2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel

Executive Summary

On behalf of SEA-LNG and SGMF

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Executive Summary

This 2nd *"Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel"* is an update of the 1st GHG study published by *thinkstep* in April 2019 (*"Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel"*). It is the first on a series of regular updates of greenhouse gas (GHG) emissions to reflect ongoing technology developments in fuel supply and marine propulsion systems.

This 2nd GHG study analyses the life cycle GHG emissions of the use of Liquified Natural Gas (LNG) as marine fuel compared with fuel oils. In addition, air quality impacts are assessed by comparing local combustion pollutants from the operation of the engines using these different fuels.

The update includes the latest data for the fuel supply consumption mixes, as well as latest fuel consumption and emission data for the different ship engines. The study hence focuses on the latest marine engine models, i.e. engine generations where at least one engine has been built and delivered.

All data are based on information from key energy suppliers and all major marine engine manufacturers. The 2nd GHG study also analyses the GHG impact of planned methane emission reduction measures until 2030 in both the supply of LNG and the use of LNG in the engines as an extension to the 1st GHG study.

As with the 1st GHG study, the 2nd GHG study was guided by a Project Consortium from the SEA-LNG and SGMF member companies. The member companies of these organisations are shown at the front of the main report.

Key Messages from the Study

The study confirms the 1st GHG study conclusion that LNG provides a significant advantage in terms of improving air quality which is particularly important in ports and coastal areas. Beyond the benefits associated with reducing air pollutants, LNG provides reduced GHG emissions from international shipping and does contribute to the International Maritime Organization (IMO) GHG reduction targets. Reducing methane emission from the supply chain and engine slip will maximise the positive impact on GHG emissions. The impact of planned measures on GHG emissions has been analysed to show the near future potential of using LNG. The comparison between LNG and oil-based fuelled engines is calculated based on a 1 kWh brake power specific unit (g CO_2-eq/kWh).

- The use of LNG as marine fuel in current marine engines shows GHG reduction of up to 23 % compared with operating on very low sulphur fuel oil ($VLSFO_{0.5}$) in deep-sea shipping (outside NECA; Tier II NO_X-limit) over the entire life cycle from Well-to-Wake (WtW). The benefit is highly dependent on the engine technology installed with the 23 % referring to a high-pressure, 2-stroke slow speed Diesel dual fuel engine (diesel cycle).
- On an engine technology basis, the WtW GHG emission reduction for gas fuelled engines compared with $VLSFO_{0.5}$ fuelled engines are between 14 % to 23 % for 2-stroke slow speed engines, and between 6 % to 14 % for 4-stroke medium speed engines.
- Looking at the combustion of the fuel in the engine (TtW), the GHG emission reduction for LNG-fuelled engines compared with $VLSFO_{0.5}$ fuelled engines are between 20 % to 30 % for 2-stroke slow speed engines, and between 11 % to 21 % for 4-stroke medium speed engines.
- The differences in the GHG emission performance of different LNG engine technologies are highly dependent on the levels of methane slip. High-pressure 2-stroke slow speed Diesel cycle engines show very little methane slip today (0.23 g/kWh brake power), which is less than 1.5 % of the overall WtW GHG emissions. Due to the low methane slip already realised, no major reductions in methane slip are projected.

- Otto cycle engines however typically have higher methane slip due to the different combustion cycle. Test-bed measurement data for a newly developed 2-stroke slow speed Otto dual fuel engine which can be ordered now and will be in operations in 2022 has been provided by an engine manufacturer. The data demonstrate a 50 % reduction of methane emissions (1.07 g/kWh brake power) compared with the current engines in operation (2.14 g/kWh brake power). This is achieved through improvements of the combustion process. By 2030, engine manufacturers state that another 15 % reduction could be possible through further improvements in the combustion process.
- For 4-stroke medium speed engines, methane reduction technologies such as oxidation catalysts or the implementation of high-pressure gas injection could reduce methane emissions by 70 % respectively 90 % potentially leading to methane emissions below 1 g/kWh. It has to be noted however that both technologies (catalyst and high-pressure gas injection at 4-stroke engines) are currently in research and development state and not commercially implemented yet.
- Local combustion pollutants, such as sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM), are reduced when using LNG compared with conventional marine fuel oils (including HFO, VLSFO, MGO). Due to the negligible amount of sulphur in the LNG fuel, SO_X emissions are reduced to near zero as long as the dual fuel engines are running mainly on LNG. NO_X emissions are reduced significantly compared with fuel oils if the engine is running on an Otto-cycle. This is of particular importance as these engines already comply with the IMO Tier III NO_X-limits. Diesel-cycle engines (e.g., Diesel-DF running on LNG and pure Diesel engines) need NO_X-aftertreatment systems (e.g., EGR or SCR) to meet the IMO Tier III limits – nonetheless the Tier II limit is easily met by the LNG Diesel-DF engine. Limited data on PM emissions is available. However, using LNG has shown the potential to reduce PM emissions up to 96 % for 4-stroke medium speed engines compared with very low sulphur fuel oil ($VLSFO_{0.5}$).
- The GHG emissions of the average supply of LNG as of 2020 (WtT) are calculated as 17.7 g CO_2-eq/MJ (LHV). Experts from different industry associations and organizations project that methane emissions in the LNG supply chain could be reduced in average by 15 % by 2025 and by 35 % by 2030 based on actual initiatives and communicated targets. This would lead to a reduction of the overall GHG emissions in the supply of LNG (WtT) of 4 % by 2025 compared with 2020 (methane contributes ~ 25 % to total GHG emissions) and by 9 % by 2030 leading to an absolute value of 16.1 g CO_2-eq/MJ (LHV) by 2030.
- By 2030, reductions of methane slip will significantly improve the GHG performance of 2-stroke slow speed Otto cycle engines as well as 4-stroke Otto-DF and Otto-SI engines. The combination of both improvements in the LNG supply (WtT) as well as improvements in the combustion process (TtW), through the use of catalysts or the implementation of direct gas injection would increase the Well-to-Wake benefit of LNG fuelled engines. For 2-stroke slow speed Diesel-cycle engines the WtW benefit of LNG compared with $VLSFO_{0.5}$-fuelled engines will be 24 % in 2030 instead of the 23 % in 2020. For 2-stroke slow speed Otto-cycle engines 24 % in 2030 instead of the today's 14 % (2020). For 4-stroke medium speed engines, the benefit of LNG fuelled engines compared with $VLSFO_{0.5}$-fuelled engines are targeted to increase for Otto-DF from 6 % to 22 % and for Otto-SI from 14 % to 21 % in 2030.
- Looking at the combustion of the fuel in the engine (TtW), the GHG emission reduction for LNG-fuelled engines with reduced methane slip compared with $VLSFO_{0.5}$ fuelled engines can reach between 27 % to 30 % for 2-stroke slow speed engines, and around 28 % for 4-stroke medium speed engines by 2030. The theoretical maximum of GHG benefit (no methane emission) is for 2-stroke engines between 31-33 %, and for 4-stroke engines around 30 % on TtW basis compared with oil-based engines. Therefore, to reach the IMO 50 % absolute GHG emissions reduction target in 2050, additional measures such as design changes and technical improvements (e.g. engine efficiency improvements) as well as operational measures (e.g. slow steaming, introduction of liquified bio- or synthetic methane), are necessary.

- As a direct comparison if the global marine transport fleet of todays (fuel consumption per engine based on 2015 data) were to completely switch to LNG as a marine fuel then there would be a GHG emission reduction of 15 % compared with fuel oils based upon engine technology alone (GWP_{100}). If the methane emissions are to be reduced as assumed above, this benefit would rise to 20 % by 2030. Further GHG emission reductions can be achieved by using liquified biomethane and synthetic methane.

Context

The international shipping industry, as other industry sectors, are under pressure to reduce emissions. The International Maritime Organization (IMO) has announced the ambition to reduce the GHG emissions from international shipping by at least 50% by 2050 compared with 2008.

While the environmental benefits of LNG as an alternative marine fuel are clear in relation to local pollutants such as sulphur oxides (SO_X), nitrogen oxide (NO_X), and particulate matter (PM), various studies have demonstrated different GHG impacts from the use of LNG. These differences have resulted from the studies using different assumptions, methodologies and data. Most importantly, the studies have used different data (primary vs. literature) and assumptions about methane emissions in the LNG supply chain, and methane slip in ship engines. The end result is that there are divergent opinions if LNG as marine fuel can play a significant role in reducing GHG emissions in the shipping industry.

The consideration of the entire life cycle from Well-to-Wake, including primary feedstock production, fuel processing, transport, bunkering and operational use, is essential for the comparison of conventional with alternative fuels. A full life cycle perspective is important to avoid a shift of burdens between single supply chain steps, e.g., a shift of GHG emissions caused during engine operation to the production of the fuel, and is fundamental to establish an level playing field for fuel comparisons with the ambition to develop to a low and zero carbon shipping industry. A simple analysis of the Tank-to-Wake GHG emissions, as currently mandated by IMO, seems to be lacking the whole picture.

Life cycle assessment of GHG emissions of LNG and oil-based marine fuels, and their use is a complex topic due to different engine technologies in operation, the different fuels bunkered and their geographically specific supply chains. In addition, fuels and their supply chain GHG emissions may change over time, e.g. due to the introduction of the low sulphur standards.

The marine engine market, in contrast to the road transport market for instance, consists of a multitude of different engine technologies for different shipping applications and power requirements. This results in the use of different engines with 2-/4-strokes, single/dual fuel, combustion cycles, efficiencies, exhaust gas cleaning systems, etc. Hence, the impact of LNG- fuelled vessels cannot be summarised by one representative technology and propulsion and power provision system.

Significant differentiation is necessary when drawing conclusions, particularly by ship type, size and operational parameters. Large container ships or bulk carriers for instance, are used to transport goods from one continent to another, and hence mainly operate in deep-sea regions (outside ECA), and mostly with a constant engine load after leaving the harbour. In these applications, 2-stroke slow speed engines are typically used. In contrast, ferries or cruise ships mainly operate in coastal areas (e.g. Emission Control Areas regions) and may change engine load more frequently and are hence typically equipped with 4-stroke medium speed engines. For smaller ships such as support vessels and tugboats, engine response with many engine load changes is crucial. There is, therefore, not one single gas engine to be considered, as the operational parameters eventually effect the choice of engine technology.

For ocean-going shipping outside Sulphur Emission Control Areas (SECAs), the fuel sulphur limit has been reduced to 0.5 wt.% since 1st of January 2020. For shipping inside SECAs, the sulphur limit has been 0.1 wt. % since 2015. For NO_X emissions, different Tier limits (Tier I-III) apply based on the construction date of the ship and the engine speed. According to MARPOL Annex VI Chapter 3 Regulation 13.5, Tier III applies when the ship is constructed on or after 1 January 2016 and is operating in the North American

NECA (Nitrogen Oxides Emission Control Area) or the United States Caribbean Sea NECA or on or after 1 January 2021 and is operating in the Baltic Sea NECA or the North Sea NECA. Outside these areas, Tier II limits apply.

Study Objectives

In 2019, SEA-LNG and SGMF commissioned *thinkstep* (now *Sphera*) to perform a comprehensive, industry-wide Well-to-Wake (WtW) GHG emission analysis on the use of LNG as marine fuel. The intention was to reduce the uncertainty regarding the GHG benefits of LNG as marine fuel compared with fuel oils as mentioned above. Special focus was given to methane emissions. The study also investigated air quality aspects. The study collected primary, state-of-the-art data and integrated external critical review before finalising the results and conclusions.

The motivation to conduct the 2nd *"Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel"* is twofold. First, to update the LNG and fuel oil supply chain mixes to the latest data year and the engine data to the latest developments and provide updated GHG intensity and local pollutant emission data. Second, to discuss planned developments in methane emission reduction in LNG supply chains and ship engines and analyse the resulting implication for WtW GHG emissions.

While the analysis has been performed on a global level, it considers:

- the most common ship engine technologies in operation, taking into account the specific fuel consumption and methane slip.
- a global average LNG supply inventory, based on 'bottom-up' calculations of different regional consumption mixes, and LNG production countries.

In 2018, the most common marine fuels were Heavy Fuel Oil (HFO), with a maximum sulphur limit of 3.5 wt. % (and a typical sulphur content of 2.7 wt. %) outside the Suphur Emission Control Areas (SECAs), and Marine Gas Oil (MGO), with a sulphur content capped at 0.1 wt. % inside the SECAs. As a consequence of the IMO's Sulphur Cap introduced on January 1, 2020, this changed due to a global sulphur limit of 0.5 wt. % unless using an approved exhaust gas cleaning system (EGCS) such as a scrubber.

In consequence, in 2020 the most common marine fuel is, according to bunkering statistics, Very Low Sulphur Fuel Oil (VLSFO) with a maximum sulphur content of 0.5 wt.% (outside SECAs), and Marine Gas Oil (MGO) with a maximum sulphur content 0.1 wt.% within SECAs.

Based on the available information, the Project Consortium defined the following fuels for consideration in this study:

- Liquefied Natural Gas (LNG)
- Very Low Sulphur Fuel Oil ($VLSFO_{0.5}$) as a blend of residual and distillate marine fuels with a sulphur content of 0.5 wt. % used as the main reference fuel when operating outside ECAs (IMO Tier II NO_X-limit)
- Marine Gas Oil ($MGO_{0.1}$) as distillate marine fuel with a sulphur content of 0.1 wt. % used as reference fuel in ECA (IMO Tier III NO_X-limit)
- Heavy Fuel Oil ($HFO_{>0.5}$) as residual marine fuel with a sulphur content of >0.5 wt. % with scrubbers as approved exhaust gas cleaning system (EGCS) is investigated in a scenario as the 1st Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel has shown only slight differences in absolute WtW GHG emissions between $HFO_{>0.5}$ with EGCS and $VLSFO_{0.5}$.

The study details the complete Well-to-Wake GHG emissions analysis of the LNG supply and use of LNG as marine fuel. The results of this analysis are compared with the WtW GHG emissions of other marine fuels in order to show the advantages and disadvantages. The study also includes an analysis of current and planned developments regarding methane emission reduction in LNG supply and LNG engines and the quantification of its implication on the Well-to-Wake GHG emission performance.

Methodology and Approach

The collaboration and support from a large number of SEA-LNG and SGMF member companies working across the entire fuel supply chain and engine manufacturers enabled the collection of up-to-date, high-quality technical data. For the main GHG emissions, the IPCC AR5 characterisation factors have been used (1 CO_2, 30 CH_4, 265 N_2O) to assess the global warming potential on a 100-year timeframe (GWP_{100}) as this is currently the most commonly used metric and also in accordance with ISO 14067:2018 on "Carbon Footprinting of Products". Methane emissions from the supply chains as well as methane released during the on-board combustion process (methane slip) have been included. Other impact categories and characterisation methods are considered in a sensitivity analysis in the main body of the study.

The global LNG supply is based on the analysis of five LNG consuming regions (Europe, North America, Asia Pacific, China, and Middle East) which are based on the LNG supply chains of the ten most important and emerging LNG producing countries (Algeria, Australia, Indonesia, Malaysia, Nigeria, Norway, Qatar, Russia (Arctic), Trinidad & Tobago and the USA), covering at least 70 % market share per region.

As with the LNG supply, the global fuel oil consumption mix of the same five main bunker regions is analysed, considering the indigenous fuel oil production of these regions as well as the fuel oil imports from producing countries outside the region.

The analysis distinguishes between the following ship engines and their specific characteristics when operating on different fuels (typical power range shown in brackets):

- 2-stroke slow speed dual fuel engines (up to 75 MW)
- 4-stroke medium speed single and dual fuel engines (up to 20 MW)
- 4-stroke high speed single fuel engines (lower one-digit MW range)
- Gas turbines in simple and combined cycle (lower one-digit MW range up to 22 MW)

These engine technologies are further differentiated by combustion cycle, i.e. Otto combustion cycle (low pressure gas injection) and diesel combustion cycle (high pressure gas injection). Steam turbines as a main fuel oil engine are not analysed in this context due to the small number of vessels in operation with this technology. However, within the LNG supply chain analysis, steam turbines are considered as engine technology in LNG carriers in this study.

The TtW data collection focussed on latest ship engine data, i.e. engine generations where at least one engine has been built and delivered, provided by seven major engine manufacturers (OEMs) and ship operators incorporating the latest engine technologies and performance attributes. Main data providers were Carnival, Caterpillar MaK, Caterpillar Solar Turbines, GE Aviation, MAN Energy Solutions, Winterthur Gas & Diesel and Wärtsilä. Data from MTU Friedrichshafen has been taken from the 1st GHG study.

The study is based on steady-state test-bed data using standard test cycles. GHG emissions based on actual operational fuel consumption and measured emissions data will differ due to load cycles and duration and could be considered as further analysis. However, this data basis is the same for both LNG and fuel oil engines. Since many vessels are used to transport goods from one continent to another, and hence mainly operate in deep-sea regions, and mostly with a constant speed after leaving the harbour, the usage of steady-state data seems a valid approach.

This assessment considers global warming as an environmental impact category only. However, the study assesses the supply and use of LNG as a marine fuel according to ISO 14040:2006 and ISO 14044:2006 and compares the GHG results with values for other marine fuels.

Air quality related local pollutants of sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM) of the fuel combustion are also presented in the results.

The focus of this study is on the data collection and calculation of the GHG emissions of ship engines for LNG and oil-based fuels. For both, primary data has been provided by the OEMs and represents the latest commercial models in operation. Data has been provided for the engine technologies under investigation and has been averaged based on the number of data sets collected.

In general, the chosen approach regarding GHG emissions can be seen as conservative from a LNG perspective (i.e. not favouring LNG) compared with oil-based fuelled engines. Black carbon emissions from oil-based engines are not considered though potentially contributing to the global warming potential from oil-based fuels. This is due to the high level of uncertainty and wide range of impact estimate of black carbon on the climate and the effects of black carbon emissions in low sulphur fuels. The key findings are presented below.

Well-to-Tank Results

Focusing on the Well-to-Tank analysis, results from the study are as follows:

- The GHG emissions of the global LNG supply is calculated at 17.7 g CO_2-eq/MJ (LHV) from Well-to-Tank.
- Contributions to GHG emissions over the total life cycle from Well-to-Tank for LNG are:
    - Gas production, processing and pipeline transport to the liquefication plant (32.5 % contribution, caused by energy consumption and methane emissions).
    - Gas liquefaction and purification (49.5 % contribution, caused by energy consumption)
    - LNG carrier transport (14 % contribution, defined by the distance travelled and the utilisation (in terms of time) of the LNG carrier).
    - LNG terminal operations and bunkering (4 % contribution, caused by energy consumption and methane emissions).
- For the LNG supply, carbon dioxide is the major GHG contributor at 74 %, followed by methane at 25 %. N_2O is negligible. The CO_2 emissions mainly come from fuel combustion, with small amounts of CO_2 vented during processing and purification of Natural Gas (CO_2-removal) if no carbon capture and storage is applied in the particular country. The main sources for the CH_4 emissions are fugitive emissions.
- The Well-to-Tank GHG analyses of the fuel oils are in the same order of magnitude, ranging from 14.0 (VLSFO) to 14.9 g CO_2-eq/MJ (LHV) fuel (MGO). The calculation of the WtT GHG results of refinery products is associated with a range of uncertainties. Different crude oil properties and refinery settings, different levels of desulphurisation and blending ratios, and assumptions made, as well as methodological differences such as different allocation methods can lead to different results. This means that interpretation of results and comparison between studies needs to be undertaken with care. However, in general terms the global supply of oil-based marine fuels has a slightly lower WtT GHG intensity than the LNG supply chain.
- For both, LNG and fuel oil supply chains, GHG emissions differ from region to region. Reasons are different natural reservoir characteristics, and hence production technologies applied, ambient temperatures at liquefaction (LNG supply only), transport distances, etc. For instance, the GHG emissions of the LNG supply range from 17.1 – 19.1 g CO_2-eq/MJ (LHV). Technology consideration as well as a specific supply chain analysis to get to a global average (17.7 g CO_2-eq/MJ (LHV)) are key for the assessment of the supply chains.
- Due to technology improvements and reductions of methane emissions in the supply chain as well as changes in the regional consumption mixes the study should be updated in 2023/2024 to ensure the validity of the results.

Well-to-Wake Results

The total WtW GHG emissions of marine engine are highly dependent on the engine technology and fuel type.

The overall Well-to-Wake GHG emissions of the marine engines operating on oil-based $VLSFO_{0.5}$, $MGO_{0.1}$ and LNG have been calculated based on fuel consumption and emission data provided by seven different engine manufacturers and members from SEA-LNG and SGMF. All data is related to compliance with the IMO Tier II NO_X limits to represent operation outside ECA (deep sea) where the majority of fuel in international shipping is burned. For ECA operation, Tier III results are also shown in the main body of the study (Otto-cycle LNG engines comply to Tier III without any aftertreatment). The data are given in brake power specific units (kWh) per engine technology weighted according to the IMO E2/E3 cycle.

The following tables show the technical parameters (all primary data are provided by engine manufacturers) that are used for the calculation of the Well-to-Wake GHG emissions of the 2-stroke slow speed and the 4-stroke medium speed engines. All energy related numbers in this study refer to the lower heating value (LHV). $MGO_{0.1}$ is assumed as pilot fuel. Pilot fuel is self-ignitable and is needed in dual fuel engines to function as an ignition source for the gas.

Table 1 Fuel consumption and methane slip for 2-stroke slow speed engines based on the IMO E2/E3 cycle (outside SECA and NECA (Tier II))

g fuel/kWh	Oil-based fuels		Gas-based fuel	
	$VLSFO_{0.5}$	$MGO_{0.1}$	LNG	LNG
2-stroke slow speed	Diesel		Diesel-DF	Otto-DF (Tier III)
Main fuel consumption	181.3	174.1	136.4	145.1
Pilot fuel consumption	-	-	6.4	1.3
Methane slip [g methane /kWh] *[%]*	-	-	*0.23* *0.17 %*	*2.14* *1.5 %*

Table 2 Fuel consumption and methane slip for 4-stroke medium speed engines based on the IMO E2/E3 cycle (outside SECA and NECA (Tier II))

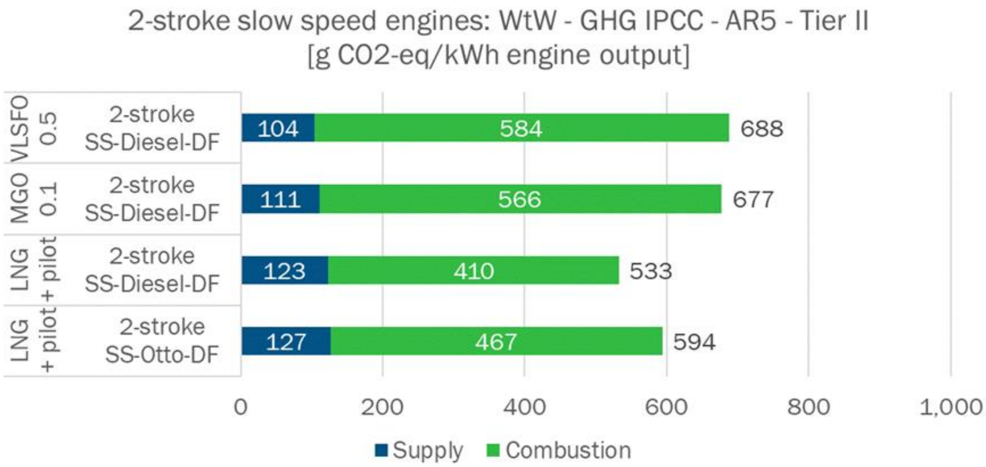
g fuel/kWh	Oil-based fuels		Gas-based fuel	
	$VLSFO_{0.5}$	$MGO_{0.1}$	LNG	LNG
4-stroke medium speed	Diesel		Otto-SI (Tier III)	Otto-DF (Tier III)
Main fuel consumption	191.0	183.7	155.8	153.7
Pilot fuel consumption	-	-	-	3.8
Methane slip [g methane /kWh] *[%]*	-	-	*2.00* *1.3 %*	*3.98* *2.6 %*

2-stroke slow speed engines burn more than 70 % of the fuel used in shipping. Due to their high efficiency and high power, these engines are mainly used in large ocean-going cargo ships. LNG is used in two forms of these engine technologies which differ in their underlying combustion cycle and gas injection system.

a) The WtW GHG emissions of the 2-stroke slow speed Diesel dual fuel engine (high pressure gas injection) are 533 g CO_2-eq/kWh when using LNG. This is 23 % less compared with the same engine operating on $VLSFO_{0.5}$ (688 g CO_2-eq/kWh) as shown in the figure below.

b) The WtW GHG emissions of the 2-stroke slow speed Otto dual fuel engine (low pressure gas injection) are 594 g CO_2-eq/kWh when using LNG. This is a reduction of 14 % compared with $VLSFO_{0.5}$ operation.

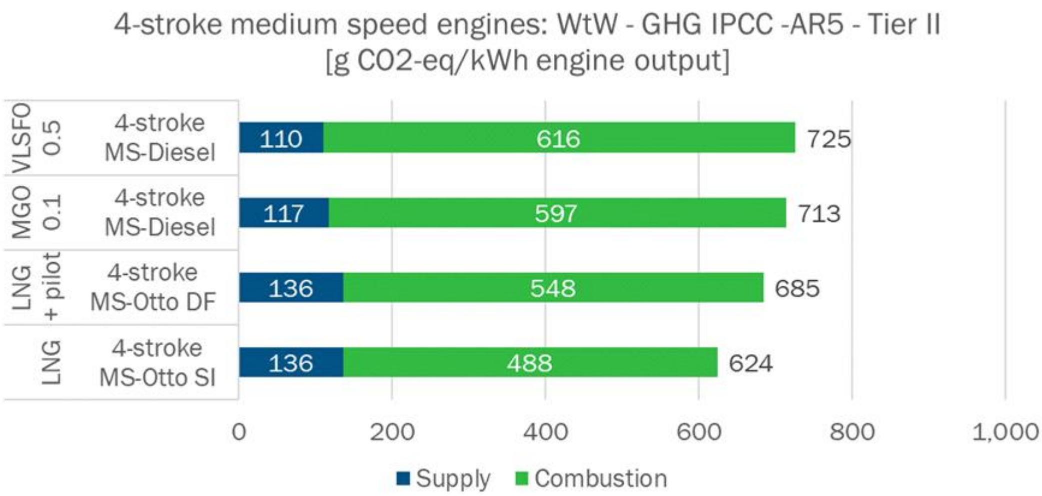
For these LNG fuelled engines, the WtT GHG emissions of the supply chain (term "supply" in figure below) contribute about 21-23 % of the entire life cycle emissions (WtW). For oil-based fuels, the supply chain accounts for 15-16 %.



4-stroke medium speed engine burn ~18 % of the fuel used in shipping. They typically have a lower engine power and are mainly used in car and passenger ferries, cruise ships as well as short sea shipping. Both engines investigated in the study are Otto cycle engines and can be differentiated according to their ability to run on single (SI) or dual fuel (DF).

a) The WtW GHG emissions of the 4-stroke medium speed Otto-DF engine are 685 g CO_2-eq/kWh running on LNG. This is a 6 % reduction compared with operation on $VLSFO_{0.5}$ (725 g CO_2-eq/kWh).
b) The WtW GHG emissions of the 4-stroke medium speed Otto-SI engine which is a single fuel, pure gas engine, are 624 g CO_2-eq/kWh. This is a 14 % reduction compared with the same engine running on $VLSFO_{0.5}$.

For these LNG fuelled engines, the WtT GHG emissions of the supply chain contribute about 20-22 % of the entire life cycle emissions (WtW). For oil-based fuels, the supply chain accounts for 15-16 %.



4-stroke high speed engines only account for 6 % of the fuel burned in global shipping, with gas turbines in simple and combined cycle operation having a minor share of 2 %. Nonetheless, these engines are also analysed in the study and described in detail in the report. The high speed engines and gas turbines only run on $MGO_{0.1}$ and LNG. 4-stroke high speed engines using LNG show a potential GHG reduction of 5 % compared with $MGO_{0.1}$ for the same engines.

Gas turbines in simple and combined cyle have a methane slip during the combustion accounting for only 0.3 % of the overall WtW GHG emissions. Simple operation gas turbines using LNG give a benefit of 21 % compared with $MGO_{0.1}$, or 24 % in combined cycle operation for the same engines.

Methane Emissions Contribution Analysis

Methane emissions can have a significant impact on the total WtW GHG emissions of marine engines. For oil-based marine fuels, methane emissions are limited to the supply chain of the fuel. In LNG operation, the methane slip in the engine (combustion) plays a role in addition to the emission from the supply chain. The following tables show an analysis along the life cycle of the fuel and the contribution of supply and combustion.

GHG emissions resulting from methane account for around 3-4 % of the total WtW GHG emissions of oil-based fuels ($VLSFO_{0.5}$ and $MGO_{0.1}$ in the following tables) and can be considered as insignificant. Methane emissions in the oil-based fuel supply are mainly fugitive emissions released during the production of crude oil. GHG emissions resulting from methane increase significantly to 22 % for certain engines combusting LNG. Methane emissions in the LNG supply chain are mainly fugitive emissions and account for ~6 % of total WtW GHG emissions. For most engine technologies (except Diesel-DF), the majority is thus coming from unburned methane during combustion.

Due to the high gas injection pressure and the combustion in a Diesel cycle, methane emissions in the combustion of the 2-stroke slow speed Diesel-DF engine are about 7 g CO_2-eq/kWh representing 1 % of the total WtW GHG emissions. The data of the 2-stroke slow speed Otto cycle engine shows that methane slip accounts for 64 g CO_2-eq/kWh which is equal to 11 % of the total WtW GHG emissions.

Table 3 Contribution of methane emissions to WtW GHG emissions of 2-stroke slow speed engines (deep-sea Tier II operation)

g CO_2-eq/kWh	Oil-based fuels		Gas-based fuel	
	$VLSFO_{0.5}$	$MGO_{0.1}$	LNG	LNG
2-stroke slow speed	Diesel		Diesel-DF	Otto-DF
Total WtW GHG emissions	688	677	533	594
- **of which** methane	23	24	38	96
- supply	*23*	*24*	*31*	*32*
- combustion	-	-	*7*	*64*

The same characteristics apply for 4-stroke medium speed engines with the two engine technologies investigated using an Otto combustion cycle. The data indicates that pure gas engines (Otto-SI) show lower methane slip. It accounts for 10 % (60 g CO_2-eq/kWh) of the total WtW GHG emissions of the Otto-SI engine. The dual fuel engines investigated in the study show GHG emissions resulting from methane slip of 119 g CO_2-eq/kWh which is equal to 17 % of the total WtW GHG emissions.

Table 4 Contribution of methane emissions to WtW GHG emissions of 4-stroke medium speed engines (deep-sea Tier II operation)

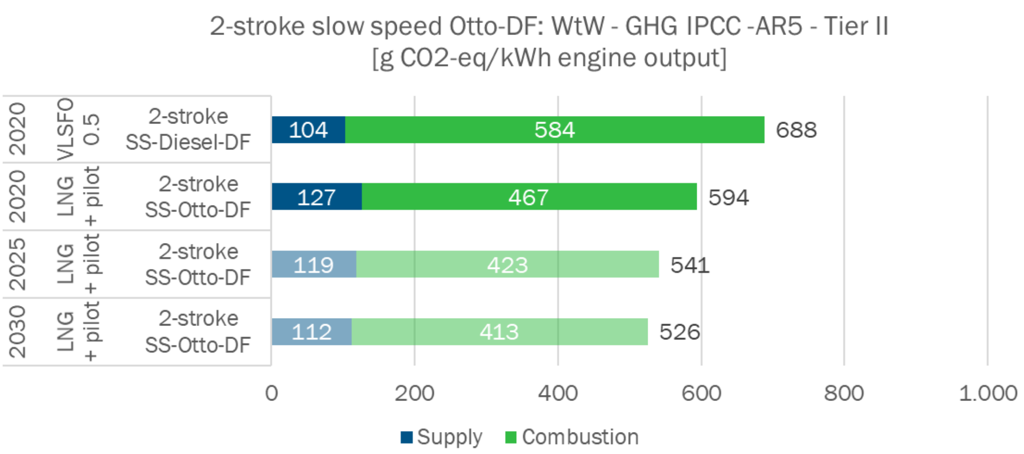
g CO_2-eq/kWh	Oil-based fuels		Gas-based fuel	
	$VLSFO_{0.5}$	$MGO_{0.1}$	LNG	LNG
4-stroke medium speed	Diesel		Otto-SI	Otto-DF
Total WtW GHG emissions	725	713	624	685
- of which methane	24	25	94	154
- supply	*24*	*25*	*34*	*34*
- combustion	-	-	*60*	*119*

Planned Measures to Reduce Methane Emissions

GHG emissions resulting from unburnt methane in the supply of LNG as well as from the combustion of LNG (methane slip) are a significant contributor to overall WtW GHG emission of LNG fuelled engines. Based on the data provided within this study, its share can be up to 22 % of total GHG emissions, of which up to ~16 % are coming from unburnt methane emissions during the combustion, and ~6 % from methane in the supply chain. Reducing methane emissions is hence a top priority for both LNG producing companies as well as engine manufacturers (OEMs).

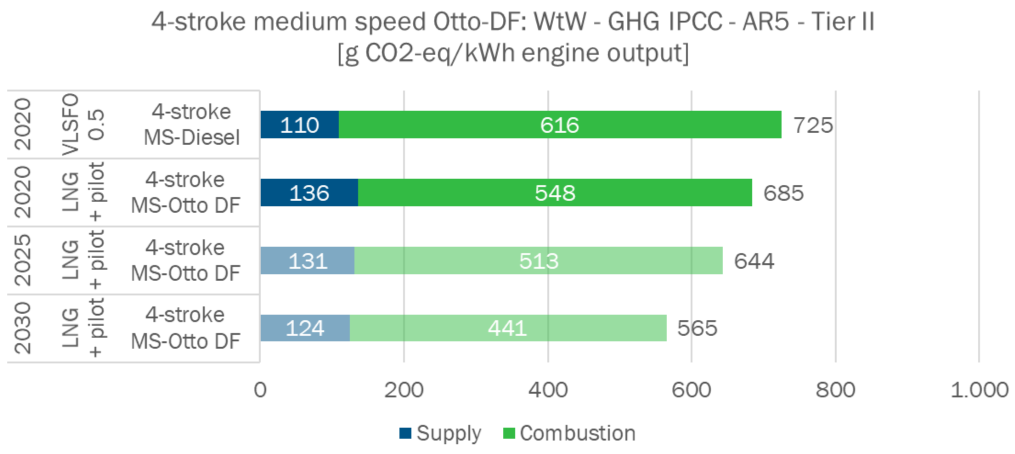
In the supply of LNG, GHG emissions coming from methane make up 25 % of total WtT emissions. Experts from different industry associations and organisations project that methane emissions in the LNG supply could be reduced by 15 % by 2025 and by 35 % by 2030 through different measures. These values are based on actual initiatives and communicated specific targets. This would lead to a reduction of the GHG emissions in the supply of LNG (WtT) per MJ bunkered of 4 % by 2025 compared with 2020 and by 9 % by 2030.

50 % reduction of methane slip for the 2-stroke slow speed Otto-DF engine has already been demonstrated by test-bed measurement data for the particular engine which is entering the market in 2022. Additional 3 % decrease in fuel consumption, as demonstrated on the test-bed, would lead to a WtW reduction by 2025 (including WtT reduction) of 8 % compared with 2020 levels. By 2030, with further announced improvements in the combustion process, the entire GHG benefit of LNG fuelled engines compared with today's $VLSFO_{0.5}$, could potentially reach 24 % instead of 14 % in 2020.



The 2-stroke slow speed Diesel-DF engine already shows very low methane slip. Given the improvements in the LNG supply, total WtW GHG emissions could be reduced by another 2 % increasing the benefit of LNG compared with $VLSFO_{0.5}$ by 2030 to 24 % (in 2020: 23 %).

For the 4-stroke medium speed engines, use of an oxidation catalyst (for pure gas Otto-SI engines) and the implementation of a high-pressure gas injection system (possible for dual fuel engines) would enable methane slip reductions of between 70 % and 90 % (leading to methane emissions below 1 g/kWh). By 2030, this could, together with the improvements in the supply of LNG, potentially decrease WtW GHG emissions of the 4-stroke medium speed engines by 9-18 % depending on the technology applied. This would increase the benefit of LNG compared with $VLSFO_{0.5}$ from today 14 % for the Otto-SI engine up to 21 % and from 6 % for the Otto-DF engine up to 22 %.



The following table gives an overview on the actual benefit of LNG compared with $VLSFO_{0.5}$ as of today.

Table 5 GHG benefit of today's and 2030's LNG fuelled engines compared with $VLSFO_{0.5}$

g CO_2-eq/kWh	2-stroke slow speed		4-stroke medium speed	
	Diesel-DF	Otto-DF	Otto-DF	Otto-SI
Benefit compared with $VLSFO_{0.5}$				
Today	23 %	14 %	6 %	14 %
2030	24 %	24 %	22 %	21 %

It should be noted that the 2025 and 2030 data only consider improvements due to planned measures to reduce methane emissions, and do not consider any other reduction activities, such as other alternative marine fuels like liquified biomethane or synthetic methane.

Air Quality and Local Pollutants

Although the focus of the study is on GHG emissions of the supply and the use of LNG compared with other marine fuels, the influence of the fuel combustion on air quality is investigated but limited to the Tank-to-Wake stage of the life cycle. Sulphur oxide (SO_X), nitrogen oxide (NO_X) and particulate matter (PM) emission data were reported by the engine manufacturers for the operation with LNG and $MGO_{0.1}$. Values for $VLSFO_{0.5}$ have been derived from $HFO_{>0.5}$. Based on these data, the following conclusions are drawn:

- Due to the absence of sulphur in LNG, sulphur oxide emissions of LNG are zero for pure gas engines, and negligible for dual fuel engines where a small amount of sulphur oxide emissions occur due to the use of pilot fuel. Oil-based pilot fuel is self-ignitable and is needed in dual fuel engines to function as an ignition source for the gas. Because it accounts for only 1 to 5 % of the fuel used in normal engine operation, LNG has a clear advantage compared with fuel oils.
- NO_X emissions are mainly dependent on the underlying combustion cycle. Most gas fuelled engines utilise the Otto cycle and comply with the strict IMO Tier III NO_X limits (e.g. for NECAs) without

any NO_X after-treatment system. The 2-stroke slow speed Diesel-DF engines complies with Tier III by incorporating exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) systems.
- PM measurement data were provided for gas turbines and 4-stroke medium speed engines as mass of PM/kWh. Based on these data, LNG can deliver a PM reduction of up to 96 % compared with oil-based marine fuels.

The study confirms that the use of LNG as a marine fuel has significant local air quality benefits.

About us

SEA-LNG is a UK-registered not for profit collaborative industry foundation serving the needs of its member organisations committed to furthering the use of LNG as an important, environmentally superior maritime fuel. www.sea-lng.org

The Society for Gas as a Marine Fuel (SGMF) is a non-governmental organisation (NGO) established to promote safety and industry best practice in the use of gas as a marine fuel. www.sgmf.info

Sphera is the leading provider of Environmental, Social and Governance (ESG) performance and risk management software, data and consulting services with a focus on Environment, Health, Safety & Sustainability (EHS&S), Operational Risk Management and Product Stewardship. www.sphera.com

The full study can be downloaded at: https://sphera.com/research/2nd-life-cycle-ghg-emission-study-on-the-use-of-lng-as-marine-fuel/