, I. (2015). *Dual-Fuel Marine Engine (Highly Reliable Environmentally Friendly Engine)* (YANMAR Technical Review). YANMAR. https://www.yanmar.com/global/about/technology/technical_review/2015/0727_2.html

Ottinger, N., Veele, R., Xi, Y., & Liu, Z. G. (2015). Desulfation of Pd-based oxidation catalysts for lean-burn natural gas and dual-fuel applications. *SAE International Journal of Engines*, *8*(4), 1472–1477.

Parfomak, P. W., Frittelli, J., Lattanzio, R. K., & Ratner, M. (2019). *LNG as a Maritime Fuel: Prospects and Policy* (No. R45488). Congressional Research Service. https://sgp.fas.org/crs/misc/R45488.pdf

Park, H., Shim, E., Lee, J., Oh, S., Kim, C., Lee, Y., & Kang, K. (2022). Large–squish piston geometry and early pilot injection for high efficiency and low methane emission in natural gas–diesel dual fuel engine at high–load operations. *Fuel*, *308*, 122015. https://doi.org/10.1016/j.fuel.2021.122015

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel* (Working Paper 2020-02). International Council on Clean Transportation. https://theicct.org/publication/the-climate-implications-of-using-lng-as-a-marine-fuel/

Peng, W., Yang, J., Corbin, J., Trivanovic, U., Lobo, P., Kirchen, P., Rogak, S., Gagné, S., Miller, J. W., & Cocker, D. (2020). Comprehensive analysis of the air quality impacts of switching a marine vessel from diesel fuel to natural gas. *Environmental Pollution*, *266*, 115404. https://doi.org/10.1016/j.envpol.2020.115404

Pescatori, A., & Stuermer, M. (2022, December). From Abundance to Thirst. *International Monetary Fund*. https://www.imf.org/en/Publications/fandd/issues/2022/12/from-abundance-to-thirst-Pescatori-

Stuermer

Qu, J., Feng, Y., Xu, G., Zhang, M., Zhu, Y., & Zhou, S. (2022). Design and thermodynamics analysis of marine dual fuel low speed engine with methane reforming integrated high pressure exhaust gas recirculation system. *Fuel*, *319*, 123747. https://doi.org/10.1016/j.fuel.2022.123747

Riviera Newsletters. (2018, March 9). More LNG owners choose low-pressure, two-stroke engines. *Riviera*. https://www.rivieramm.com/opinion/opinion/more-lng-owners-choose-low-pressure-two-stroke-engines-25440

Rochussen, J., Jaeger, N. S. B., Penner, H., Khan, A., & Kirchen, P. (2023). Development and demonstration of strategies for GHG and methane slip reduction from dual-fuel natural gas coastal vessels. *Fuel*, *349*, 128433. https://doi.org/10.1016/j.fuel.2023.128433

Roman-White, S., Rai, S., Littlefield, J., Cooney, G., & Skone, T. J. (2019). *Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update* (DOE/NETL-2019/2041). National Energy Technology Laboratory. https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf

Ross, J. (2022, May 4). Visualizing Historical Oil Prices (1968-2022). *Advisor Channel*. https://advisor.visualcapitalist.com/historical-oil-prices/

Sachgau, O. (2022). Can methane slip be controlled? Interview with MAN Energy Solutions expert Gunnar Stiesch. *MAN Energy Solutions*. https://www.man-es.com/discover/can-methane-slip-be-controlled

Sardone, S., & Paulus, J. (2022). *Methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942, Proposal for a regulation (COM(2021)0805 – C9-0467/2021 – 2021/0423(COD))* (PE736.476v01-00; Amendments 41-149). European Parliament. https://www.europarl.europa.eu/doceo/document/CJ10-AM-737438_EN.pdf

Schramm, J. (2020). *Methane Emission Control* (Annex 51-1). IEA-AMF, Advanced Motor Fuels Technology Collaboration Programme. https://iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_51.pdf

Schuller, O., Kupferschmid, S., Hengstler, J., & Whitehouse, S. (2021). *2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel* (V1.0). Sphera, on behalf of SEA-LNG and SGMF.

SEA-LNG. (2022a). *LNG as a Marine Fuel: The Retrofit Investment Opportunity*. SEA-LNG. https://sea-lng.org/wp-content/uploads/2022/08/VLCC_Retrofit_Investment_Case_Study.pdf

SEA-LNG. (2022b). *The Role of Bio-LNG in the Decarbonisation of Shipping: Report Key Findings*. SEA-LNG. https://sea-lng.org/wp-content/uploads/2022/10/SEA-LNG_BioLNG-Study-Key-Findings-Document_October-2022.pdf

Sharafian, A., Blomerus, P., & Mérida, W. (2019). Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential. *Energy Policy*, *131*, 332–346. https://doi.org/10.1016/j.enpol.2019.05.015

Ship & Bunker News Team. (2023, June 15). MSC Cruises to Take on Synthetic LNG From Gasum. *Ship & Bunker*. https://shipandbunker.com/news/world/356231-msc-cruises-to-take-on-synthetic-lng-from-gasum

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D. S., Ng, S., Agrawal, A., Winebrake, J. J., Hoen, M., … Pandey, A. (2015). *Third IMO Greenhouse Gas Study 2014* [Executive Summary and Final Report]. International Maritime Organization. https://www.imo.org/en/ourwork/environment/pages/greenhouse-gas-studies-2014.aspx

Sommer, D. E., Yeremi, M., Son, J., Corbin, J. C., Gagné, S., Lobo, P., Miller, J. W., & Kirchen, P. (2019). Characterization and Reduction of In-Use CH4 Emissions from a Dual Fuel Marine Engine Using Wavelength Modulation Spectroscopy. *Environmental Science & Technology*, *53*(5), 2892–2899. https://doi.org/10.1021/acs.est.8b04244

Stenersen, D., & Thonstad, O. (2017). *GHG and NOx emissions from gas fueled engines* (OC2017 F-108-Unrestricted). SINTEF Ocean AS.

Stoppard, M. (2015, April 7). Low Oil Prices and LNG: Withstanding the Rough Seas Ahead. *Global Gas at IHS Energy, Wall Street Journal*. http://online.wsj.com/ad/article/ceraweek-low-oil-prices-lng-withstanding-rough-seas-ahead

Stoumpos, S., Theotokatos, G., Boulougouris, E., Vassalos, D., Lazakis, I., & Livanos, G. (2018). Marine dual fuel engine modelling and parametric investigation of engine settings effect on performance-emissions trade-offs. *Ocean Engineering*, *157*, 376–386. https://doi.org/10.1016/j.oceaneng.2018.03.059

Swanson, C., Levin, A., Stevenson, A., Mall, A., & Spencer, T. (2020). *Sailing to Nowhere: Liquefied Natural Gas is not an Effective Climate Strategy* (R: 20-08-A). Natural Resources Defense Council. https://www.nrdc.org/sites/default/files/sailing-nowhere-liquefied-natural-gas-report.pdf

Taghi Zarrinkolah, M., & Hosseini, V. (2023). Methane slip reduction of conventional dual-fuel natural gas diesel engine using direct fuel injection management and alternative combustion modes. *Fuel*, *331*, 125775. https://doi.org/10.1016/j.fuel.2022.125775

The LEVON Group. (2015). *Liquefied Natural Gas (LNG) Operations: Consistent Methodology for Estimating Greenhouse Gas Emissions* (V1.0). Energy American Petroleum Institute. https://www.api.org/~/media/files/ehs/climate-change/api-lng-ghg-emissions-guidelines-05-2015.pdf

The Norwegian Tax Administration. (2023). *NOx tax*. The Norwegian Tax Administration. https://www.skatteetaten.no/en/rates/nox-tax/

The U.S. Department of Energy. (2021, December 2). DOE Awards $35 Million for Technologies to Reduce Methane Emissions. *Energy.Gov*. https://www.energy.gov/articles/doe-awards-35-million-technologies-reduce-methane-emissions

Thomson, H., Corbett, J. J., & Winebrake, J. J. (2015). Natural gas as a marine fuel. *Energy Policy*, *87*, 153–167. https://doi.org/10.1016/j.enpol.2015.08.027

United Nations. (1997). *7. A Kyoto Protocol to the United Nations Framework Convention on Climate Change*. United Nations Treaty Collection. https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-7-a&chapter=27&clang=_en

United Nations Climate Change. (n.d.). *Global Warming Potentials (IPCC Second Assessment Report)*. United Nations Climate Change. Retrieved July 10, 2023, from https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials

United States Environmental Protection Agency. (2006). *Installing Vapor Recovery Units on Storage Tanks*. Lessons Learned from Natural Gas STAR Partners. https://www.epa.gov/sites/default/files/2016-06/documents/ll_final_vap.pdf

United States Environmental Protection Agency. (2022). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020* (EPA 430-R-22-003). The U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf

United States Environmental Protection Agency. (2023, April 18). *Understanding Global Warming Potentials* [Overviews and Factsheets]. United States Environmental Protection Agency. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

Urdahl, K. (2023, February 22). Regional sulphur emission limits at a glance. *Gard, Managing Risk and Its Consequences*. https://www.gard.no/web/updates/content/29212584/regional-sulphur-emission-limits-at-a-glance

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

Van Roy, W., Merveille, J. B., Van Nieuwenhove, A., Scheldeman, K., & Maes, F. (2023). Policy Recommendations for International Regulations Addressing Air Pollution from Ships. *Submitted for Publication to Marine Policy on June 06, 2023*.

Wankhede, A. (2021, April 21). Why 2-stroke Main Engines are Used over 4-stroke on Ships? *Marine Insight*. https://www.marineinsight.com/main-engine/why-2-stroke-engines-are-used-more-commonly-than-4-stroke-on-ships/

Wärtsilä. (n.d.-a). *Boil-off rate (BOR)*. WÄRTSILÄ Encyclopedia of Marine and Energy Technology. Retrieved July 10, 2023, from https://www.wartsila.com/encyclopedia/term/boil-off-rate-(bor)

Wärtsilä. (n.d.-b). *Greenhouse gas (GHG) emissions reduction upgrades*. Wärtsilä. Retrieved July 10, 2023, from https://www.wartsila.com/services-catalogue/engine-services-4-stroke/ghg-emissions-reduction-upgrades

Wärtsilä. (2018, August 27). Shipping in 2020: Choosing the right fuel and propulsion system. *Wärtsilä*. https://www.wartsila.com/insights/article/shipping-in-2020-choosing-the-right-fuel-and-propulsion-system

Win GD. (2020). *Marine Installation Manual: RT-flex50DF*. Winterthur Gas & Diesel Ltd.

Winnes, H., Fridell, E., Ellis, J., Forsman, B., Ramsay, W., & Westermark, H. (2020). *Aftertreatment of methane slip from marine gas engines*. Lighthouse Swedish Maritime Competence Centre. https://www.diva-portal.org/smash/get/diva2:1746960/FULLTEXT01.pdf

Yang, R., Theotokatos, G., & Vassalos, D. (2020). Parametric investigation of a large two-stroke marine high-pressure direct injection engine by using computational fluid dynamics method. *Journal of Engineering for the Maritime Environment*, *234*(3). https://doi.org/10.1177/1475090219895639

Zannis, T. C., Katsanis, J. S., Christopoulos, G. P., Yfantis, E. A., Papagiannakis, R. G., Pariotis, E. G., Rakopoulos, D. C., Rakopoulos, C. D., & Vallis, A. G. (2022). Marine Exhaust Gas Treatment Systems for Compliance with the IMO 2020 Global Sulfur Cap and Tier III NOx Limits: A Review. *Energies*, *15*(10), Article 10. https://doi.org/10.3390/en1510363