Evaluation of Methane Emissions Originating from LNG Ships Based on the Measurements at a Remote Marine Station

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ABSTRACT: We analyzed pollution plumes originating from ships using liquefied natural gas (LNG) as a fuel. Measurements were performed at a station located on the Utö island in the Baltic Sea during 2015–2021 when vessels passed the station along an adjacent shipping lane and the wind direction allowed the measurements. The ratio of the measured concentration peaks $\Delta CH_4/\Delta CO_2$ ranged from 1% to 9% and from 0.1% to 0.5% for low and high pressure dual fuel engines, respectively. The ratio of the measured concentration peaks of $\Delta NO_x/\Delta CO_2$ varied between 0.5‰ and 8.7‰, which was not explained by engine type. The results were consistent with previously measured on-board or test-bed values for the corresponding ratios of emissions. While the methane emissions from high pressure dual fuel engines were found to fulfill the goal of reducing the climatic impacts of shipping, the emissions originating from low pressure dual fuel engines were found to be substantially high, with a potential for increased climatic impacts compared with using traditional marine fuels. Taking only the global warming potential into account, we can suggest a limit value for the methane emissions; the ratio of the emissions $\Delta CH_4/\Delta CO_2$ originating from LNG powered ships should not exceed 1.4%.

KEYWORDS: natural gas fuel, shipping emission, methane slip, pollution plume, unburnt methane, maritime transport, climate impact

INTRODUCTION

Combustion in ship engines produces a range of primary and secondary pollutants that have important environmental, health, economic, and climatic impacts. The greenhouse gas (GHG) emissions attributed to shipping contain carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O); these can collectively be evaluated as carbon dioxide equivalent (CO$_2$e). The CO$_2$e of total global shipping increased 9.6% from 2012 to 2018.

In addition to GHG emissions, shipping produces significant emissions of other pollutants like sulfur and nitrogen compounds. In an aim to reduce the environmental impacts, new global standards have been applied since January 1, 2020 for marine fuels. The new limit for fuel sulfur content (FSC) is 0.5%, which implies a significant decrease from the previously allowed maximum FSC of 3.5%. An even stricter regulation of 0.1% FSC has been set in sulfur emission control areas (SECAs) since January 1, 2015. In Europe, these comprise the Baltic and North Seas as well as the English Channel. In complying with the limit values within SECAs, ships are currently mandated to use fuel oil within the FSC limits. Alternatively, vessels may (i) be equipped with abatement systems, commonly SO$_x$ (sulfur oxides) scrubbers, that decrease sulfur emission in the exhaust to reach the limits or (ii) switch to alternative fuels, including liquefied natural gas (LNG).

The introduction of vessels using LNG as a fuel may be a promising and economically viable solution in the future, especially as it may also comply with NO$_x$ ECA emission limits. The high energy content of LNG enables a more efficient consumption of fuel, compared to using liquid fuels. LNG is also a clean fuel in most respects. Anderson et al. performed particle number size distribution and exhaust gas measurements onboard an LNG dual fuel ship. They found that emissions of particles, NO$_x$, and CO$_2$ were clearly lower when using LNG instead of marine fuel oils. Alalen et al. also observed lower particle emissions from an LNG engine, compared to marine diesel oil (MDO) or marine gas oil.

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(MGO). Moreover, Peng et al.3 observed 93%, 97%, and 92% reduction of emissions in particles, black carbon, and NOx, respectively, when changing from diesel fuel to LNG as a fuel. However, at the same time, the formaldedhyde (HCHO), carbon monoxide (CO), and CH4 outflow increased several-fold.3,4

The contribution of unburnt methane should not be neglected when considering the GHG emissions and emission reduction agreements from the shipping traffic. Increased CH4 emission results in difficulties with emission reductions of greenhouse gases. Over the period 2012–2018, the CH4 emissions of shipping increased 87%, partly due to increased consumption of LNG and the increase in the use of dual-fuel machinery that has higher specific exhaust emissions of CH4.5

A large scale introduction of LNG powered ships may in the worst case result even in an increased climatic impact. The emission of unburned methane in marine engines (also called as the methane slip) depends on engine load; it is largest for lower loads. Methane slip emissions can impact climate change since methane has 28–34 times higher global warming potential than CO2 over a time span of 100 years (GWP100), see e.g., refs 8 and 9. As pointed out by Ushakov et al., methane slip has been previously ignored but has recently received more attention.6 However, the amount of relevant measurement data is scarce regarding the methane slip; in addition, the existing data originated mainly from test-bed measurements by engine manufacturers. In previous research, no studies have been presented that have measured and analyzed measurement data for several ships that use LNG-fueled marine diesel engines in their actual operating environments. However, such data are urgently needed to be able to realistically analyze the climatic impacts of the rapidly increasing LNG powered shipping.

The overall aim of this study was to evaluate, quantitatively, the methane emissions originating from a wide range of LNG powered ships. The more specific objectives were (i) to quantify the methane emissions for the LNG ships that have traveled past the Uto island in the Baltic Sea during 2015–2021, (ii) to evaluate the impacts on the methane emissions in terms of the different types of engines of the ships, and (iii) to discuss the importance of methane slip in terms of the climatic impacts and potential future emission limits.

### MATERIALS AND METHODS

**Engine Types and Methane Slip.** Currently, there are three engine types available for marine applications; these are based on different combustion characteristics. According to Ushakov et al., they can be grouped as (1) lean burn spark ignited engines, for medium and high speed with a four-stroke cycle (LBSI), producing a power range of 0.5–8 MW; (2a) low pressure dual fuel engines for medium speed with a four-stroke cycle (LPDF) producing 1–18 MW; (2b) low pressure dual fuel engines for low speed with a two-stroke cycle (LPLSDF) producing 5–63 MW; (3a) a high pressure dual fuel engine for medium speed with a four-stroke cycle (HPMSDF) producing 2–18 MW; and (3b) a high pressure dual fuel engine for low speed with a two-stroke cycle (HPLSDF) producing over 2.5 MW. Stenersen and Thonstad10 report that in December 2016, approximately 120 LNG vessels were in operation, from which approximately 41% had type 1, 47% type 2a, 3% type 2b, and 8% used type 3 engines.

The spark-ignited and low-pressure dual fuel engines have low NOx emissions, making them attractive from the point of view of the Nitrogen Oxide Emission Control Area (NECA) operation, as they are IMO tier III compliant. However, these engines emit unburnt methane, especially at low engine loads. In contrast, the high-pressure engines emit much less methane but are only IMO tier II compliant, which necessitates the use of exhaust gas after-treatment, such as Selective Catalytic Reduction (SCR), to achieve tier III NOx reduction. The reduction of NOx emissions by using low-pressure dual fuel engines is a tempting feature for ship fleets operating on NECAs, but in the absence of a regulation for the methane slip, methane emissions would be likely to increase.

In an internal combustion engine, the emissions of NOx are formed predominantly through a process called thermal NOx formation: the diatomic nitrogen present in the combustion air oxidizes at high temperatures and forms nitrogen oxides. The rate of NOx formation is in part dependent on the combustion temperature; by reducing the peak combustion temperature, one can therefore achieve a reduction of the formed NOx emissions. This is one of the design principles of the LBSI and LPDF engine types. They operate on the basis of the so-called Otto cycle, applying a lean air–fuel mixture ratio, which translates into low thermal loading.

In an LBSI engine, the ignition of the air–fuel mixture is done using a prechamber, in which a spark plug ignites a locally enriched air–fuel mixture. Similarly, in an LPDF engine, the air–fuel mixture is ignited in a prechamber using pilot diesel fuel. The drawback of these engine types is the emitted unburnt methane, or methane slip, which occurs due to two factors. First, the lean combustion and consequent low thermal loading makes the engine susceptible to quenching. Quenching means that the methane cools down rapidly in the combustion chamber, and, as methane requires a relative high temperature to autoignite (>600 °C), it may remain unignited. Methane slip resulting from quenching is particularly intensive at low engine loads as shown, for example, by Ushakov et al. A secondary cause for methane slip is related to the working principle of the Otto cycle. In an Otto engine, the fuel is injected to the intake manifold, and a homogeneous air–fuel mixture is then formed in the combustion chamber before its ignition. The residence of methane in the combustion chamber before its ignition allows it to be pushed to the crevice volumes of the chamber, for example, to the gasket area between the cylinder head and cylinder liner, during the compression stroke. This may prevent its ignition and thus result in a methane slip.

The methane slip can be considered to be caused by the trade-off of the emissions of NOx and CH4. An engine, such as the LBSI and LPDF, can be optimized to run with a minimal thermal loading, resulting in low NOx emissions. On the other hand, the downside of these types of engines is the emitted methane slip. In contrast, the diesel cycle-based high-pressure engines (HPMSDF and HPLSDF) are less susceptible to quenching, due to their compression ignition-based operation and higher thermal loading. Moreover, the methane slip due to crevice volumes is not an issue, as the methane burns as it is being injected to the combustion chamber; there is no possibility for it to escape to the crevice volumes during the compression stroke. However, high-pressure engines emit NOx emissions to the degree that requires them to be equipped with an SCR system to be IMO tier III compliant. As methane emissions—unlike NOx emissions—have remained unregulated up to date, it is to be expected that shipping companies
consider the use of LNG engines producing low NO\textsubscript{x} emissions.

In the future, an improved design of engine components and engine process control may further reduce the methane slip.\textsuperscript{10} However, the IMO should consider the introduction of methane emission limits as soon as possible, and the regulatory framework should be sufficiently comprehensive. In the current regulatory approach, only emissions originating from ships are considered. From the point of view of shipping emissions, the fossil, bio-, and synthetic methane are equivalent. However, these various methane fuels are substantially different in view of their climatic impacts, if one will also consider the impacts during their production process.

**Measurement Site.** Utö is an island with an area of 0.81 km\textsuperscript{2} (N59° 47.034′, E21° 22.030′) situated in the Baltic Sea, approximately 90 km south of continental Finland and the closest city Turku. Utö is a bare, rocky island with some low-growing vegetation, mainly consisting of bushes and with a permanent population of less than 50 people. A map showing the location of Utö island at the Finnish southern coastline is given in Figure 1. A densely trafficked shipping lane passes to the west of the island at a distance of about 600 m. Besides the shipping emissions, there are no other significant sources of CH\textsubscript{4} or CO\textsubscript{2} in the area.

Meteorological conditions are windy. Monthly wind speed conditions ranged from 5.6 m s\textsuperscript{−1} in July to a maximum of 8.9 m s\textsuperscript{−1} in December with an average of 7.1 m s\textsuperscript{−1} over the year. The prevailing wind direction is southwest; the winds from the south–northwest sector prevail for approximately 60%.\textsuperscript{11} The measurements at Utö Atmosphere and Marine Research Station are described in detail in Laakso et al.\textsuperscript{12}

**Experimental Setup.** We have used the data measured at the Integrated Carbon Observation System (ICOS) Atmosphere Station and at the Marine Research Station. The measurements at these two stations have been briefly described in the following. For a more detailed description of these

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**Figure 1.** Upper panel, the location of Utö island (red arrow) on the southern coast of Finland. The lower panel presents an aerial photo of Utö island and its immediate surroundings. The arrows A, B, and C show the locations of the sea station, the ICOS station, and the air quality station, respectively. The thin solid white line in the sea area indicates the shipping lane (≈ 600 m from the island), and the lane area (300–1100 m from the island) is marked with dotted lines. Copyright of the map and the aerial photo is owned by National Land Survey of Finland and licensed under a Creative Commons Attribution 4.0 International License.
measurements, the reader is referred to Laakso et al. and Kilkki et al.12

The ICOS Atmosphere Station. The atmosphere station of Utö is for long-term high-precision observations of greenhouse gases. The station has been part of the European ICOS atmospheric measurements network since March 2018. The location of the station is shown in Figure 1, marked with the arrow B. The 60 m tall tower is located at a distance of approximately 200 m from the coastline in the northern part of the island. The concentrations of CO₂ and CH₄ were measured using a Cavity Ring-Down Spectrometer (CRDS), G2401 (Picarro, Inc., Santa Clara, CA, U.S.A.), together with calibration standards traceable to the scales of WMO CCL (World Meteorological Organization, Central Calibration Laboratory). In addition, the Picarro instrument measured carbon monoxide (CO) and water vapor, the latter of which was used by the analyzer to calculate dry gas concentrations. The analyzer measured each species consecutively within ca. 2.5 s. According to the manufacturer, the precision on a time period of five seconds is better than 1 ppb for CH₄ and 0.05 ppm for CO₂. Sampling height was 56 and 64 m with respect to the surrounding terrain and the mean sea level, respectively. The length of the sampling line was 124 m. The time lag caused by the sampling line was about 40 s. At the top of the tower, wind speed and direction were measured with a 3-D sonic anemometer, USA-1 or uSonic-3 Scientific (Metek GmbH, Elmshorn, Germany), which recorded the three wind components and the acoustic temperature at a frequency of 10 Hz.

The Marine Research Station. The Marine Station is situated approximately at a distance of 500 m to the west of the ICOS station (Figure 1, location A). This station is located at a horizontal distance of a couple of meters from the shore. The station consists of a 9-m-tall mast, which is mounted on a cliff that is approximately at a height of 3 m above the mean sea level. The mast is mainly used for micrometeorological greenhouse gas flux measurements; it contains a Metek USA-1 3D sonic anemometer and an LI-7000 fast-response infrared gas analyzer (Licor Biosciences, Lincoln, NE, USA) for measuring the CO₂ and H₂O concentrations. In addition, the Marine Station includes a Thermo Scientific 42i NO—NO₂—NOₓ analyzer for measuring the concentrations of nitrogen oxides and a Thermo Scientific 43i-TLE analyzer for measuring the SO₂ concentrations. In addition to the atmospheric observations, a large number of underwater variables are measured at the station, including sea surface dynamics and marine bio-geochemistry.

Preprocessing of the Measurement Data. To detect a pollution plume originating from a passing ship, the wind direction has to be in a specific sector from a direction of the shipping lane toward the two applied measurement stations. A further examination of the emissions was started if there was (i) a simultaneous increase of the concentrations of CO₂ and CH₄, (ii) the maximum peak value for CH₄ was larger than 5 ppb, and (iii) the maximum peak of CO₂ was higher than 0.5 ppm above the corresponding background concentration value. The CH₄ concentration peaks were easy to detect, due to a temporally fairly constant background. However, if the CO₂ concentration was close to the background level (no clear peak), the pollutant plume could have originated from a
Such cases were therefore excluded from further analysis.

On the basis of the AIS information on each passing ship, we compiled the type of the engine of that particular ship based on a ship properties database. If the ship used LNG as a fuel, we analyzed the wind direction and both the measured concentrations of CH4 and CO2. We also subtracted the background concentration from the measured peak concentration data. The auxiliary variables contained in the AIS signals, such as vessel speed and direction, were also archived for such cases. In addition, the relevant measured meteorological data, such as the wind speed and direction, were saved.

An objective of this study was to study the pollutant plumes in terms of the engine types of the LNG ships. We have therefore marked the studied ships using letters (T, P, C, R, F, V, H, and M) in presenting the results. These ships were then divided according to the main engine types, as categorized by Ushakov et al. 4

### RESULTS AND DISCUSSION

#### The Passes by of the LNG Fueled Ships

The passes by of LNG fueled ships past the island of Utö have been compiled in Table 1. In total, we were able to observe 38 LNG ship passes by (eight different ships) during the period 2015–2021. The numbers of passes by varied substantially from year to year showing an increasing trend during the most recent years; in particular, in 2020, LNG ships passed the station 20 times. The conditions satisfied the above-mentioned criteria for detecting experimentally the pollution plume a total of 18 times. The wind directions that were favorable for the detection of the plumes ranged from 184° to 331°.

Characteristic measured concentration variations at the ICOS station for two passes by of ships have been illustrated in Figure 3. If the vessel is equipped with a diesel engine (panel a), the concentration curves contain a distinct peak of CO2 and there is no increase in the concentration of CH4. However, for a pass by of a vessel using LNG as a fuel (panel b), both the

![Table 1. Numbers of LNG Fueled Vessels That Have Passed the Island of Utö Shown Separately for Each Year during 2015–2021](https://doi.org/10.1021/acs.est.1c03293)

| vessel | T | P | C | R | F | V | H | M |
|--------|---|---|---|---|---|---|---|---|
| produced | 2014 | 2016 | 2017 | 2018 | 2015 | 2018 | 2018 | 2020 |
| ship type | other | other | tanker | tanker | tanker | cargo | cargo | passenger |
| engine type | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 2 |
| year when passed Utö | 2015 | 1 | 1 | 2016 | 1 | 1 | 2017 | 1 | 2 | 2018 | 2 | 2 | 2019 | 2 | 1 | 4 | 2020 | 2 | 1 | 2 | 5 | 2021 | 1 | 1 |
| sum | 9 | 7 | 6 | 2 | 5 | 2 | 2 | 5 | 20 |

aIndividual vessels are referred to using letters (T, P, C, R, F, V, H, and M). The types of ships, the production year, and their engine types have also been presented. For example, vessel T passed Utö nine times during Jan 2015 to Feb 2021. bThe engine production year.

![Figure 3. Examples from two different days presenting the measured concentrations of CO2 and CH4 at the ICOS station on the island of Utö during the passes by of ships. The panels show measured concentrations for the plumes from two passing cargo ships using a diesel engine on November 5, 2020 (panel a) and one ship using an LNG fueled engine (type 2a) on October 5, 2020 (panel b). The CO2 concentrations are shown by the black curves, using the left-hand-side axis, and the CH4 concentrations by the red curves, using the right-hand-side axis. Note that values depend also on the plume dispersion, and the absolute values are not fully comparable.](https://doi.org/10.1021/acs.est.1c03293)
concentrations of CO₂ and CH₄ at the ICOS station were before the vessel had passed the island. The measured concentrations of CO₂ and CH₄ at the ICOS station were increasing slowly for a period of approximately ~5 min. After the ship had passed the station, increased turbulence by the wake of this large cruise ship caused an intensive fluctuation of the measured concentrations. Naturally, the absolute values and total measurement time depend on how well the plume reaches measurement devices at Utō Island, and therefore they cannot be directly compared between different passes by.

The Ratios of the Concentrations of Methane and Carbon Dioxide in the Pollution Plumes. First, the background concentrations were subtracted from the measured concentrations; this results in the concentrations attributed to the local ship emissions (increment values, marked with ΔCH₄, ΔCO₂, or ΔNO₂). Second, we have plotted ΔCH₄ as a function of ΔCO₂. A simple linear regression equation without an intercept was used, ΔCH₄ = k × (ΔCO₂), where k is the slope of the linear regression. Clearly, k is also the ratio of the gas concentrations.

The measurements during the passes by of the LNG fueled ships have been summarized in Table 2. The table summarizes the dates of the passes by, the engine types of the passing ships, the maximum peak height values, details on how the passes by occurred, and selected meteorological parameters. The table includes also the ΔCH₄/ΔCO₂ ratios calculated from measurements at the ICOS station, the adjusted coefficient of determination of the corresponding numerical fits (R²), and also the ΔNO₂/ΔCO₂ ratios derived from observations at the Sea Station.
$R^2$ describes the proportion of variance in the dependent variable, which can be explained by the independent variable, also taking into account the number of variables in the model. $R^2$ ranged from 0.84 to 1.00 for the considered individual cases. This indicates that both concentration signals most likely originated from the same local source. Both CO$_2$ and CH$_4$ can be considered to be chemically inert in the short transport times considered in this study; both gases are therefore dispersed and transported in the atmosphere in almost the same manner. The ratio of $\Delta$CH$_4$ and $\Delta$CO$_2$ in the ship plumes is therefore directly indicative of the amount of methane slip in the emissions.

The pollutant plumes were detected at the measurement station for a substantial time period, the detection period ranged from 20 to 570 s (Table 2). In some cases, the plumes were detected already before the ship had passed the station, typically in the case of a tailwind. In some other cases, the plume was detected after the ship had already passed the station, typically in the case of a headwind. The first detection time ranged from $-9$ min to $+15$ min with respect to the pass by of the ship, defined according to the shortest distance between the ship and the station. The minus sign indicates that the plume was detected before the ship passed the island. The variation in the first detection time is influenced by meteorology, the vessel’s speed and direction, and the height of the exhaust funnels. For example, the release height of the exhausts for vessel M was approximately 65 m, which is comparable to the height of the measurement tower.

The rows in the table are organized so that the separate visits by the same vessel are ordered in time. The $\Delta$CH$_4$/ΔCO$_2$ values calculated based on the linear fit ranged between 0.1% and 9.3%. There were five vessels, which had traveled past the island of Utö more than once under the conditions for which the plume detection in the stations was possible: the ships T, C, R, F, and M. For the ship T, the $\Delta$CH$_4$/ΔCO$_2$ ranged 3.0–9.3%; for C, 1.9–2.7%; for R, 1.9–2.7%; for F, 1.9–3.4%; and for M, 2.5–6.4%. The ships P, H, and V have been observable only once with a $\Delta$CH$_4$/ΔCO$_2$ of 1.5%, 0.5%, and 0.1%, respectively. The lowest values for the CH$_4$-slip were observed for the ships H and V, both of which were equipped with a class 3 type engine. Plumes emitted by the ships M and T had the highest $\Delta$CH$_4$/ΔCO$_2$ ratios. The rest of the vessels, C, R, F, and P, had similar values for $\Delta$CH$_4$/ΔCO$_2$.

In addition to the type of LNG engine, also the engine load could potentially influence our results. We investigated this possibility by correlating the ratio $\Delta$CH$_4$/ΔCO$_2$ with the speed of the vessel and the wind vector; no statistically significant correlation was found. However, we did not have information on the amount of cargo onboard the detected ships; clearly, this is one of the key factors in view of the engine load.

The ratio $\Delta$NO$_x$/ΔCO$_2$ varied from 0.5‰ to 8.7‰; the average value was approximately 4‰. This ratio was not clearly dependent on the type of the vessel engine. These ratios were similar to the corresponding ratios measured by Stenersen and Thonstad.
The Methane Slip Values in Terms of Ships and Engine Types. The same analysis is performed for all plume data we have from passing LNG ships and are shown in Figure 4. By combining all data points from individual passes by, we can get the average ratio (1.5% to 5.4%) for $\Delta \text{CH}_4/\Delta \text{CO}_2$. As already shown earlier, the vessels P, H, and V include only one pass by; R, two; T, C, and M, three; and F, four. In particular, it is possible to see that the data from three passes by of vessel M deviate clearly from each other depending probably on the engine load (the values for different slopes presented in Table 2). However, $R^2$ is higher than 0.72 for all of these vessels, and the remaining unexplained variation does not affect the conclusions made based on this data.

Figures 4 and 5 present the ratios $\Delta \text{CH}_4/\Delta \text{CO}_2$ for all the considered vessels. The data have been presented separately for type 1, 2, and 3 engines. The ratio $\Delta \text{CH}_4/\Delta \text{CO}_2$ deviates clearly from each other depending probably on the engine load. For type 2 engines, the median value for the type 3 engines was clearly below 1%, ranging from 0.1% to 0.5%. For type 3 engines, the median value for CO2 emissions originating from vessels equipped with diesel engines is 1% and 0.7%, respectively, ($c_{\text{di}}(\text{CO}_2) = 1$; $c_{\text{LNG}}(\text{CO}_2) = 0.7$). In addition, we assume that the emission of CH4 attributed to a diesel engine is negligible, ($c_{\text{di}}(\text{CH}_4) = 0$, $c_{\text{LNG}}(\text{CH}_4) = 0$).

For the sake of a policy, we require that the GWP of diesel and LNG engines be equal. This yields the equation

$$\text{GWP}(\text{di}) = \text{GWP}(\text{LNG})$$

Taking into account the GWPs attributed to the emission of both CO2 and CH4, for diesel and LNG engines, eq 1 can be written as

$$c_{\text{di}}(\text{CO}_2) \times \text{GWP(\text{CO}_2)} + c_{\text{di}}(\text{CH}_4) \times \text{GWP(\text{CH}_4)}$$

$$= c_{\text{LNG}}(\text{CO}_2) \times \text{GWP(\text{CO}_2)} + c_{\text{LNG}}(\text{CH}_4) \times \text{GWP(\text{CH}_4)}$$

arranging eq 2 yields

$$c_{\text{LNG}}(\text{CH}_4) = \frac{\text{GWP(\text{CO}_2)}}{\text{GWP(\text{CH}_4})} \times \frac{c_{\text{di}}(\text{CO}_2) - c_{\text{LNG}}(\text{CO}_2)}{c_{\text{LNG}}(\text{CO}_2)}$$

which, according to the above-mentioned assumptions, has a numerical value

$$c_{\text{LNG}}(\text{CH}_4) = \frac{1}{30} \times 1 - 0.7 \approx 0.014$$

The implication of this computation is that the ratio $\Delta \text{CH}_4/\Delta \text{CO}_2$ in the emissions originating from LNG vessels should be equal to or below 1.4%, if we require that the climatic forcing for 100 years caused by shipping fueled by LNG should be on the same order of or lower than the corresponding forcing using diesel engines. According to the present study, the considered vessels equipped with type 3 engines satisfied this criterion, but none of the vessels equipped with 2a-type engines complied with the criterion.

If the forecasting period would be substantially shorter, for example, 20 years, the GWP for CH4 would be $\sim 85$ times higher than that for CO2. In that case, the threshold value for $\Delta \text{CH}_4/\Delta \text{CO}_2$ would be substantially lower, 0.5%. Even with using this shorter forecasting period, type 3 engines considered
in this study would satisfy the criterion. The method that is already presently used in sulfur monitoring, measuring the ratio SO2/CO2, would be applicable also for monitoring the CH4 emissions. This could be implemented by setting up a monitoring network near shipping lanes, by on-board measurements and using other remote monitoring techniques, such as concentration measurements by unmanned aerial vehicles, e.g., drones.

No emission directives or standards are currently in place, which would directly regulate the methane slip for marine LNG engines, e.g., ref 4. In our view, such regulations should be urgently prepared, to mitigate the climatic impacts related to the methane slip of the LNG powered shipping. Such regulations should ideally address the functioning of the marine engines, their emissions including the methane slip, and the environmental and climatic effects of the production and distribution chain of the fuel. On-board measurements of airborne pollution also should be extended to include all the relevant pollutants, in particular, the methane slip of LNG fuelled ships.10

In formulating the policies for controlling the CH4 emissions attributed to LNG powered ships, one will need to take into account the impacts of emissions to air (also including black carbon) and discharges to sea, especially on human health and marine environments. The cost efficiency of various solutions also needs to be considered. For example, reducing the sulfur emissions is clearly important for human health; however, this could result in a reduction of the formation of aerosol particles, which will have a climatic cooling effect.10

Thus, fact-based decision making regulating the shipping emissions should be based on a number of different aspects including impacts of direct emissions of pollutants on the environment and air quality, impacts of fuel production on the climate, air quality and biodiversity, economical costs, security of supply, and climate change. Proper analysis should also include a clear division between the local impacts (e.g., regional air quality) and global, existential crises like climate change and biodiversity loss.

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**Notes**

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