Up to now, only few independent scientific studies cover methane emissions from the LNG shipping specifically. The aim of this TGD is to reference these studies and provide more guidance on the quantification of methane emissions from the LNG sector, based on best available data.

General introduction

Under LNG shipping, the following emission sources are considered (other emission sources are detailed in this TGD or in their respective TGDs, see System Boundaries below):

- Boil-off gas (BOG) emissions management from the ship, including onboard reliquefaction unit
- Incomplete combustion/methane slip from ship engines

BOG emissions management on the ship

LNG, specially designed double-hulled vessels are used for shipping LNG, to ensure safe and reliable transport, while reducing the LNG that boils-off from the vessel. The boil-off gas management system maintains the cargo tank pressure below the maximum allowable relief valve settings, by ensuring safe management of the boil-off gas. and temperature.

Several options exist to manage the gas released from the tank to avoid over pressure, these can include:

- BOG routed as fuel via a fuel gas supply system
- BOG routed to the onboard reliquefaction unit, to be reinjected in the cargo tanks
- BOG redirected to a Gas Combustion Unit (GCU) (commonly not part of typical operations)
- BOG vented to the atmosphere (commonly not part of typical operations)

Typically, the LNG boil-off gas can be routed as fuel via a fuel gas supply system (FGSS) for the main propulsion system and onboard power generation When boil-off gas is used as fuel, it can typically be used directly in the gas engine or for boilers in a steam engine. . Depending on the boil-off rate, ships can typically adjust power generation in their engines by consuming more or less of the BOG. The boil off gas may be combined with supplementary fuel oil to power the engines or boilers. Some newer vessels also have reliquefication facilities onboard, to reliquefy the boil-off gas, to be returned to the ship's tank as LNG.

Recent trends in LNG carrier vessels are designed to have on-board full or partial reliquefaction units, or subcoolers, to manage excess BOG from the LNG cargo tanks at times when the engine load is not sufficient to consume all BOG. It works following the same principles as land-based liquefaction plants with a series of compressors, heat exchangers (typically, nitrogen-based), expanders and flash tanks where the cooled gas is condensed.[1] In full reliquefaction systems, the boil off gas is sent back to the cargo tanks whilst a partial reliquefaction system will be sized to handle any of the remaining boil off gas that is not being can be either looped back into the system, used consumed as fuel.

In the event of the FGSS and reliquefaction systems being unable to handle the boil off volume it may be redirected to a GCU) where the gas is burned.or vented (commonly not part of typical operations).

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[1] Wartsila, *Encyclopedia of Marine and Energy Technology,* https://www.wartsila.com/encyclopedia/term/lng-reliquefaction-system

Incomplete combustion/methane slip from ship engines

The energy generation and heat processes are required for the transport of LNG to power ship turbines and cover other energy needs onboard the LNG carrier (e.g. compressors of the reliquefaction unit).

In many cases, the combustion, product of these processes, when gas is burned in main engines, auxiliary engines, boilers, GCU and other combustion equipment, the entirety of the fuel is not transformed to CO_2. When gas is used as a fuel for such equipment, this incomplete combustion of methane and release into the atmosphere from the equipment exhaust stack is known as methane slip. [2]

System boundaries

All emission sources from LNG shipping, not covered by other TGDs (see list below) are included in this TGD.

All emissions from components link to the LNG value chain while the gas is under the custody of the Vessel Manager is to be reported under the relevant reporting category, this includes all annex operations performed at the terminal that could have associated methane emissions, such as, for example, bunkering, cool-down, reloading, transshipment and gassing-up. Emissions occurring before or after the point at which the transfer of custody of the gas occurs are to be considered by the Operator/Vessel manager having the custody of the gas at that point, including, for example, emissions from loading and unloading operations. For example, this can be considered at the flange connecting the shore arm to the ship's manifold. This also includes emissions occurring when the ship is on a return journey and transporting only the heel LNG.

Emissions from unintended equipment leaks should be reported under the corresponding category. The distinction between incidents and leaks is to be considered based on the regulations and practices in place at the facility. Unintended methane emissions, considered to fall within the *leaks* category should be reported as such (Leaks TGD). As defined in the *General Principles TGD*, these should be allocated to the most appropriate reporting category.

Any emissions resulting from an incident, emergency stop or malfunction which are sent to a flare fall under that category (Flaring TGD), emissions which are vented are covered by the *Incidents TGD*.

All intended or expected emissions (vents) are to be reported under their respective category (such as pneumatics, centrifugal compressors, reciprocating compressor rod packing, and other venting and purging). Guidance on materiality is presented in the *General principles TGD*.

Many types of methane emission sources can be found during LNG shipping operations, most of which are covered by other TGDs and are to be reported under their specific category. The table below describes the most common emissions sources from LNG carriers, and the associated TGD for assessing their emissions.

With regards to BOG management, this does not represent a category as such, but associated emissions are to be reported at source level, depending on the equipment or processes involved (e.g. compressor, GCU, venting, …)

Emission source	Corresponding TGD
Leaks	Unintended equipment leaks (Leaks TGD)

[2] Adapted from OGMP 2.0, *Incomplete combustion TGD,* 2022, https://ogmpartnership.com/wp-content/uploads/2023/02/Incomplete-Combustion-TGD-SG-Approved.pdf

Incidents and malfunctions	Incidents, emergency stops and malfunctions
Power and heat generation – including propulsion and auxiliary engines	Incomplete combustion / methane slip *Additional information on methane slip from LNG-powered ship engines and auxiliary engines are provided as part of this TGD*
Centrifugal compressors seals	Centrifugal compressors
Reciprocating compressors packing	Reciprocating compressors
Coupling connectors / hose connections	Unintended equipment leaks (Leaks TGD) Purging and venting, starts and stops and other process and maintenance vents (following disconnection) *Typically under the responsibility of the export or import terminal, refer to LNG liquefaction TGD or LNG regassification TGD.*
Cryogenic heat exchanger	Unintended equipment leaks Incidents, emergency stops and malfunctions *No emissions are typically expected from normally functioning cryogenic heat exchangers*
Controllers	Pneumatic controllers, pumps, shutoff valves and control instruments
Pumps	Pneumatic controllers, pumps, shutoff valves and control instruments
Flaring and incinerators (including GCU – Gas Combustion Unit)	Flaring efficiency
Pressure relief valves	Incidents, emergency stops and malfunctions
BOG management/venting	*Covered by this TGD*
Purging and cleaning of the cargo tank (gassing up / inerting operations)	Purging and venting, starts and stops and other process and maintenance vents
Purging of fuel gas lines (including inerting operations)	Purging and venting, starts and stops and other process and maintenance vents
Connection and disconnection of loading and unloading arms (nitrogen and methane purge)	Purging and venting, starts and stops and other process and maintenance vents *Typically under the responsibility of the export or import terminal, refer to LNG liquefaction TGD or LNG regassification TGD.*

Methane emissions from other processes of the LNG value chain are covered by their respective TGD (see *LNG liquefaction TGD* and *LNG regassification TGD*)

Level 3 Quantification Methodologies

Due to the wide variability of sources, there is limited documentation of source-level emission factors for LNG specific processes. However, emissions factors or other quantification methods used in other natural gas value chain processes or other shipping industries could be relevant for use in LNG shipping. This is the case for example for incomplete combustion of gasified LNG in ship engines, which can rely on methane slip data from LNG as a marine fuel from other types of ships, or for methane emissions from compressor seals, which can use emission factors from the gas processing segment as the processes and gas compositions can be similar between the two segments.

The emission factors for each corresponding equipment can be used, based on their relevant OGMP TGDs, manufacturer provided Emission Factors or other relevant quantification method.

Methane emissions from LNG shipping can be quantified at Level 3 using different quantification methodologies such as emission factors, manufacturer estimates or simple engineering calculations, depending on the source type.

Emission factors

Accepted source-level emission factors, as defined in the *General Principles TGD*, or those prescribed by local regulation or international standards are considered as providing Level 3 estimates, provided they are specific for the source type. Vessel Operators are encouraged to use emission factors that best represent conditions and practices at their facilities and adjust factors, where warranted, to more accurately estimate emissions given differences between the reference system on which the emission factor is based, and their systems.

Incomplete combustion (methane slip) – additional information

The main elements to quantify methane emissions at Level 3 from incomplete combustion are covered by the *Incomplete combustion TGD*. Partners are encouraged to rely on emission factors which are specific to the type of engine and fuel used. This value is often provided by engine manufacturers, see below Section on Manufacturer estimates. This section provides additional examples, specific to marine engines running on LNG[3]

Engine type	Methane slip (g CH_4/kWh) – central estimate	Methane slip (%)[4]
LBSI, medium-speed	4.1	3.0%
LPDF, medium-speed, four-stroke	5.5	4.1%
LPDF, slow-speed, two-stroke	2.5	1.9%
HPDF, slow-speed, two-stroke	0.2	0.15%
Steam turbine	0.04	0.03%
Gas turbine	0.06	0.04%

In addition, other factors such as exhaust temperature or the engine load[5] have been shown to have a major impact on the methane slip of the marine engines of LNG carriers. Therefore, Vessel managers are encouraged to take the variation of engine load over time into consideration when quantifying methane emissions from incomplete combustion. Examples of the impact of load factors on the methane slip include:

- Pavlenko, N. et al., *The climate implications of using LNG as a marine fuel,* Appendix B, 2020, ICCT, https://theicct.org/publication/the-climate-implications-of-using-lng-as-a-marine-fuel/

BOG management

LNG storage tanks, including ship tanks, could be another important source of emissions. LNG in tanks is kept in a near constant cryogenic temperature. The temperature is controlled by boil off gas (BOG) escaping, in a process known as auto-refrigeration. Usually, the BOG is used for fuel to power the vessel's main or auxiliary engines, burned in the GCU, reliquefied or, vented (commonly not part of typical operations). For the case where BOG is vented, a typical loss may be estimated as 0.15% per day (but can typically range from less than 0.1% to 0.6% depending on the size of the tank and other ship characteristics) of the total tank

[3] Pavlenko, N. et al., *The climate implications of using LNG as a marine fuel,* 2020, ICCT, https://theicct.org/publication/the-climate-implications-of-using-lng-as-a-marine-fuel/

[4] Assuming methane content of 90% and LHV of 0.02 t CH4/GJ, assuming methane slip values provided for 90% load and relying on thermal efficiency provided by (2)

[5] P. Balcombe, D. A. Heggo, M. Harrison, *Total Methane and CO_2 emissions from Liquefied Natural Gas Carrier Ships: The First Primary Measurements,* 2022, https://pubs.acs.org/doi/10.1021/acs.est.2c01383

volume on LNG vessels[6]. This value is often provided by ship manufacturer, see below section on Manufacturer estimates.

$$BOG\ from\ LNG\ Vessel\ Storage\ Tank\ per\ day = Tank\ volume\ * Daily\ Boil\ off\ rate\ of\ vessel$$

BOG might not always be managed in the same manner over time. It is therefore recommended that Vessel Operators maintain records on the distribution of the methods used to manage the BOG throughout operations (e.g. used as fuel when at sea, sent to the GCU when the ship is idle as the fuel requirements are lower, or vented – not commonly part of typical operations) to best reflect methane emissions from BOG management.

Other vents

Emissions from other generic vents could be calculated using a general material balance approach based on source-specific measurements or estimates of the vent rate, frequency of occurrence, duration and concentrations, as described in Level 4 quantification.

For emission sources which are only present in the LNG segment, such as pressure valve expanders and evaporators, source-specific emission factors could be employed, where relevant for sources where venting can occur. References similar to the following could be used for the sources present at the facility:

- API Compendium reports Of Greenhouse Gas Emissions Methodologies For The Natural Gas And Oil Industry, 2021 – Section 6.7
- API, LNG Operations – Consistent Methodology For Estimating Greenhouse Gas Emissions, 2015
- Default national emission factors (e.g., US EPA)
- Academic papers

It is important to note that this list is non-exhaustive and that all vented sources might not be covered by the references and categories listed above. If no emission factor is available in the literature for a specific emission source, the emission factor of a similar source or reasonable estimate can be used based on the participant's best judgement and provided justification of the methodology employed to quantify emission at level 3.

Manufacturer estimates

For routine emissions coming from commercial equipment, including but not limited to incomplete combustion of fuel used in main and auxiliary ship engines, manufacturer estimates can be used to quantify methane emissions at Level 3. Other examples of this typically include the boil off rate which may be determined based on data provided by the manufacturer or other source documenting vessel characteristics presenting this value.

Simple engineering calculations

Simple engineering calculations, specific to the emission source, can be used to quantify methane emissions from emission sources in the LNG segment at Level 3, where relevant.

Level 4 Quantification Methodologies

Depending on the emission source, measurements (including CEMS), measurement-based emission factors, process simulation and/or engineering calculations can be accepted for level 4 quantification.

Direct measurement and Measurement-based Emission factors - Venting

[6] K. Kyunghwa, K. Park, G. Roh, K. Chun, *Case Study on Boil-Off Gas (BOG) Minimization for LNG Bunkering Vessel Using Energy Storage System (ESS),* 2019

A general material balance approach is required to account for emissions from loading, unloading and coupling/decoupling, and BOG management. For estimating total CH_4 emissions, the following data are needed during the time of interest[7]:

- Gas release flowrate
- Duration of the event (purge, vent, blowdown, …)
- Methane content

Methane emissions from gas emitted for each emission category is the multiplication of these three elements.

Measuring gas release flow rate

Accepted equipment and techniques, as defined in the *General Principles TGD*, for determining gas flow are to be employed. Practitioners are encouraged to select an appropriate measurement device depending on the characteristics of the vent. Following are typical equipment to measure emissions from vents, but the list is not exhaustive[8,9]:

- Vane anemometer
- Hotwire anemometer
- Turbine meter
- Electronic packing vent monitor
- Calibrated vent bag
- Coriolis meter
- Orifice meter
- Hi-flow sampler
- Thermal mass meters

Some measurement techniques allow direct measurement of total methane emissions, in which case, it is not necessary to measure methane content separately to quantify emissions.

Methane content

It can be necessary to determine the methane content of the gas flow to quantify methane emissions from venting. Depending on the vent, the methane content can differ from the average methane content of the facility.

Accepted equipment and techniques, as defined in the *General Principles TGD,* for determining methane content can be employed. In cases where the gas characteristics can be assumed to meet a regulated specification, methane content can be determined in accordance with the *General Principles TGD*.

Frequency and duration of events

Venting events can be random, periodic, or regular. For all types of venting events, it is recommended that operated records are maintained to accurately represent events.

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[7] API, LNG Operations – Consistent Methodology For Estimating Greenhouse Gas Emissions, 2015

[8] More details on various detection and measurement equipment can be found at CCAC, *Conduction Emissions Surveys, Including Emission Detection and Quantification Equipment – Appendix A of the OGMP Technical Guidance Document*, 2017

[9] More details on various detection and measurement equipment can be found at Marcogaz, *Assessment of methane emissions for gas Transmission and Distribution system operators*, 2019 – Section 7 (p. 34-39)

Engineering calculations, process simulation and models - Venting

Accepted engineering calculations, process simulations and models, as defined in the *General Principles TGD*, which do not rely on default emission factors or values can be considered as Level 4 quantification methodologies. This method can be applied to determine methane emissions from loading, unloading and coupling/decoupling, and BOG management

For example, emissions from depressurization of systems, equipment or connections can be calculated using physical volume, pressure drop and temperature data, specific to the equipment being depressurized. It is to be noted that stored LNG is kept in its liquid state at a near constant cryogenic temperature, which is controlled by allowing the BOG to escape from the tank. The following formula would apply for volume of gas, not the volume of liquid LNG inside the tank or other equipment.

$$\frac{p_i * V_i * T_f}{p_r * T_i} = V_f$$

Where:

p_i = Initial pressure of the equipment/system
p_r = Remaining pressure of the equipment/system (generally, atmospheric pressure)
T_i = Initial temperature of the gas being released (kelvin)
T_f = Temperature of the gas after being released (generally, atmospheric temperature) (kelvin)
V_i = Physical volume of the vented equipment or system (m^3)
V_f = Volume of gas released (scm)

Where applicable, standard/normal/atmospheric conditions for the vented equipment or system may be considered (typically, atmospheric pressure and 0 or 20°C atmospheric temperature)

Direct measurements and measurement-based emission factors – Incomplete combustion

Measurements (including continuous or periodic monitoring), or emission factors developed from representative measured emissions (including predicted emissions) are considered Level 4 emissions quantification. When quantifying methane emissions resulting from incomplete combustion using direct measurement and measurement-based emission factors, measurements must be taken that consider the mass or volume and methane content of the exhaust gases.

The following are considered as providing Level 4 estimates:

Parameters	**Continuous or Intermittent Combustion**
Mass of exhaust gases	Direct measurement or calculated based on fuel quantity and inlet air flow (where relevant) measurements, or volume of exhaust determined through the application of correlations based on representative sampling
Methane content of exhaust	Measurement-based methane content in the exhaust gas or methane content determined through the application of correlations based on representative sampling

Level 4 emissions quantification shall be based on measurements conducted on a representative sample considering parameters that affects the content of methane in the exhaust (e.g. load and other parameters).

System configurations and operating conditions should be considered in determining 'like' systems that carry common parameter value Each system that is not 'like' will require determination of a separate parameter value (mass and methane content of the exhaust) for that system based on the appropriate measurement studies. For guidelines on the methodology to develop a statistically representative sample, please refer to the Uncertainty and reconciliation guidance.

Measurement-based emission factors derived from a representative sample expressed in terms of emission per volume of fuel combusted allow for easy adjustment of activity data.

The methane content of the exhaust can also be derived from techniques that combine measured fuel and airflow parameters combined with other equipment metrics (such as temperature) and kinetic models, such as predictive emissions monitoring (PEMS) techniques. For such systems, there needs to be clear validation and calibration with physical measurements.

Mass of exhaust

Measurement-based methane mass of exhaust, mass of exhaust determined through the application of correlations based on representative sampling, or in some cases engineering calculations (as discussed below) are considered Level 4 emissions quantification. Measurement of volume of exhaust, converted to mass, using measured gas density can also be used for Level 4 emissions quantification.

Accepted measurement equipment and techniques, as defined in the *General Principles TGD,* for determining the volume of exhaust gas are to be employed. Following is a non-exhaustive list of such measurement solutions:

- Ultrasonic Flowmeters
- Thermal Flowmeters
- Differential Pressure Flowmeters
- Turbine meters
- Dynamic pressure measurement
- Impeller anemometer

The volume of exhaust gas can also be calculated based on the measured fuel and air flows that are combusted, depending on the load at which the engine is running. Similarly, the total exhaust flow rate can be determined based on fuel flow rate and exhaust O_2 or CO_2 content using combustion stoichiometric.

Methane content of the exhaust

Measurement-based methane content of the exhaust or methane content of the exhaust determined through the application of correlations based on representative sampling are considered Level 4 emissions quantification.

Accepted measurement equipment and techniques, as defined in the *General Principles TGD,* for determining methane content in the exhaust are to be employed. Following is a non-exhaustive list of methodologies/approaches/technologies to measure methane content:

- Differential Absorption Lidar (DIAL) Link (Measures directly methane content in the exhaust, removes the requirements for composition of the fuel and if continuous monitoring, gas flow does not have to be measured either)
- ORSAT Methane Analyzer
- Heated Flame Ionization Detector
- Fourier transform infrared (FTIR)
- Tracer gas in combination with Fourier transform infrared (FTIR) for mass flow determination Link

When measuring methane content in the exhaust, it is important to take ambient methane content into consideration and to quantify the delta between the ambient methane and the methane present in the exhaust to accurately quantify methane emissions from unburned fuel. Ambient methane can be disregarded, as it leads to conservative estimates.

An alternative to quantifying these two parameters separately is to determine gas flow, methane content and destruction efficiency, similarly to the methodology described in *Gas flaring TGD.*