COLLABORATORY
TO ADVANCE METHANE SCIENCE

SCIENTIFIC INSIGHTS

First Primary Measurement of Emissions from Liquefied Natural Gas (LNG) Ships

Background and Objectives

Methane is the second most prevalent greenhouse gas (GHG) contributing to man-made global warming. Over a 100-year time horizon, methane possesses as much as 28 times the Global Warming Potential (GWP) of carbon dioxide (CO_2).[1] As the world moves to curb global temperature rise to 1.5 or 2°C, aggressive mitigation measures are growing increasingly urgent.

In 2020, natural gas systems were the second largest anthropogenic cause of methane emissions in the United States, accounting for 25.4% of total methane emissions (164.9 MMT CO_2eq)[2]. While there has been significant research and development of measurement technologies to identify and quantify methane emissions in natural gas systems, no previous studies have been done around methane emissions on LNG ships.

In this study, the Collaboratory to Advance Methane Science (CAMS) supported researchers from Queen Mary University of London (QMUL) and SLR International in a first-of-its-kind study to directly measure methane and carbon dioxide emissions of an operating LNG transport vessel. With global LNG demand expected to double over the next 20 years, LNG plays an increasingly critical role in international gas markets.[3] Yet until now, limited attention has been paid to the direct measurement of emissions from LNG shipping. These first-of-their-kind measurements were performed on the Gaslog Galveston LNG carrier—owned and operated by Gaslog Ltd. and chartered by Cheniere Energy Inc.—during a roundtrip voyage between Corpus Christi, Texas and Zeebrugge, Belgium.

The objective of the CAMS study was to identify and quantify the methane and carbon dioxide emissions associated with an LNG carrier using direct measurements, with the aim of identifying the key contributors to total emissions and understanding the factors that inform mitigation strategies. Full details of the study are described in the peer-reviewed paper (Balcombe et al. 2022) published recently in the Journal of Environmental Science & Technology.[4]

1 *Based on IPCC AR6 GWP Impacts.*
2 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 – Executive Summary (epa.gov)*
3 *Wood Mackenzie, "Prices, FIDs and the energy transition: three key factors for global LNG," July 29, 2021. https://www.woodmac.com/news/opinion/prices-fids-and-the-energy-transition-three-key-factors-for-global-lng/*
4 *Balcombe et al., Total Methane and CO_2 Emissions from Liquefied Natural Gas Carrier Ships: The First Primary Measurements, Environ. Sci. Technol. 2022 (https://doi.org/10.1021/acs.*

Methodology

Measurements were carried out during loading, laden voyage, discharging, ballast voyage, and bunkering operations. With a capacity of 174,000 cubic meters, the ship used two low pressure dual fuel (LPDF) 2-stroke engines for propulsion and four dual fuel generator engines for auxiliary power production. The measurement setup was based on an inventory of all potential emission sources from the ship, with emissions categorized as exhausts, vents, and fugitive emissions. The potential sources of emissions and the corresponding measurement setup are described in Table 1.

Table 1. Sources of methane and CO_2 emissions and their measurement set-up

Source	Methane	CO_2	Measurement Setup
Main engine 1 (M1)	x	x	Fourier Transform Infrared (FTIR) continuous emission monitoring systems (CEMS)
Main engine 2 (M2)	x	x	FTIR CEMS
Generator engine 1 (G1)	x	x	FTIR CEMS
Generator engine 2 (G2)	x	x	FTIR CEMS
Generator engine 3 (G3)	x	x	FTIR CEMS
Generator engine 4 (G4)	x	x	FTIR CEMS
Gas Combustion Unit (GCU)	x	x	FTIR CEMS
Auxiliary boiler		x	Estimated using diesel combusted volume
Vent mast 1 (forward)	x		Gas concentration monitor; inline flowmeter; Optical Gas Imaging (OGI) camera
Vent mast 2	x		Gas concentration monitor; OGI camera
Vent mast 3	x		Gas concentration monitor; OGI camera
Vent mast 4	x		Gas concentration monitor; OGI camera
Engine room vent	x		OGI camera
Vents from loading/unloading	x		OGI camera
Vents from maintenance activities	x		OGI camera
Fugitives from gas-handling equipment	x		Strategic daily walking OGI surveys

After the voyage was completed, the measured and ancillary data were collected and synthesized and total methane and CO_2 emissions from the voyage were estimated using a multiparametric emissions model. Researchers then normalized emissions estimates on a per tonne delivered basis.

In-house monitoring of methane emissions—such as by targeted installation of methane CEMS to ship stacks—would provide additional assurance and help in further understanding and mitigating the emissions.

Results

On a per unit of LNG delivered basis for the ship measured, total emissions rates amounted to 104 gCO_2eq per kg LNG over a 100-year time horizon. Total GHG emissions were dominated by CO_2 emissions (4600 t CO_2), both from the main engines (45% of total GHGs) and the generator engines (18%). Of the total methane emissions (68.1 t CH4), 60% were caused by generator engines, and just under 40% of emissions were produced by main engines.

Venting and fugitive methane emissions were found to comprise a minor proportion of the total emissions. The power output of generator engines was found to be substantially lower than that of the main engines, but with higher amounts of uncombusted methane in engine exhausts, known as "methane slip." The methane slip rate—expressed as a percentage of LNG throughput—was around 2% for each of the two main engines, while methane slip rates of the generator engines ranged from just under 8% to 14%, depending on engine loads and engine exhaust temperatures.

The voyage operated on a philosophy of zero routine venting for the storage system. The small quantity of venting emissions were either from fuel switching of the engines from gas to diesel, or from testing and maintenance activities. A small amount of venting also occurred during loading and unloading while connecting and disconnecting the arms before and after LNG transfer. In addition, two fugitive leaks were found identified during the roundtrip voyage using Optical Gas Imaging ("OGI") cameras. Both leaks were found

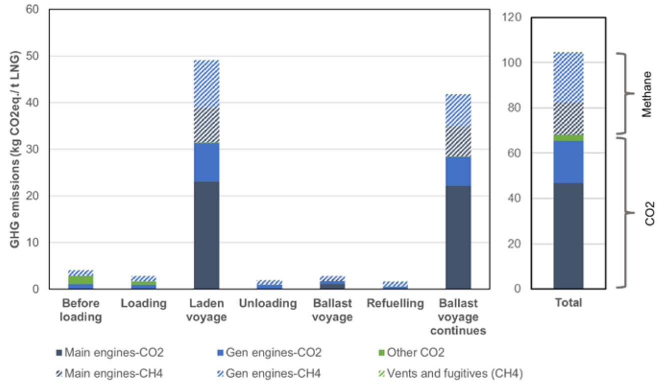

Figure 1. GHG emissions from different voyage segments, split by emission source, expressed in kgCO_2eq./ t LNG delivered, using a GWP100 of 36. 'Other CO_2' includes CO_2 emissions from the gas combustion unit and from the auxiliary boiler. Data from <link to paper>.

to be negligible (less than 0.2% of total methane emissions). The findings from the CAMS study were compared with the results of three recent studies that used similar parameters and scenarios.5 Total GHG emissions were similar in this latest study compared with previous studies, but the contribution from methane was found to be substantially higher (at about 35% of total GHG emissions on a GWP100 basis). The CAMS study represents a significant opportunity for further study and underscores the importance of considering all emissions sources to better understand emission profiles and where the greatest reductions lie.

Key Findings

The CAMS study found five key findings:

- The methane slip rates from the generator engines on the LNG carrier were higher than anticipated based on previous analysis in the existing literature (though consistent with manufacturer test data for the operators).
- Ship operations commonly ran two generators, lowering the generator load on each and consequently increasing methane slip.
- Engine load had a more pronounced effect on slip in generator engines compared with main engines.
- The correlation between methane slip and engine exhaust temperatures were governed by the air-to-fuel ratio, with higher temperatures and lower air-to-fuel ratios correlated with lower methane slip.
- Although methane slip rates of main engines broadly conformed with the manufacturer's specifications, large deviations were observed at lower engine loads.

5 *Differences of around 7%. See Roman-White et al., LNG Supply Chains: A Supplier-Specific Life-Cycle Assessment for Improved Emission Accounting, ACS Sustainable Chemistry & Engineering 2021, 9, (32), 10857-10867. See also Schuller, O. et al., Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel; thinkstep: 2019; pp 1-158.*

Improvement Opportunities

While the total GHG emissions were comparable to those found in earlier studies, the contribution of methane to total emissions was found to be higher. Moreover, around 99% of methane emissions and around 35% of total emissions (on a 100-year time horizon) resulted from engine methane slip. Reducing methane slip from engines thus presents a significant opportunity for reducing the environmental emissions and climate impacts from LNG carriers.

Since this was only the second voyage of this LNG carrier, multiple engines were operated through the journey. The average engine load across the main and generator engines was therefore only 40%. If the engines were operated closer to 80% load, methane emissions could be reduced by half. Additional opportunities to reduce methane slip exist in the ship design, engine exhaust treatment, and the way that engines are operated. For example, a new version of the XDF engine that is being used as the main propulsion engines has the potential to reduce methane slip by approximately half. Such a reduction is achieved by exhaust treatment of the main engines.

To better understand the methane and CO_2 emissions from LNG carriers, a representative sample of the global LNG fleet—with nearly 650 active vessels in 2022[6]—can provide a more comprehensive picture of emissions variations across ships, engines, storage technologies, and operators. Top-down measurements using drones or unmanned aerial vehicles (UAVs) could complement the measurements and analysis performed in the CAMS study to provide a more complete emissions estimate. In addition to independent measurement campaigns, self-monitoring of methane emissions by the industry is important. In-house monitoring of methane emissions—such as by targeted installation of methane CEMS to ship stacks—would provide additional assurance and help in further understanding and mitigating the emissions.

Around 99% of methane emissions and around 35% of total emissions (on a 100-year time horizon) resulted from engine methane slip.

The CAMS study recommends three important next steps:

1 A broader independent measurement study to understand fleet-wide methane emissions for ships with different propulsion systems and operating practices.

2 A review by operators of their operations to consider opportunities to reduce slip by increasing loading on generator engines.

3 Increased industrial methane emissions self-monitoring, including installing exhaust methane emission monitoring, and conducting periodic leak detection campaigns.

6 *IGU World LNG Report 2022; International Gas Union; https://www.igu.org/wp-content/uploads/2022/07/IGU-World-LNG-Report-2022_final.pdf*