Reducing methane emissions onboard vessels

An overview of methane emission sources and levels onboard vessels and the technologies, solutions, and regulatory drivers that can help reduce them.

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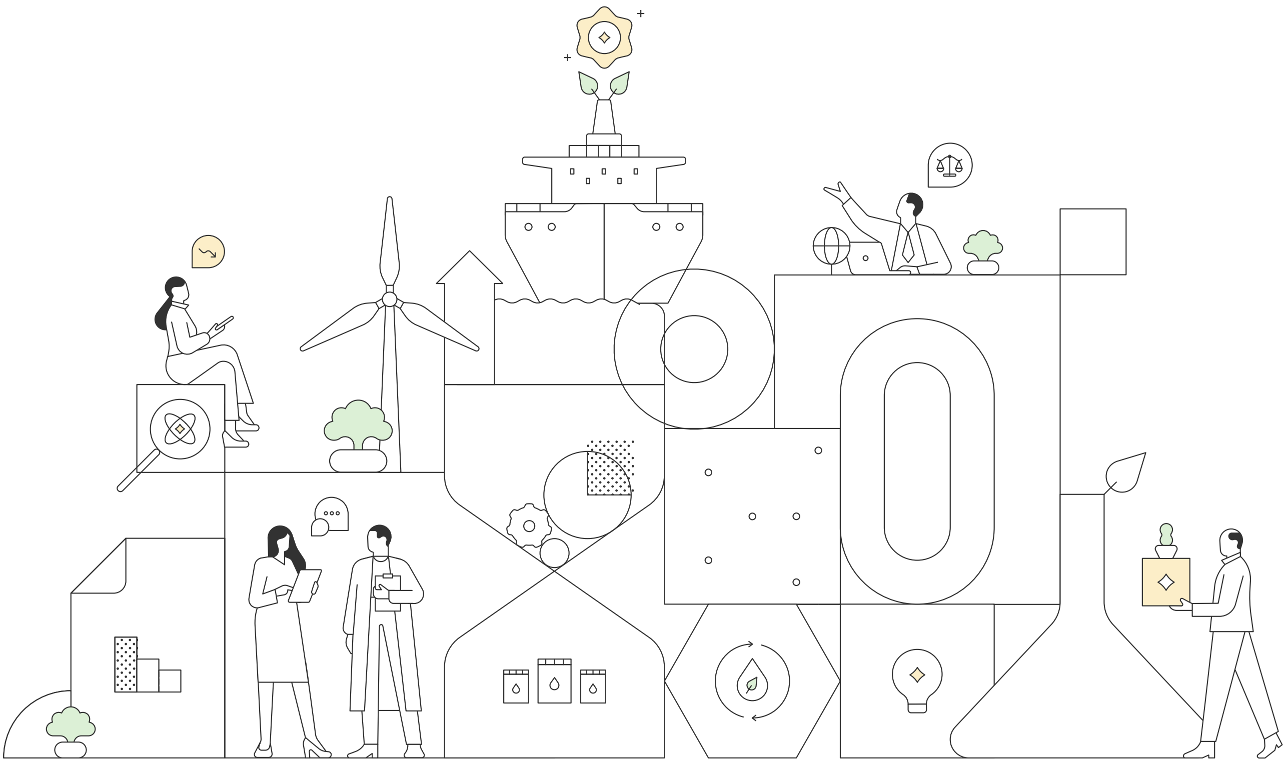
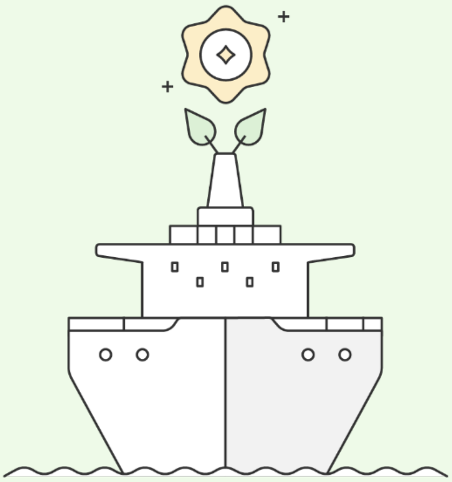


Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping



This paper is the second in the Onboard Vessel Solutions series:

Vessel Emission Reduction Technologies & Solutions

The paper series covers the impact and role of vessel greenhouse gas and air pollutant emission reduction in maturing alternative fuel pathways. Onboard impact is defined in terms of tank-to-wake global warming potential with the role of onboard emission reduction either being for regulatory compliance or as an option to reduce emissions. Fuel pathway maturity is an assessment of solution readiness across the entire value chain.

Based on identified vessel emission risks, the paper series deep dives into specific emissions that need to be addressed to increase alternative fuel pathway maturity. The objective of these deep dives is to understand current or potential emission levels, set reduction targets, and identify and map applicable technologies and solutions. Emission reduction potential is then determined, and recommendations given to mature the selected fuel pathways. Finally, areas or concepts for further research and development are identified including recommended future project topics.

Papers are based on work completed as part of Center projects and working groups consisting of Center partners and external participants and contributors. Working groups provide a collaborative framework facilitated by the Center to jointly engage partners and external experts and companies on specific topics to deliver clear and impactful results.

Abbreviations

AEs	Auxiliary Engines
BOG	Boil-off gas
CH_4	Methane
CO	Carbon monoxide
CO_2-eq	CO_2-equivalent
DAC	Direct air capture
D/G	Diesel Generator
DF	Dual-fueled
EGR	Exhaust gas recirculation
ESD	Emergency shutdown device
EU	European Union
GCU	Gas combustion unit
GHG	Greenhouse gas
GWP	Global warming potential
HFO	Heavy fuel oil
HP	High pressure
HP2st	High-pressure 2-stroke engine
HTL	Hydrothermal liquefaction
HV	High-voltage
IMO	International Maritime Organization
KG	The vertical distance between the ship's keel and its centre of gravity
LCA	Lifecycle assessment
LCV	Lower calorific value
LNG	Liquified natural gas
LNGC	Liquified natural gas carrier
LP2st	Low-pressure 2-stroke engine
LP4st	Low-pressure 4-stroke engine

MBMs	Market-based-measures
ME	Main engine
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
MOC	Methane oxidation catalyst
MRV	Monitoring, reporting, and verification
Pd	Palladium
PM	Particulate matter
PRS	Plasma reduction system
SFOC	Specific fuel oil consumption
SGC	Specific gas consumption
S/G	Shaft generator
TDC	Top dead center
TTW	Tank-to-wake
WTT	Well-to-tank
WTW	Well-to-wake

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Executive Summary

Liquefied electro- and bio-methane have been identified by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) as potential low-emission alternative fuel pathways. In addition, given the rapid expansion of the liquified natural gas (LNG)-fueled vessel fleet and industry projections, the use of LNG as a fuel for the maritime industry will continue well into the future. The use of these methane-based fuels, however, present both a regulatory compliance and climate risk related to onboard vessel methane emissions, in particular methane slip from internal combustion engines, that increases a vessel's overall CO_2-equalivent (CO_2-eq) emissions.

Potential and upcoming regulation of onboard vessel methane emissions presents a risk for methane-based fueled vessel owners, operators, and charterers. Currently, there are no international regulations on methane emissions from vessels, however, ongoing initiatives and regional guidelines indicate that regulations are highly likely to appear soon. The FuelEU for Maritime regulation, for example, will include methane slip in its CO_2-eq methodology.

While CO_2 is the main source of shipping's climate impact with over 90% of total greenhouse gas (GHG) emissions[1], methane has a higher climate impact in terms of global warming potential (GWP). As a result, methane emission reduction can be an efficient way to reduce a vessel's overall CO_2-eq emissions, allowing compliance with upcoming regulations and increasing the viability and competitiveness of methane-based alternative fuel pathways.

A dedicated MMMCZCS working group was established to study reducing methane emissions onboard vessels, which is one vessel specific emission-related consideration for methane-based alternative fuel pathways. Based on its results, the following conclusions have been made:

- **A vessel's total methane emissions should be considered:** While the main source of onboard vessel methane emissions is methane slip from main and auxiliary internal combustion engines, total methane emissions of a vessel is highly dependent on a vessel's operations, system dimensioning, machinery configurations and connected technologies. In addition to selecting baseline engine and potential after-treatment technologies, system solutions can significantly reduce onboard vessel methane emissions.
- **Cost-efficient onboard vessel methane emission reduction is possible but limited for existing vessels:** For the vessels studied, onboard methane emissions can be cost-efficiently reduced by 40-80% for a newbuild and 20-50% for an existing vessel through the selection of baseline engine technologies and the use of after-treatment technologies and system solutions. These reductions translate to onboard methane emissions being reduced from 7-14% of total tank-to-wake (TTW) GHG emissions to 2-8% for a newbuild and 4-12% for an existing vessel. 'Cost efficiency' is defined here as an abatement cost less than about \$200/tonCO_2-eq (which is assumed to be the approximate abatement cost for using bio-methane). Ship owners should carefully consider

1 In terms of 100-year global warming potential (GWP) as defined within the Fourth IMO Greenhouse Gas Study (voyage-based calculation)

onboard methane emission reduction at the newbuild phase to avoid potential costly modifications later in the vessel's lifetime. While it is technically feasible to further reduce onboard vessel methane emissions beyond these levels, utilizing other options like the use of low-emission fuels could be more cost-efficient if further GHG emission reductions are required.

- **Reducing onboard vessel methane emissions are needed to increase viability of electro- and bio-methane fuel pathways:** Reducing onboard vessel methane emissions to these cost-efficient levels increases the longer-term viability of the electro- and bio-methane fuel pathways, however, it is still unclear if upstream well-to-tank fugitive emissions can be reduced to acceptable levels. Using the FuelEU methodology and cost-efficient onboard methane emission reduction measures, GHG WTW emissions can be reduced to 5-9 gCO_2eq/MJ using 100% electro-methane and hydrothermal liquefaction (HTL) Oil as a pilot fuel (a 90-95% decrease relative to heavy fuel oil).
- **Proposed FuelEU for Maritime limits are not strict enough to activate onboard vessel methane emission reduction:** For the vessels studied, GHG emission levels are already compliant with the 2025 and 2030 FuelEU GHG intensity index limits without introducing any onboard vessel methane emission reduction measures. This is due to LNG's lower CO_2 emission factor used within its 100-year GWP methodology. If a CO_2-eq regulation with the proposed FuelEU limits is introduced, no emission reduction actions would be needed until 2035.
- **Regulation is required for widespread adoption of onboard vessel methane emission reduction technologies and solutions:** Without strong incentives or regulatory requirements to reduce methane emissions, there is limited commitment from ship owners to adopt methane emission reduction technologies and solutions. There are ongoing discussions at the IMO to include methane into its LCA methodology, a CO_2-eq approach like FuelEU. There is also the possibility that methane is regulated in a more direct way using a vessel's Technical File like NO_X emissions. This type of regulation could more directly target methane slip levels and the need to reduce them onboard the vessel either for newbuilds or existing vessels if retroactive.

To properly assess the viability of methane-based alternative fuel pathways like electro- and bio-methane, the ability to reduce upstream well-to-tank fugitive emissions needs to be fully understood. Upstream fugitive emissions are not covered in this paper but are currently being studied at the MMMCZCS to enable a complete viability assessment of the methane-based fuel pathways. The MMMCZCS also plans to study onboard vessel emissions in operation where factors like dynamic engine loads and sea states can influence methane emission levels.

1 Introduction

A Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) assessment of vessel emissions from the main alternative fuel pathways[2] found that methane slip from methane-based fuels, including liquified natural gas (LNG), presents a risk of increased CO_2-equalivent (CO_2-eq) emissions. The assessment stated that methane slip reduction solutions have been identified but not fully developed, tested, or demonstrated (see Figure 1). The MMMCZCS established a dedicated working group to complete a deep dive into the emission risks from methane and get a better understanding of the topic. This paper presents the results from the working group, including an overview of regulatory drivers, onboard methane emission sources and expected emission levels, reduction technologies and solutions, and techno-economics.

While CO_2 is the main source of shipping's climate impact, with over 90% of total greenhouse gas (GHG) emissions[3], methane has a higher climate impact in terms of global warming potential (GWP). As a result, methane emission reduction can efficiently reduce a vessel's overall CO_2-eq emissions, allowing compliance with upcoming regulations and increasing the viability of methane-based alternative fuel pathways. There are different options when targeting CO_2-eq emission reduction, including energy efficiency initiatives, alternative fuels, or onboard emission reduction technology. Reducing methane emissions onboard can be a cost-efficient way to make meaningful GHG emission reductions for methane-based alternative fuel pathways.

In addition to a selected fuel, emissions are directly related to the main onboard energy storage and conversion technologies. Internal combustion engines are predominantly used onboard vessels today and will continue to play a role in the future. As a result, in this work, we assume that methane-based fuels will be used with dual-fueled (DF) internal combustion engines. Other energy converters, such as fuel cells, are available or under development and could play a larger role in the future. The emissions from fuel cells and reformers are important to understand and will be covered in an upcoming dedicated MMMCZCS working group.

The structure of this paper (Figure 2) is based on the working group's approach to understanding, quantifying, and assessing

[2] Detailed in the first paper in the Vessel Emission Reduction Technologies & Solutions paper series entitled "Determining the impact and role of onboard vessel emission reduction"

[3] In terms of 100-year global warming potential (GWP) as defined within the Fourth IMO Greenhouse Gas Study (voyage-based calculation)

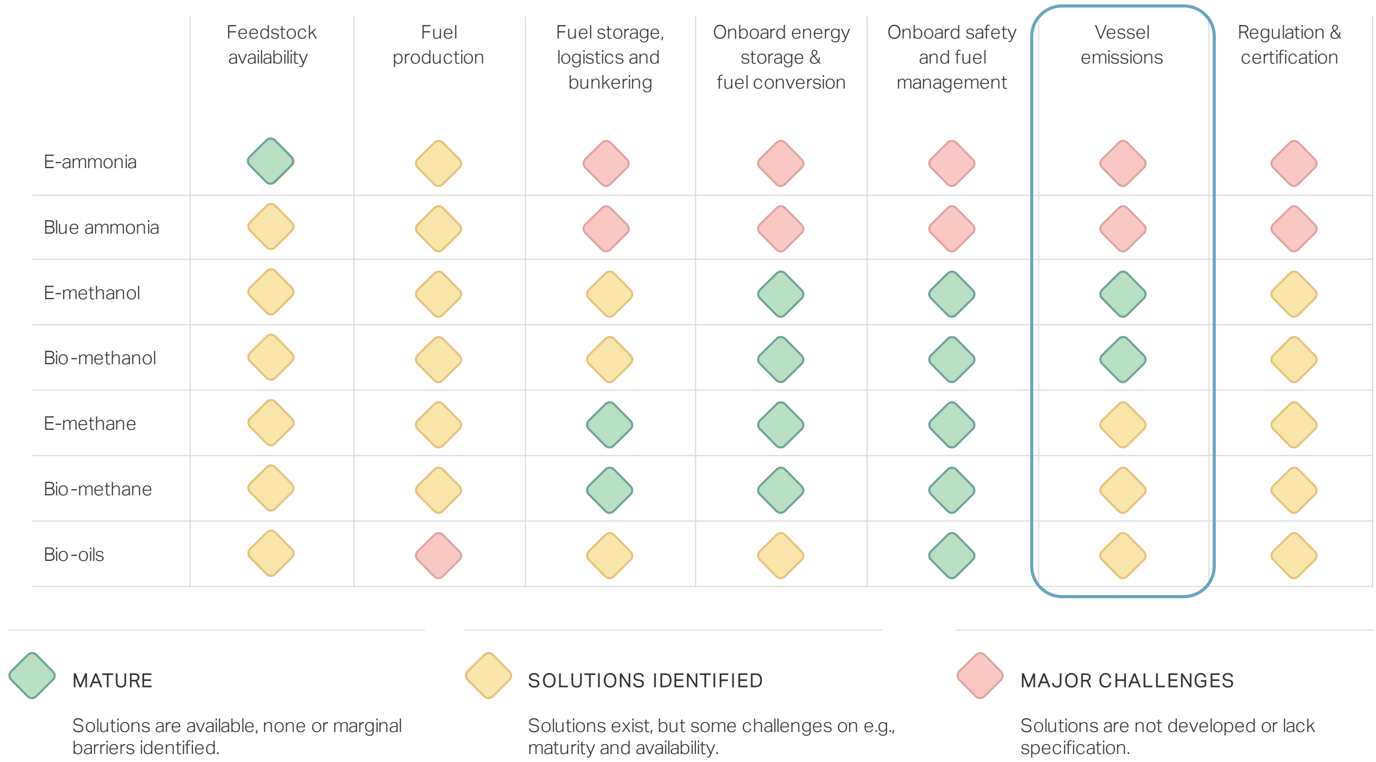


Figure 1: Fuel Pathway Maturity Map (Source: MMMCZCS)

onboard vessel methane emissions. First, we summarized the current and future regulatory drivers. Then we identified and quantified (or approximated) onboard methane emission sources and levels. Next, we mapped currently available technologies and solutions for reducing or eliminating methane emissions for each emission source, calculated achievable emission reduction levels for each solution, and analyzed how they could be integrated into vessels. Then, utilizing the work from the previous steps, we developed a vessel-level calculation model and performed a techno-economic assessment of the identified technologies and solutions. The model was based on the draft Fuel EU calculation methodology, which considers methane slip from a well-to-wake perspective.

Using our vessel-level calculation model, we analyzed the effects of emission reduction solutions for two case studies; an LR2 Tanker and an LNG Carrier. Based on the calculation model results, we identified cost-efficient technologies and solutions to reduce methane emissions in line with regulatory or company targets. This paper concludes with our analysis of how much onboard methane emissions can be reduced and our recommendations for new regulations and technology developments required to realize these reductions.

2 Methane-based fuel pathways

There are three main methane-based fuel pathways: LNG, liquified electro-methane, and bio-methane (Figure 3). LNG is a fossil fuel and is not considered a long-term alternative fuel pathway. Electro-methane is synthesized from green hydrogen and CO_2 captured either from point-source or direct air capture (DAC). Bio-methane is produced from anaerobic digestion of biowaste or biomass. Methane emissions might occur throughout the value chain of the fuel pathways, including production, transportation, and consumption onboard the vessel.

Methane combustion produces a unit quantity of energy with 24% less CO_2 emissions, 90-99% less SO_x, and 90% less particulate matter (PM) emissions than heavy fuel oil (HFO) Tier II. Methane has a shorter lifetime than CO_2 when released into the atmosphere; however, its GWP is higher than CO_2: 1 gram of methane is equivalent to 28 (on a 100-years basis) and 84 (on a

Figure 2: Paper Structure.

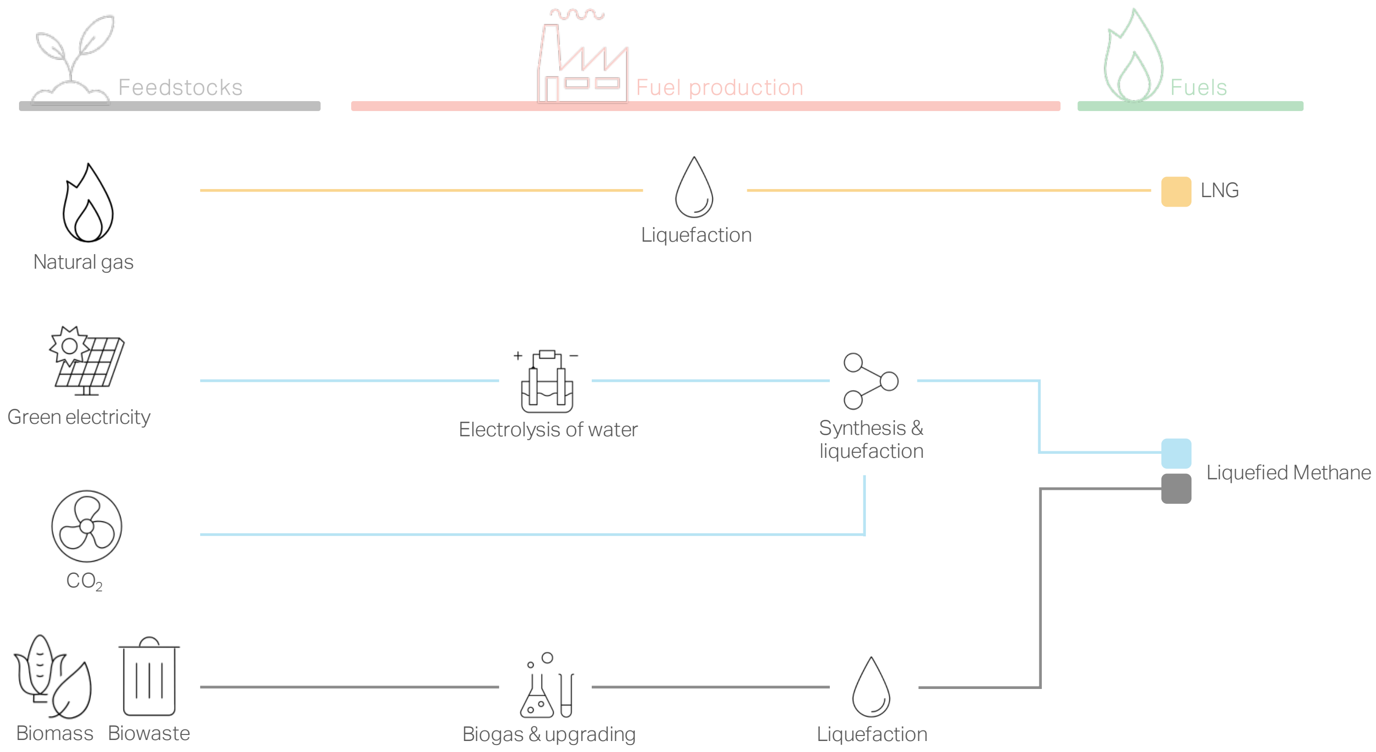


Figure 3: Methane-based fuel pathways.

20-year basis) grams of CO_2[4]. As a result, its overall climate impact is relatively higher than CO_2 for the same quantity of emissions.

Methane emissions occur throughout the natural gas or liquefied methane supply chain, known generally as fugitive emissions in the upstream part. While all sources of methane emissions should be addressed, this paper focuses on tank-to-wake (TTW) emissions which predominantly consists of methane slip. This paper does not cover fugitive methane emissions from the gas system upstream, bunkering, and the associated climate impact.

In 2021, the global LNG-fueled ship fleet expanded rapidly, with 240 orders recorded. Furthermore, the rise of LNG-fueled container, tanker, and cruise ships translates into an increase in the LNG bunker ship fleet. There are now about 694 LNG-fueled ships in operation and under construction, with about 213 more considered LNG-ready. About 20% of the total vessel orders in 2021 were LNG-fueled.[5] The LNG-fueled fleet growth has led to an increasing trend in contracting dual fuel two- and four- stroke engines. According to MAN ES, as of July 2022 the two-stroke dual-fuel contracting reached 53% of contracted engines, measured on a year-to-date basis, in kW. More than 90% of those are LNG-fueled. Given the increased uptake and industry projections, the use of LNG as a fuel for the maritime industry will continue well into the future. What's more, LNG-fueled vessels can also transition to other drop-in methane-based fuels such as liquified bio- or electro-methane in the future.

3 Regulatory outlook

Currently, there are no international regulations on methane emissions from vessels. However, ongoing initiatives and regional guidelines indicate that regulations will likely appear soon. A global methane pledge to cut methane emissions by 2030 was announced at the 2021 United Nations Climate Change Conference (COP 26), signed by both the United States and the European Union (EU). While this can only be considered a manifestation of intent by these countries and covers all methane emission sources, it highlights the importance of methane emissions. It could accelerate the implementation of regulatory measures within shipping. Such measures may include national regulations, efforts to reduce methane slip, or international rules accounting for methane in addition to CO_2, such as inclusion in the next EEDI phases, market-based measures (MBMs), and lifecycle assessment (LCA) guidelines.

While the International Maritime Organization (IMO) does not have specific regulations for methane slip, methane could be included in the IMO regulatory framework in a variety of ways, including:

[4] Synthesis Report - IPCC's Fifth Assessment Report (AR5)

[5] ABS – Setting the Course to Low Carbon Shipping: Zero Carbon Outlook – 2022

- Incorporating methane slip into marine fuels lifecycle GHG assessment guidelines (as agreed at the IMO's 78th Marine Environment Protection Committee meeting (MEPC 78)).
- Including methane slip in EEDI Phase 4 (ISWG-GHG 7/3 and MEPC 75/7/10).
- Including methane slip measurement with the standardized methods (NO_X technical file) during engine certification with methane determined as a CO_2-eq.

At a regional level, the EU is implementing the Fit for 55 package that includes a set of methane-related measures, including:

- By 31 December 2024, the Commission shall assess the impact on the global climate of greenhouse gas emissions other than CO_2, including methane, nitrous oxide, and particles with a global warming potential, from ships arriving at, within, or departing from ports under the jurisdiction of a member state (EU ETS).
- The FuelEU for Maritime regulation considers methane slip. This regulation (applicable from 2025) will limit CO_2-eq emissions by ships on a well-to-wake basis. The effect of methane slip is introduced as a percentage of the mass of the fuel used by the engine (Cslip)
- The Fit for 55 program predicts methane emission reductions in the energy sector.
- Inclusion of CO_2, nitrous oxide, and methane in Monitoring, Reporting, and Verification (MRV) Regulation.

Chinese regulations on marine engines include limits (GB15097-2016 2nd stage: 1 g/kWh) and measurement methods for exhaust pollutants from marine engines (CHINA II). This regulation, which entered into force in 2018, applies to vessels with Chinese flags engaged in inland navigation. This is an important landmark, even if not directly applicable to international shipping.

4 Methane slip from engines

This section outlines the baseline engine technologies and quantifies their associated emissions. The dual fuel (DF) engine market is mainly comprised of three baseline engine technologies:

- A low-pressure 2-stroke engine (LP2st) based on the Otto cycle combustion principle, with gas admitted at a maximum pressure of 13 bar. The LP2st is a main engine (ME) option.
- A high-pressure 2-stroke engine (HP2st) based on the Diesel cycle combustion principle, with gas injected at a pressure of maximum 300 bar. The HP2st is a ME option.
- A low-pressure 4-stroke engine (LP4st) based on the Otto cycle combustion principle, with gas admitted at a maximum pressure of 13 bar. The LP4st can be both a ME and auxiliary option.

The most dominant engine in the market is the LP4st, as it can be used both as an auxiliary engine and for main propulsion in a diesel-electric arrangement. LP4st engine technology was also the first to be introduced and was used on the first LNG vessels. As of 2022, around 42% of all methane dual fuel main engines (ME) are LP4st (by installed power), 34% LP2st, and 25% HP2st.

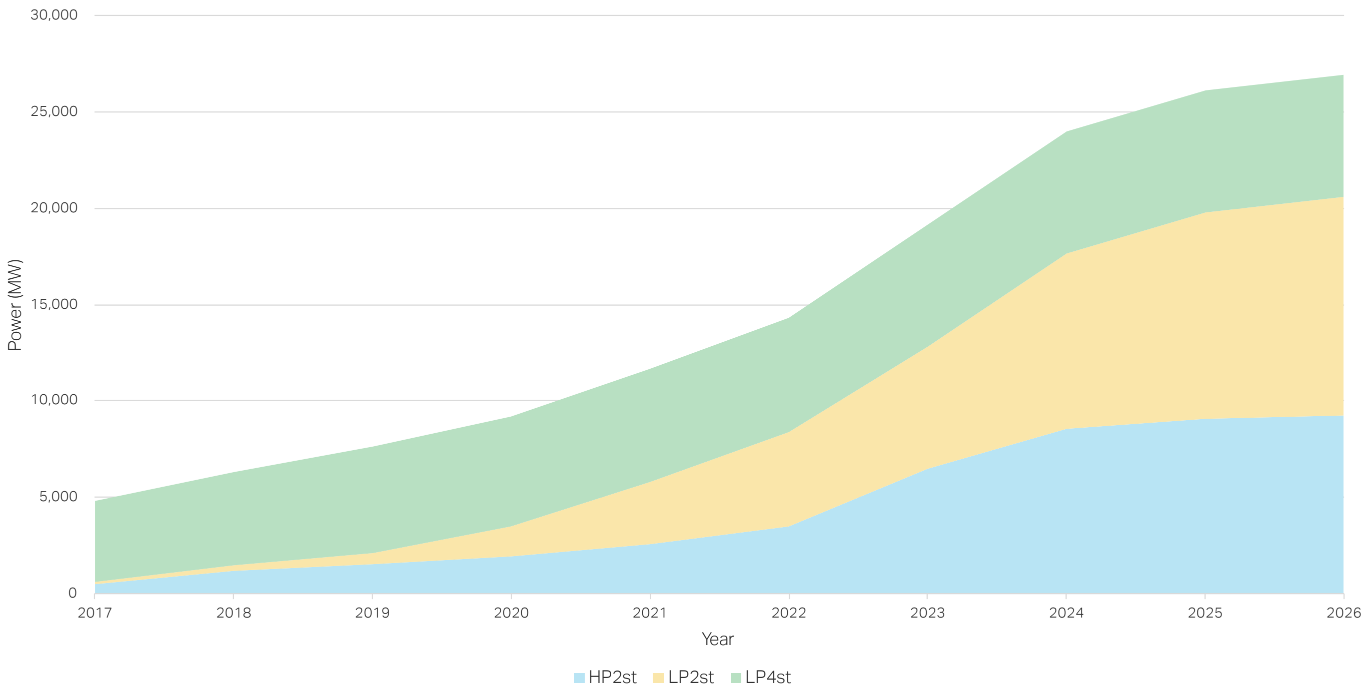


Figure 4: Methane dual fuel main engine market share (Source: Clarksons).

Orders for both LP2st and HP2st engines are continuing to grow as more LNG-fueled vessels are ordered. Market share values in Figure 4 exclude gas/steam turbines, and spark ignition engines, which either have very low methane slip or make up a small market share. Also, auxiliary engines are not included.

Based on current main engine market share analysis, methane emissions need to be considered for all three baseline engine technologies as the two-stroke engine market share continues to grow. However, four-stroke main engines continue to hold a large market share due to their use as auxiliary engines.

4.1 What is methane slip?

There are a variety of ways that methane can escape unburnt into the atmosphere.The most referenced source of methane is 'methane slip,' where a specific methane quantity evades combustion and is emitted via engine exhaust during combustion.

There are two main types of methane slip emissions. Combustion slip occurs with partial or incomplete combustion, and direct slip happens when methane gas flows directly through the exhaust valve during gas admission. In LP2st engines using the Otto cycle (Figure 5), gas is injected and mixed with the scavenging air. As a result, gas-rich and gas-lean areas are created, and the temperature each area reaches varies. The lean and the cold regions can be only partially combusted, leading to combustion slip. Combustion slip can also be load-dependent (dynamic slip): as load decreases, lean mixtures occur more frequently and, in combination with cold parts formed, increases methane slip. Change in gas composition over time also impacts the optimal air/fuel ratio and can lead to a change in methane slip. The ambient conditions also affect the amount of methane slip as the optimal air-to-fuel ratio varies with temperature. What's more, during fluctuating load conditions (i.e., when the vessel encounters heavy weather), the turbocharger cannot follow the changing air demand, resulting in higher methane slip.

Direct slip can also occur with an LP2st engine, with several potential sources. At the time of gas admission, the exhaust valve is "partly" open; therefore, a small amount of gas may flow directly to the exhaust receiver and into the stack. The position of the gas admission valve, exhaust valve timing, and gas admission timing can be optimized to reduce or eliminate the direct slip. Pockets between the liner and piston contain a mix of air and gas that do not ignite, increasing slip. Furthermore, the gas-air mixture that hits the boundary of the combustion is cooled due to heavy cooling of the liner and is also likely to remain unburnt. Pre-ignition of lube oil or from dripping atomizers can lead to early combustion and unstable and incomplete combustion, further increasing methane slip.

Four-stroke DF engines operate on the Otto combustion process, where gaseous fuel is pre-mixed with air before ignition. The air/fuel mixture is compressed and ignited by a spark-plug or liquid fuel pilot injection and is thus in the cylinder for all of the induction and compression strokes and part of the power stroke. In addition, because the four-stroke engines rely much more for gas exchange on inlet and exhaust valves, in the four-stroke Otto process there are increased opportunities for the gaseous fuel to evade combustion (overlap of inlet and exhaust valve openings). Valve overlap creates an unavoidable period during the inlet stroke of a four-stroke engine when both inlet and exhaust valves are open in order to "scavenge" the cylinder. i.e., replace exhaust gases with charge air or air/fuel mixture. Additionally, combustion chamber's geometry can increase the likelihood of "crevice volumes" - areas where pockets of unburnt gas can be trapped that cannot be reached by the flame torches during combustion - thus resulting in methane slip when the exhaust valve opens. The main differences between a LP4st and a LP2st, is that in four-strokes there are typically four valves (meaning four valve pockets and the corresponding crevice

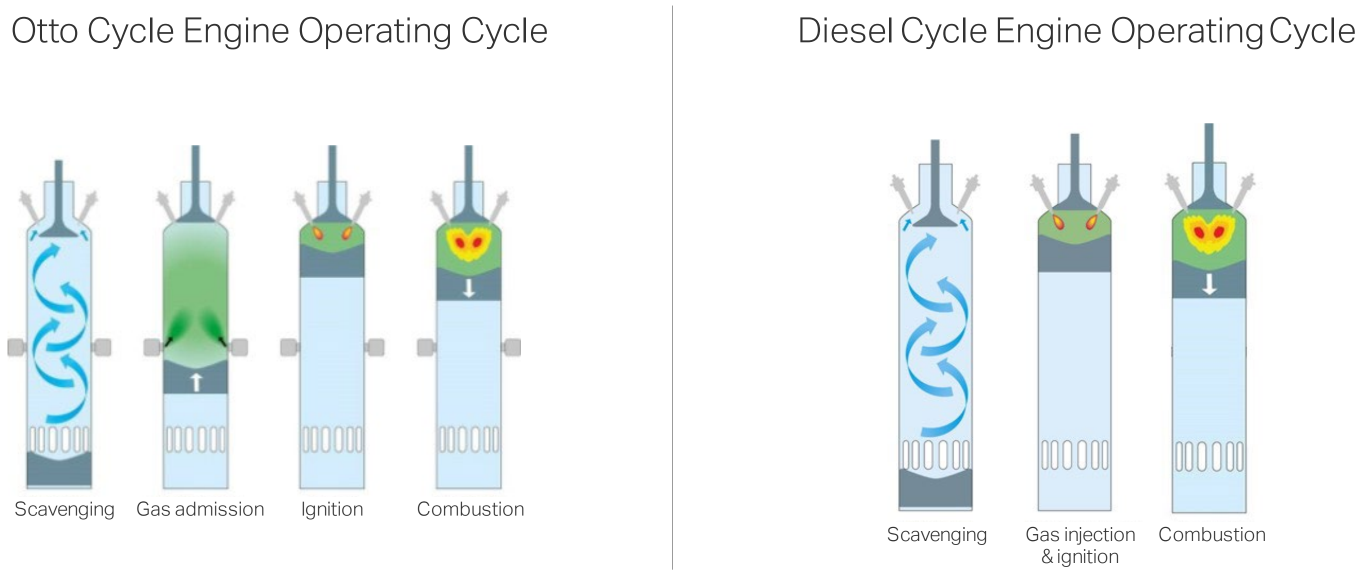


Figure 5: Otto and Diesel cycle engine operating sequences (Source: MAN ES).

volumes) and that four-stroke engines have a smaller combustion chamber (surface-to-volume ratio) plus more moving parts. Engine manufacturers are working on design and system improvements to significantly reduce the methane slip on LP4st engines.

For HP2st engines using the Diesel cycle, gas is injected into the compressed charge air around the top dead center slightly after the liquid fuel pilot, when the pilot has already ignited. Since the gaseous fuel only enters the cylinder after the exhaust valve has closed and ignites immediately, there is no opportunity for methane to escape during cylinder scavenging, which means no direct slip occurs. The injection pressure of the gas will generate a jet stream that "drags in" the needed air from the surroundings, so with the right injection pressure sufficient air is being mixed with the methane gas, and an ideal combustion can take place immediately. This means that no unburnt methane has the possibility to be trapped in crevice volumes, such as the "top land" between the piston and cylinder liner. Such a combustion principle translates to very low combustion slip.

4.2 Methane slip emission levels

Representative methane emission levels were defined for each baseline engine technology based on engine manufacturer data to be used for further emission reduction evaluations. These are provided in Figure 6 and Table 1, in terms of raw methane emissions (g/kWh), CO_2-eq emissions (gCO_2eq/kWh) and (gCO_2eq/MJ) as well as percentage (%) of methane slip in the weight of fuel burnt using a 100-year GWP[6]. The range of values is associated with different engine loads. The emission levels are also shown for typical engine loads (25-85% for two-stroke engines and >50% for four-stroke engines). Methane slip from some engines varies based on engine load, with higher slip typical at lower loads. For the LP2st engine, a configuration with and without exhaust gas recirculation (EGR) is shown. While the initial LP2st engines were introduced without an EGR, it is expected to become a standard part of an LP2st engine delivery. A detailed description of an EGR and its emission reduction potential is provided in Section 5.1.

Table 1: Methane slip emissions levels per engine

Engine Type	CH_4 slip (%wt)	GHG WtW (gCO_2eq/MJ)
HP2st (>25%&<85%)	0.19	76.6~77.9
LP2st without EGR (>25%&<85%)	1.1~1.4	81.3~83.1
LP2st with EGR (>25%&<85%)	0.8~1	79.5~80.9
LP4st (>50%load)	1.5~3.3	83.6~93.0

The baseline engine technology with the highest methane slip is the LP4st, which is typically used as an auxiliary engine onboard LNG-fueled vessels or as part of a diesel-electric arrangement. The LP4st range shown in Figure 6 represents emissions from modern LP4st engines. Older LP4st engines may have higher methane slip emission levels. There is a significant difference between the main engine options, as the HP2st engine has very low methane slip levels (0.20-0.28 g/kWh), whereas the LP2st engine has higher levels of methane slip.

The main assumptions used when defining methane slip emission ranges is that the testbed data for engines are conducted under controlled conditions: the engine operating in a stable condition, without fluctuating loads and without temperature fluctuations. The gas composition is also controlled and within specification, and the injectors are clean and combustion chamber is in good condition. Conditions during vessel operations are more dynamic and variable including varying engine loads, equipment conditions, and sea states. This can lead to increased methane emissions during operation relative to testbed measurements, however, it is difficult to quantify such a difference.

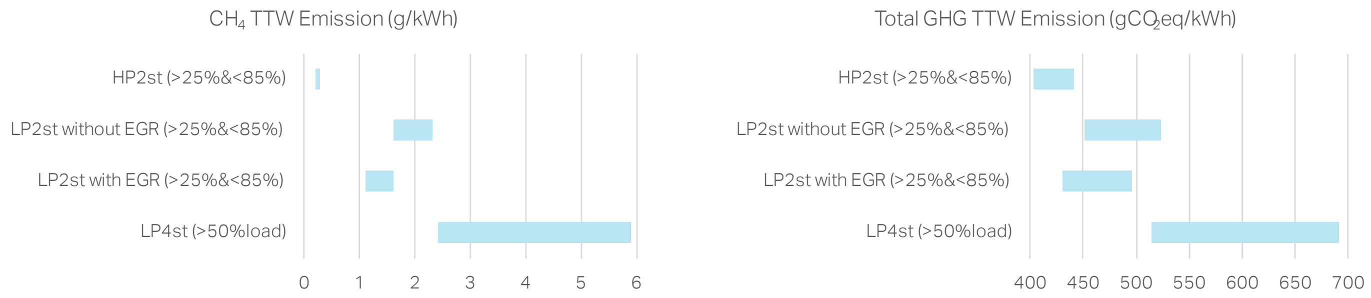


Figure 6: Methane slip emission levels for baseline engine technologies.

[6] CO_2 equivalent values have been calculated on the basis of the Fuel EU proposal methodology (Source: Fuel EU – COM(2021) 563 final)

5 Reduction technologies and solutions

Emission reduction solutions, including engine-related and after-treatment technologies, and their integration into power, propulsion, and other systems will play an important role in reducing methane emissions. The three main emission reduction solution categories include:

1. **Engine technology:** fully integrated with the engine,
2. **After-treatment technologies:** separate from the engine but integrated, and
3. **System solutions:** system dimensioning, configuration, and connected technologies.

Some solutions span multiple categories based on how they are integrated. How technologies and solutions are integrated together and into existing systems is critical and should be considered during design and development. Here, we review engine technologies, after-treatment technologies, and system solutions for methane emission reduction identified by the working group.

5.1 Engine technology

The working group identified four engine technologies for reducing methane slip: **high pressure (direct) injection, exhaust gas recirculation (EGR), engine tuning and control software, and engine component design optimization.** Engine technology development and implementation is driven by the engine designers and manufacturers. Methane slip reduction has been a topic for engine developers for over 10 years and improvements have been made as new engine designs are developed and made commercially available. Engine technologies can only be considered for new engine designs as they are linked to the hardware of the engine and/or require laboratory testing to obtain a valid NO_X Technical File.

High pressure (direct) injection is used on HP2st engines based on the Diesel cycle, which have the lowest methane slip values (0.20 - 0.28 g/kWh across the engine load range) compared to other baseline engine technologies. The low methane slip values are mainly achieved using the Diesel cycle combustion principle. The Diesel cycle is characterized as follows:

- The gas is injected through gas injectors on the cylinder head
- No overlapping of gas injection and exhaust valve timing
- A higher compression ratio, high combustion pressures, and lean operation lead to higher efficiency
- Very high combustion temperatures in combination with a rich mixture can lead to complete combustion, which results in little to no unburned methane molecules
- The high injection speed of the methane allows for an ideal mixture of air and gas

As such, another way to reduce methane slip from four-stroke engines could be to use a similar operational principle to HP2st engines. In this case, the gas and pilot fuel could be injected together directly into the cylinder in the compressed air environment when the piston has reached the top dead center. This would leave no possibility for methane to escape during the four-stroke cylinder scavenging process, resulting in reduced methane slip. While the technical solution of using high pressure injection for four-stroke engines may exist, it might not be commercially viable due to difficulty in implementing and economically less feasible. While NO_X emissions of an HP DF engine are above Tier III limits, known technologies like an SCR or EGR can be used to reduce NO_X to well below Tier III limit levels.

Exhaust gas recirculation (EGR) recirculates a portion of the exhaust gas back into the engine. In combination with other design elements, engine makers have used EGR technology to achieve significant reduction of methane slip in LP2st engines. Second generation engines have EGR technology incorporated as an integral part of engine tuning, and according to engine makers these second generation LP2st engines with EGR technology have 50% lower methane slip than first generation LP2st engines.

Engine tuning is a common practice that uses advanced engine control software to improve combustion performance for four-stroke engines and can reduce methane slip. However, it is hard to quantify the reduction potential of this method. Engine turning software can regulate the following combustion parameters to reduce methane slip:

1. Gas admission, intake, and exhaust valve timing can be optimized during valve overlap.
2. Combustion timing can be optimized to prevent misfiring.
3. Cylinder cut-off can be achieved for loads up to 50%. By cutting off every Nth cylinder, the combustion velocity can be enhanced, and the flame quenching can be decreased.
4. Pilot fuel injection timing and quantity to improve combustion by pre-dispersion and post-ignition of the pilot fuel.

Engine components design optimization is like engine tuning. Engine component optimization is integrated into the engine design process by engine designers and manufacturers as they constantly strive to improve engine component design. Engine design optimization can be used to reduce methane slip by minimizing "dead volumes" in the combustion chamber (Figure 7).

Figure 7: "Dead Volumes Areas" in the combustion chamber (Source: MAN ES).

"Dead" or crevice volumes should be reduced as these are areas where pockets of unburned gas can be trapped. If the combustion flames cannot reach these gas pockets, there is a high likelihood of methane slip. An example of a design modification to reduce dead volume would be changing the position of the piston cleaning ring lower face closer to the top dead center (TDC) of the uppermost piston ring. This change can effectively limit one of the trapped gas/cold areas that cause methane slip.

5.2 After-treatment technologies

The working group identified two main after-treatment solutions: methane oxidation catalysts (applicable only to four-stroke engines) and plasma reduction technology.

Methane oxidation catalyst (MOC) reduces methane emissions in DF methane-fueled engines using a precious (noble) metal-coated catalyst. Methane oxidation can also be achieved via a precious metal free catalyst. Although the tetrahedral structure of the methane molecule is very stable and difficult to break, it can be oxidized using a catalyst.

For oxidation to occur, the following three requirements apply:

1. The catalyst surface must be coated with a noble metal (either platinum, palladium, or rhodium). Palladium (Pd) is considered the most active catalyst for methane oxidation under dry and sulfur-dioxide (SO_2)-free reaction conditions[7].
2. The exhaust gas temperature needs to be high (above 390 ºC).
3. The sulfur content in the exhaust gas should be limited to around 3 ppm. As the main active component on the surface of the catalyst is Pd, an increased amount of sulfur in the exhaust gas will form $PdSO_4$, which will greatly reduce the catalytic performance and lead to an effect called "poisoning."

The presence of water and sulfur can have a detrimental impact on the catalytic performance. A fresh catalyst (no presence of water or sulfur) can achieve significant methane conversion/reduction at sufficiently high temperatures. A catalyst operating at higher levels of sulfur can only perform under high temperatures that cannot realistically be achieved consistently with four-stroke engines downstream of the turbocharger. As sulfur compounds are typically found in fuel and lubricant oils, the sulfur poisoning issue needs to be addressed when using a MOC.

There are four potential options to resolve the issue of sulfur poisoning causing reduced catalytic performance:

1. Direct oxidation desulfurization technology: A desulfurization reactor to trap sulfur placed upstream of the MOC (in front of the catalyst layer)
2. Catalyst regeneration: A thermal treatment to reduce surface residues.
3. Development of low temperature, high efficiency, sulfur resistant catalyst
4. Exclusive use of low sulfur pilot oil

The relatively low temperature (200-300 °C) and high-volume exhaust gas emissions produced by two-stroke DF engines make methane oxidation almost impossible, even in the presence of a catalyst. However, four-stroke DF engines have an exhaust gas temperature range of 275-580 °C, and (according to Topsoe) a MOC could achieve up to 99% methane removal at these temperatures.

The optimal location for an oxidation catalyst is before the turbocharger (Figure 8), where exhaust gas temperatures are high enough for effective operation of the catalyst. However, this location creates additional engineering challenges for both the turbocharger and engine design. An alternative location is after the turbocharger (Figure 8). This location would circumvent engineering challenges with the turbocharger and engine design. However, the lower exhaust gas temperatures will reduce the effectiveness of the MOC and overall methane emission reduction.

To better understand the methane emission reduction potential of MOCs, two case studies were completed[8] based on an LR2 tanker and a 174,000 m^3 LNG carrier, which will be used as case study vessels throughout this paper. Both case studies located the MOC after the turbocharger.

The LR2 tanker case study includes three 1 MW LNG-fueled LP4st auxiliary engines. We assumed that the LNG fuel contained 2 ppm sulfur and the diesel pilot fuel contained 50 ppm sulfur (indicative value). A summary of the parameters and results is shown in Table 2.

[7] Topsoe statement

[8] Case studies were completed by Topsoe

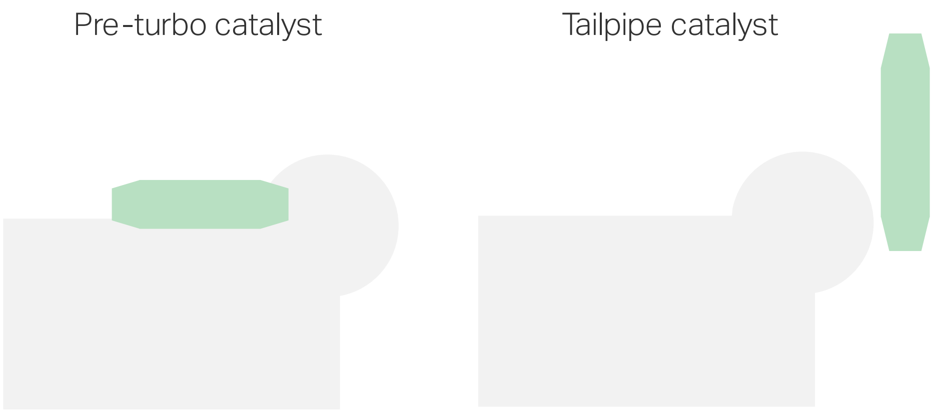


Figure 8: Potential methane oxidation catalyst locations.

The exhaust temperatures from the auxiliary engines of the LR2 tanker allow for a catalytic methane conversion/reduction of 99%, even with sulfur present in both the LNG and diesel pilot fuels.

The 174,000 m^3 LNG carrier case study includes two 3 MW and two 4 MW LNG-fueled LP4st auxiliary engines. Again, we assumed that the LNG fuel contained 2 ppm sulfur and the diesel pilot fuel contained 50 ppm sulfur. A summary of the parameters and results is shown in Table 3.

The exhaust temperatures from the auxiliary engines of the LNG Carrier are too low for maximum methane conversion with sulphur present in the exhaust gas. A methane conversion of 30-66% can be achieved depending on engine load.

The case studies show that with sufficient temperature, high methane emission conversion is possible for LP4st engines.

Moving the MOC upstream of the turbocharger effectively increases the gas temperature to achieve better catalytic activity. However, this brings engineering challenges, as described earlier in this section.

In addition to determining the methane emission reduction potential, a design integration study was completed[9] to assess the feasibility of adding a MOC to a typical vessel. An LNG carrier was used for this integration study. We found that locating the MOC either upstream or downstream is technically feasible. Space is available at both locations, there is a minimal weight increase of around 10 tons and no major impacts on stability or structure. For the upstream position, auxiliary engine fuel consumption will increase by about 1%. For the downstream position, pressure drop was manageable for the vessel studied, but this must be validated.

Table 2: MOC LR2 tanker case study summary.

	1 MW LP 4-st -20 bore engine			
Scenario 1 LR2 Tanker auxiliary engines: 3 x LP 4-stroke 1 MW. Load	%	60	70	75
Methane engine outlet	g/kWh	5,7	5,4	5,3
Exhaust Temp	°C	471	464	461
Catalytic CH_4 removal	%	99	99	99
Methane catalyst outlet	g/kWh	0,057	0,054	0,053

[9] Study was completed by Mitsui

Table 3: MOC 174,000 m^3 LNG carrier case study summary.

Scenario 2 LNGC auxiliary engines: LP 4-stroke 2 x 6 cyl 3 MW + 2 x 8 cyl 4 MW Load		3 MW LP 4-st 6 cyl -35 bore engine			4 MW LP 4-st 8 cyl -35 bore engine		
	%	76	78	83	76	78	83
Methane engine outlet	g/kWh	3,22	3,17	3,05	4,29	4,23	4,07
Exhaust Temp	°C	420	415	408	420	415	408
Catalytic CH_4 removal	%	66	60	30	66	60	30
Methane catalyst outlet	g/kWh	1,09	1,27	2,14	1,46	1,70	2,85

MOC solutions are currently being investigated as a potential solution to reduce methane slip by engine manufacturers and catalyst vendors. The technology is now in the developmental stage, and we expect the first units to be launched between 2024 and 2027. The expected operational lifetime of a MOC would be 2-3 years, depending on the sulfur concentration in the exhaust gas, frequency of operation, and service intervals.

Some key MOC project timelines:

- Topsoe Catalyst: Development period 2020-2022. Field testing 2023 with the market launch anticipated 2024.
- MAN ES 4-Stroke - IMO KAT II project timeline: 2021-2023 investigation of catalyst-engine interaction (including field testing) with the market launch anticipated in 2025.
- Hitachi Zosen – NEDO project timeline: Development period 2021-2026, including: bench scale tests (2022-2023), practical demonstration on a coal carrier (2024-2026), with market launch anticipated in 2026.

Plasma reduction systems (PRS) consist of a catalyst and absorbent-free after-treatment technology that utilizes electric power to convert methane to carbon monoxide (CO) and H_2O. Applying a high voltage current to a PRS cartridge generates a non-thermal plasma called a dielectric barrier discharge between the high voltage electrode and the ground electrode. The non-thermal plasma generates a partially ionized gas with its energy stored in energetic electrons inside the cartridge. The energetic electrons generate hydroxyl radicals which react with methane, breaking it down via a series of transient species to the main products of methane oxidation, H_2O, and CO (Figure 9).

During initial laboratory tests by Daphne Technology, PRS removed up to 78% of the methane from exhaust gases. These tests used an exhaust gas mix with a methane slip of 4.8 grams per kilowatt-hour (g/kWh). A multi-component gas analyzer monitored the breakdown of methane and concomitant product

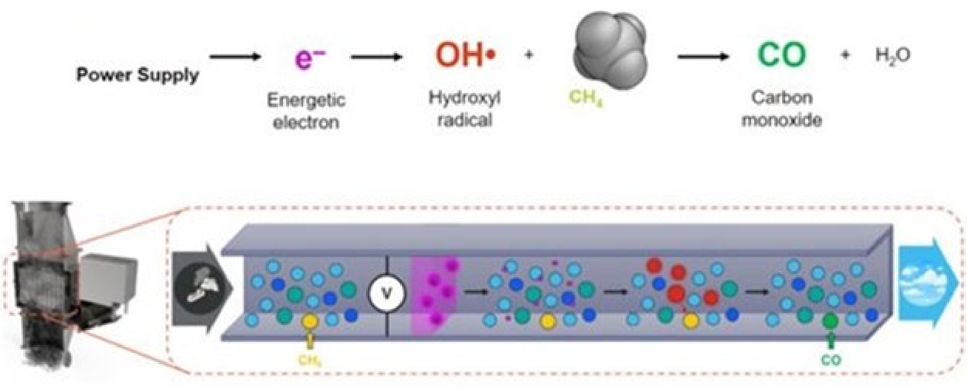


Figure 9: Methane breakdown mechanism with PRS (Source: Daphne Technology).

formation, and 3.7 ± 0.1 g/kWh of methane was removed from the exhaust gas.[10]

The experimental results showed that methane emission reduction rates were higher at higher exhaust temperatures. PRS can be placed both before and after the economizer for two-stroke engines without significant methane removal degradation. PRS can also operate efficiently without methane removal degradation at a wider temperature range (≈150-400 °C) than MOC systems. Furthermore, methane removal efficiency is not affected by sulfur content or high humidity in the exhaust gas.

Additional electrical consumption of around 4% of the main engine output is required to power the PRS, influencing overall GHG emissions. Also, cartridges will need to be replaced at an undefined frequency. A better understanding of all emissions resulting from the use of PRS is necessary before implementation, including confirmation that regulatory compliance can be maintained, for example, for NO_X emissions.

A design integration study was completed[11] to determine the feasibility of adding PRSs to the LNG carrier case. We conducted a total of three PRS design integrations, including two sets for the 12 MW main engines and one 6 MW set dimensioned for two out of the four auxiliary engines. We found that PRS integration is technically feasible and has a total weight increase of around 200 tons and an increase in gross tonnage of less than 1%. The increased weight and location of the PRS will lead to a 0.2-0.4% higher KG and about a 6% increase in bending moment (conservative estimation). The vessel's existing stability and longitudinal strength margins are sufficient to handle these increases. Pressure drop is expected to be around 40 mmaq and is considered acceptable for most designs that typically have a 50-60 mmaq margin.

Figure 10 provides an overview of the LNG carrier PRS integration designs. The red lines indicate the PRS for the main engines, and the green lines represent the PRS for the auxiliary engines.

PRS technology is still under development and not yet proven at large scale onboard vessels. After the successful small-scale lab

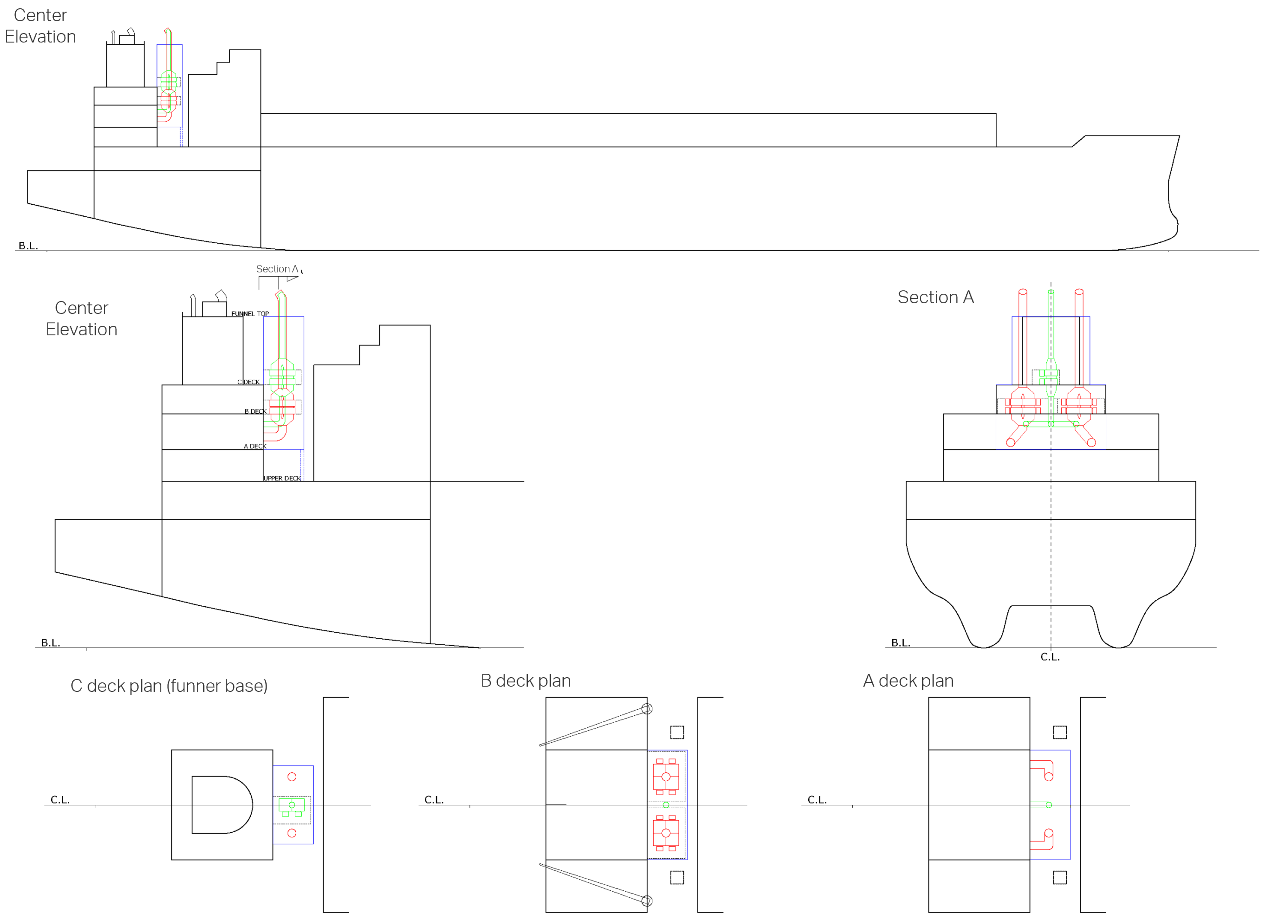


Figure 10: PRS vessel integration.

[10] The provided data for the methane emission reduction of plasma are indicative values based on available small scale test results. All data must be confirmed by large scale testing.

[11] Study was completed by Mitsui

testing by Daphne Technology in the third quarter of 2021, the technology will now be tested onboard an LNG Carrier by Daphne Technology during Q1-Q2 of 2023.

5.3 System solutions

System solutions for methane emission reduction include system dimensioning, configurations, and connected technologies. System solutions that could be primarily considered energy efficiency technologies can also play an important role in reducing specific emissions. For example, methane slip from some internal combustion engines varies based on engine load, with higher slip typical at lower loads. A shaft generator or batteries can be used to increase the engine load and reduce the specific fuel consumption resulting in less methane slip emissions. They could also be used to reduce the use or eliminate the need for auxiliary engines. The emission reduction potential of these solutions is highly vessel-dependent, and general reduction levels cannot be determined. Instead, we considered them part of our holistic ship calculations in our case studies.

Shaft generators can be installed for the main engine with the main objective of increasing the main engine load and, as a result, reducing consumption and emissions from the auxiliary diesel generator sets. Methane slip from LP4st engines is higher than from two-stroke engines, so covering the total electric demand while sailing with the shaft generator allows the operating hours of the auxiliary engines to be reduced, reducing methane emissions overall. Fuel consumption is also improved because a two-stroke engine's specific gas consumption (SGC) is lower than auxiliary four-stroke engines. A shaft generator can either be mounted at the aft end or the front end of the main engine.

Shore power uses a similar principle as the shaft generator to reduce partially or totally the use of auxiliary engines while in port. A shaft generator cannot be utilized in port as the main engine is not operating, so the total electric demand is supplied from shore. The vessel-specific fuel consumption and associated emissions are reduced while using shore power. There are, however, still shore-based emissions associated with providing the electrical power to the vessel via a shore power connection that are not accounted for in vessel-specific calculations such as the FuelEU regulation.

5.4 Methane emission reduction potential overview

An overview of methane slip emission reduction, including engine, after-treatment, and combined technologies, is provided in Figure 11 for each baseline engine technology. The graphs on the left show methane emission reduction potential in g/kWh of methane slip, and the graphs on the right show the total TTW GHG emissions in gCO_2eq/kWh. In some cases, emission reduction technologies can decrease or increase CO_2 emissions while reducing methane emissions. Both emission changes are captured in the total TTW emissions.

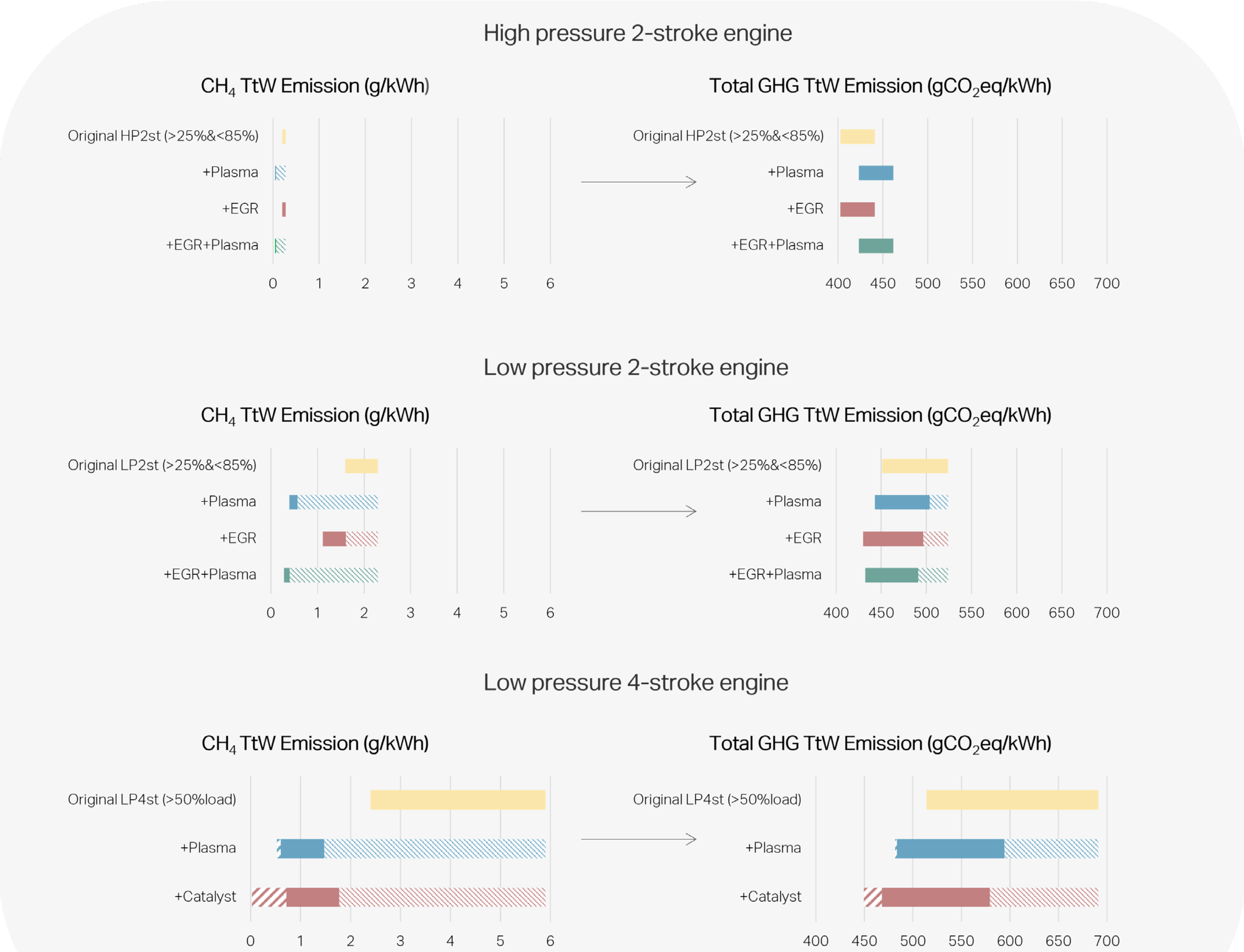
The EGR and the two after-treatment solutions (MOC and PRS) are considered for each baseline engine technology based on applicability. Other engine-specific reductions are considered part of the baseline engine technology emissions. System solutions cannot be addressed at a general level, as shown but are considered later when looking holistically at the total methane emissions of a vessel.

As shown in Figure 11, HP2st engines have such low baseline methane slip levels that applying an after-treatment technology to reduce methane slip leads to a worse overall impact on total GHG emissions in most cases.

The most effective way to reduce methane slip on an LP2st engine is a combination of EGR and PRS. However, the additional energy required to operate the PRS increases the total GHG emissions. Using an EGR requires less additional energy. However, only up to a 48% reduction can be achieved. Most recent newbuilds with LP2st main engines are equipped with an EGR system to reduce methane slip.

LP4st engines have the highest methane slip emissions. Both after-treatment technologies (MOC and PRS) that can be applied to this type of engine are in developmental stages, and only lab test results are available. However, depending on the baseline emissions level of a particular LP4st, using a PRS could reduce methane slip by 50-78%. A MOC can achieve a methane conversion from 70% to 99%[12] (when it is placed downstream or upstream of the turbocharger). When comparing the two solutions in terms of total GHG emissions contribution, the catalyst provides an advantage as it requires no additional energy to operate and, as a result, can achieve lower total GHG emissions. However, the catalyst's performance depends on the exhaust gas temperature and sulfur content.

[12] The stated methane conversions with given sulfur concentrations and temperatures are based on lab results from Topsoe and have not yet been demonstrated on board a sailing vessel. Full scale engine tests are pending.



Yellow Bar: Baseline engine emission value.
Hatched Bars: A technology's emission reduction potential.
Solid Bars: A technology's reduced emission range.
Hatched Lines: The hatched lines to the right indicate the reduction amount relative to the baseline engine technology. Hatched lines to the left indicate for some cases the maximum potential of the technology for some applications.

Figure 11: Methane emission reduction potential overview.

6 Non-engine methane emissions

While combustion and direct methane slip is the predominant source of methane emissions while operating DF methane-based engines, there are other potential sources of methane emissions that are not related to the engine or combustion directly. These non-engine methane emission sources can be categorized into three main emission types: fugitive emissions, operational releases, and emergency releases.

In this section we introduce the main non-engine related sources and recommendations to minimize their effect.[13]

Table 4 lists onboard methane emission sources, including methane slip and other non-engine methane emissions.

It is important to highlight that some of the included emissions are extremely rare and should not occur if proper procedures are followed, and that there are no accidents that result in bunkering or fuel tank (during maintenance) methane releases. Operational measures can reduce or eliminate most of the non-engine methane emissions identified.

[13] TGE Marine provided the main recommendations within this section.

Table 4: Onboard methane emission sources.

Methane Slip Source	From Where?	To Where?	Occasion	Type
Exhaust Gas	Low Pressure 2-Stroke DF ICE	Funnel	Normal Running Condition	"Direct" or "Combustion" Slip
	High Pressure 2-Stroke DF ICE	Funnel	Normal Running Condition	"Combustion Slip" (Negligible Quantity)
	Low Pressure 4-Stroke DF ICE	Funnel	Normal Running Condition	"Direct" or "Combustion" Slip
	GCU or Boiler	Funnel	Normal Running Condition	"Combustion Slip" (Negligible Quantity)
Purging 1 ("Leftover" Gas purged by Inert Gas)	Gas Fuel Piping	Vent Mast	Occurs when gas firing stops (Fuel Changeover)	"Operational Releases"
	Bunkering Piping	Vent Mast	Occurs at the end of Bunkering process	"Operational Releases"
	Fuel Tank	Vent Mast	Gas Freeing Process before Maintenance	"Operational Releases"
Purging 2 ("Leftover" Inert Gas purged by Fuel Gas)	Bunkering Piping	Vent Mast	Occurs at the beginning of the Bunkering Process	"Operational Releases"
	Fuel Tank	Vent Mast	Gassing Up Operation	"Operational Releases"
Leaks from Shaft Seals	High or Low-Pressure Compressors	Vent Duct	Normal Running Condition	"Fugitive Emissions"

6.1 Fugitive emissions

Fugitive emissions are small quantities (in the ppm range) of methane that leak from piping or equipment due to imperfections, screwed connection openings, wear in joints, poor sealing of valves, and other sources.

The Society of International Gas Tanker and Terminal Operators (SIGTTO) issued industry guidelines called "Detection and Reporting of Fugitive Emissions from LNG Carriers" in May 2022. These guidelines provide additional information on the various areas that should be surveyed for potential fugitive emissions. Their five categories of fugitive emission sources include: cargo tanks (tank dome, hold spaces), cargo and fuel piping (pipe penetrations, flanges, flexible connections), cargo and fuel valves (process valves, relief valves, vent valves), cargo equipment (heat exchangers, compressors, pumps on deck) and combustion equipment (engine crankcase assembly, instrumentation, pipe connections).

While the SIGTTO guidelines refer to LNG Carriers, they provide a reasonable basis for methane-fueled vessels. See Figure 12 for a comparison of fugitive emission sources of an LNG carrier compared with an LNG-fueled bulk carrier. We noted that four of the five fugitive emissions categories identified in SIGTTO guidelines also appear in the LNG-fueled bulk carrier.

From these guidelines, we identified a set of measures to reduce the likelihood and amounts of fugitive emissions. These can all be considered as a part of good design and operational practice and include the use of:

- High integrity equipment, where available
- Minimum number of flanges and gas-tight gaskets
- Zero leakage valve specifications
- Combined bursting disc and safety valve arrangements
- Test connection downstream of safety valves and vent connections
- Vent outlets equipped with gas detectors
- Sweep N_2 purge for vent system to allow early detection
- Maintenance plans and instructions
- Immediate repair in case of leakage

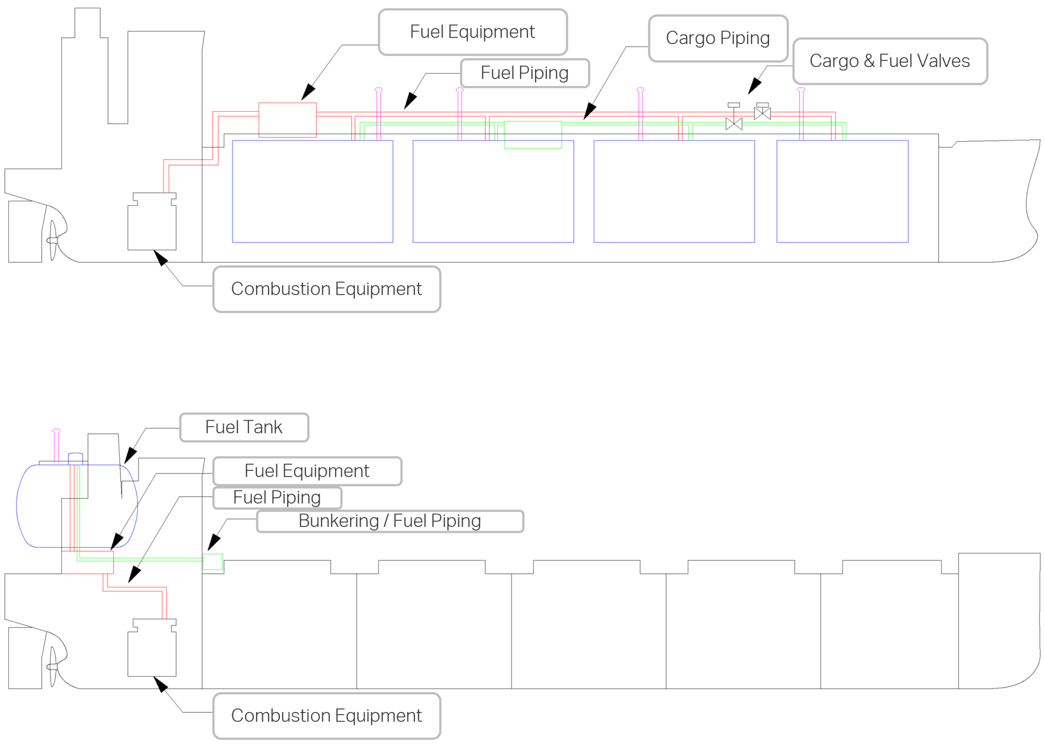


Figure 12: Onboard fugitive methane emission sources.

6.2 Operational releases

Operational releases can also occur and result in higher emission levels (in the kg-tons range) relative to fugitive emissions. These are generally related to releases resulting from the operation of methane-fueled vessels in situations including: purging, cooling down, gas freeing, and inerting. These are typical operational measures that will occur many times during the lifetime of a vessel.

As seen in Figure 13, the effect of "blow-off" gas (operational release) has a marginal effect compared to the combustion-related methane slip and CO_2eq emissions on a yearly basis. This scenario considers one DF engine operating at 75% load and 20 purging operations in 300 days.

The volume of an engine, the diameter and distance of the piping of the fuel supply system, and the density and pressure of the injected fuel can affect the mass of vented methane that occurs during each operational release. Higher density gas in an HP2st engine could mean a higher volume of gas released during blow-off, though the overall quantity of release during blow-off is still low compared to emissions during combustion, as shown in Figure 13.

Measures can be taken to minimize the frequency and quantity of methane emissions from operational releases. These include:

- Optimizing engine supply for maximum gas usage (e.g., reduced feed pressure and heating value in low load)
- Considering the installation of on-board systems/connection to external systems to allow gas dumping when putting tanks into or out of service (tank maintenance procedure)
- Gas freeing from the tank should be avoided (e.g., during Gas Trials or before scheduled Dry-Dock)

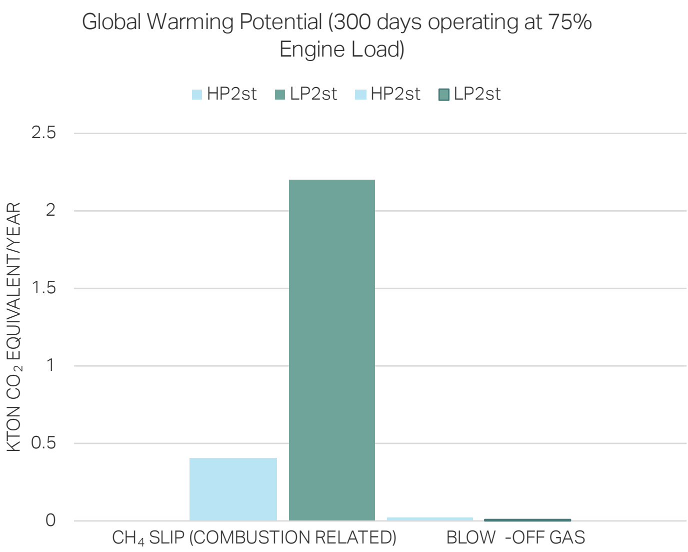


Figure 13: The effect of operational releases in LP2st and HP2st engines (Source: MAN ES).

Recommended equipment to reduce operational release emissions include:

- High Pressure (HP) pumps (permanent leak stream – pistons)
- Boil-off gas (BOG) compressors (mechanical seal)
- LNG Pumps (seal-less – submerged or magnetic coupling)
- During the start-up of the LNG pump system, LNG is recirculated across the LNG pump, pipes, and valves. A procedure for handling this warm gas should be made available to avoid venting this gas.

6.3 Emergency releases

Emergency releases (in the range of kilo-tons) can also occur during the vessel's lifetime; however, such a situation is extremely rare in operation. These emergency releases are caused by emergency shutdown device (ESD) activation, blowing safety valves into the atmosphere, and accidental leakage from equipment failures. While these emissions are rare, there are design and operational measures that can be taken to reduce their likelihood, including:

- Route relief valves back to tanks where possible
- Use high integrity equipment (e.g., double-walled heat exchangers)
- Exclude blocked-in liquid scenarios as much as possible
- Carrying out of maintenance and testing at regular intervals
- Immediately repair in case of leakage (Always have sufficient spares available or build in redundancy in the system. Spares can be pipes, valves, pump sealings and valve seats, piston rings, etc.)

6.4 Quantifying non-engine methane emissions

While we would like to quantify non-engine fugitive, operational, and emergency release methane emissions, there is little information available on the frequency and amounts of these emissions.

For fugitive emissions, high-pressure systems generally have a higher number of emission sources (valves, flanges, etc.) than low-pressure systems; thus, a higher level of fugitive emissions should be expected. Higher power output and machinery loads can also result in higher fugitive emissions as larger supporting equipment is required.

Operational releases depend on operating procedures and the equipment installed/setup for non-standard operations (DF boilers, GCU, etc.). Operational releases are generally higher for high-pressure systems compared to low-pressure systems. More methane is released into the atmosphere per engine vent due to the pressure and the density of the gas compared to low-pressure Otto engines.

Emergency releases directly result from operation and maintenance procedures and directly relate to crew training, knowledge, and operating practices. For example, opening the tank safety release valve would cause a methane release, but this should not happen during the ship's lifetime. In general, emergency releases should be rare when the vessel is operated correctly.

Quantifying the effects of non-engine fugitive, operational, and emergency emissions is an intricate and challenging task that needs to be investigated further but falls outside the scope of this report.

7 Vessel-level methane emissions

Looking at the baseline engine technologies and emission reduction technologies and solutions independently does not provide a holistic view of the total methane emissions from a vessel. To determine the GHG emissions of methane DF engines at a vessel level, we developed a complete vessel emission calculation model using the draft FuelEU methodology. The model can help quantify the total methane emissions of a vessel and determine if the vessel complies with a CO_2eq regulation, such as the regulations proposed in FuelEU.

The formula used in the FuelEU proposal (Equation 1) to calculate a GHG intensity index is broken down into two parts: well-to-tank (WTT) and tank-to-wake. The WTT component considers the CO_2 equivalent emissions from each fuel delivered to the ship per MJ of energy delivered to the ship and the CO_2 equivalent emissions from electricity delivered to the ship at every connection point per MJ of energy delivered to the ship. The TTW component considers the CO_2 equivalent emissions from each fuel combusted in every consumer of the ship under consideration, per MJ of energy delivered to the ship and the

Equation 1: FuelEU GHG intensity index formula (Source: Fuel EU - COM (2021) 563 final)

GHG intensity index	WtT	TtW
GHG intensity index $\left[\frac{gCO_{2eq}}{MJ}\right]=$	$\frac{\sum_i^{n\ fuel} M_i \times CO_{2eqWtT,i} \times LCVi + \sum_k^c E_k \times CO_{2eq\ electricity,k}}{\sum_i^{n\ fuel} M_i \times LCVi + \sum_k^c E_k}$	$+\frac{\sum_i^{n\ fuel} \sum_j^{m\ engine} M_{i,j} \times \left[\left(1-\frac{1}{100}C_{engine\ slip\ j}\right)\times\left(CO_{2eq\ TtW,j}\right)+\left(\frac{1}{100}C_{engine\ slip\ j} \times CO_{2eq\ TtW,slippage,j}\right)\right]}{\sum_i^{n\ fuel} M_i \times LCVi+\sum_k^l E_k}$

CO_2 equivalent emissions from un-combusted fuel (slip) from each consumer of the ship per MJ, of energy delivered to the ship.

We applied the complete vessel emission calculation to our two case studies: an LNG-fueled LR2 tanker and a 174,000 m^3 LNG carrier. All calculations are based on operating profiles summarized in the Appendix. For both vessels, an LP2st and HP2st DF main engine was investigated along with LP4st auxiliary engines. The LR2 tanker LP2st case includes an EGR as part of the baseline engine technology, while the LNG carrier does not have an EGR part of its baseline.

The main fuel in our case studies was LNG, with a low-sulfur marine gas oil assumed to be the pilot fuel. The emission and energy input in various operations was calculated at representative average load points. The purged methane from the tank at gassing-up or gas-free operation was assumed to be oxidized in a gas combustion unit or boiler. All the methane slip, SFOC, and lower calorific value (LCV) values used were indicative values by engine manufacturers.

The total well-to-wake (WTW) GHG emissions (gCO_2eq/MJ) for both vessels are shown in Figure 14. We include total WTT GHGs and TTW CO_2, methane, and N_2O for easy comparison to the FuelEU WTW GHG intensity index. Onboard methane emissions were 6-11% of the total WTW GHG emissions, with the LP2st ME + LP4st AEs (for both ships) associated with the largest methane emission contribution. While total GHG emissions are less for the HP2st ME + LP4st AEs, this option produces slighter higher GHG TTW (CO_2) emissions, mainly due to the additional energy consumption of the high-pressure equipment needed.

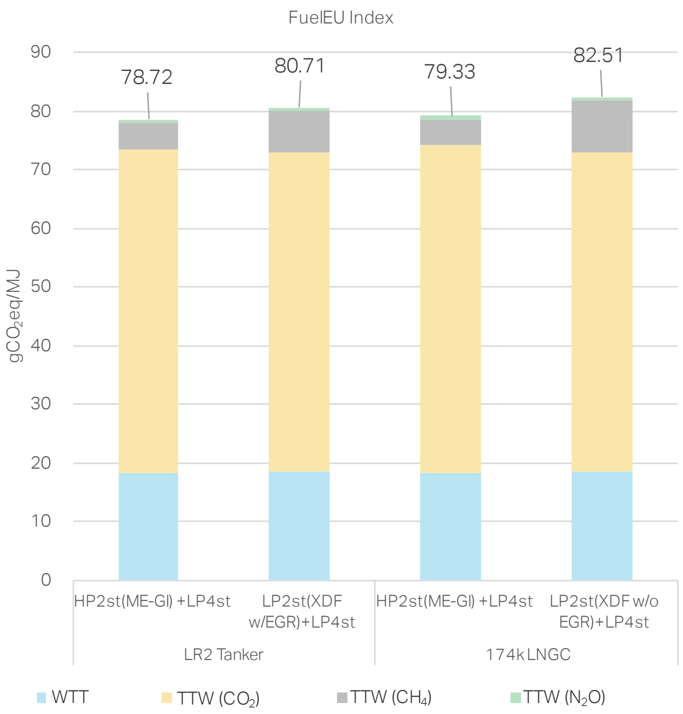


Figure 14: Total well-to-wake GHG emissions.

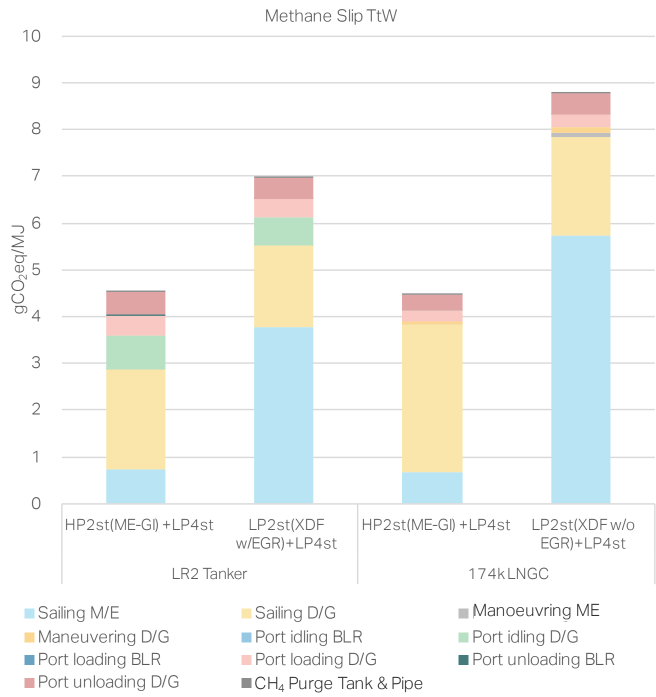


Figure 15: Methane emission contributions by operation type.

In addition to the selected baseline engine technologies, methane emissions depend highly on the operational profile and the onboard power and propulsion concept. Figure 15 shows the methane emission levels associated with different types of operations.

Overall, methane slip levels are higher for the vessel configurations with an LP2st ME than an HP2st ME (7.0 gCO_2eq/MJ versus 4.6 for the LR2 tanker and 8.8 versus 4.5 for the LNG carrier). This difference can mainly be attributed to the methane slip from the ME. For the LP2st ME configuration, the ME contributes more than 50% of the total methane slip while at sea. For the HPs2t ME configuration, the ME contributes less than 20% of the total methane slip.

In the vessels with an LP2st ME, methane slip is mainly emitted in sailing mode when almost all emissions are from the ME. This indicates that the baseline ME technology selection will be a primary driver in reducing total methane emissions. As sailing days represent the largest amount of time in the operational profile, in the HP2st cases, it was found that LP4st engines are the biggest methane slip contributor.

For the LR2 tanker and LNG carrier, methane slip emissions are also increased during cargo operations, where high LP4st engine usage is required. However, the days a given vessel spends at the port are much less than sailing days. Thus, the methane slip impact during cargo operations represents a smaller fraction of the overall methane emissions.

8 Reducing vessel-level methane emissions

The baseline main engine technology can be a major contributor to the vessel's total emissions and, as a result, should be the initial focus for emission reduction efforts. With an HP2st ME configuration, methane emission reduction efforts should start with reducing methane emissions associated with the LP4st AEs. With an LP2st ME configuration, investigating methane emission reduction associated with the main engine should be considered first. Applicable emission reduction technologies and solutions will depend on if the vessel is a newbuild or if retrofitting an existing vessel is being considered. For example, retrofitting a shaft generator is unlikely to be feasible due to the vessel's existing hull form design; however, one can be integrated into a newbuild.

We calculated the vessel-level methane emission reduction potential for each technology or solution discussed previously, as outlined in Figure 16. The solutions studied include PRS for the main and auxiliary engines, MOC only for auxiliary engines, shaft generator, EGR for main engine and shore power. Combinations, including shaft generator, shore power, and other solutions, were also evaluated and can be found in the Appendix. CAPEX is estimated on a newbuild basis, an LNG fuel price of $610/ton is used, and the electric cost for shore power is estimated at $0.2/kWh.

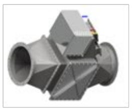
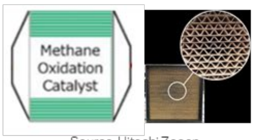
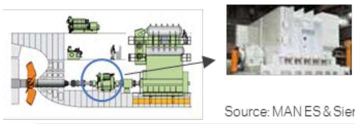
Measure	Application	Principle
Plasma Technology  Source: Daphne Technology	Applicable for both M/E & D/G Not recommended for HP2st, since additional CO_2 by plasma is higher than reduced CH_4 slip	CH4 is decomposed to H_2O and CO by plasma power. No restriction is required for inlet exhaust gas condition. But additional power for plasma cause additional CO_2. The performance of the device is expected as below. - LR2 tanker M/E : 75% at 4% power of engine consumed - LR2 tanker D/G : 50% at 4% power of engine consumed (Only operated at sailing and port idling for 1 D/G operation) - LNGC M/E : 75% at 4% power of engine consumed - LNGC D/G : 70% at 4% power of engine consumed (Only operated sailing for 2 small D/G operation)
Catalyst  Source: Hitachi Zosen	For D/G under development For M/E, temperature is too low to oxidize CH_4 and interference of the performance could be caused, if the catalyst is installed at the inlet of turbo charger.	Oxidization catalyst can oxidize CH_4 to CO_2 and H_2O. But, generally, Sulphur content in fuel cases deterioration of performance and higher exhaust gas temperature is required. Low pressure 4 stroke engine which is normally used as D/G, has relatively higher exhaust gas temperature so that application of the catalyst is easier than 2 stroke engines. The expected performance of the catalyst is 70% CH_4 reduction. The catalyst is operated only at sailing and port idling for 1 D/G operation in case of LR2 tanker and at sailing for 2 small or 1 large D/G operation in case of LNGC.
Shaft Generator  Source: MAN ES & Siemens	Installed for M/E, but the main aim is reduction of emission from D/G	CH4 slip from low pressure 4 stroke engine is higher than that from 2 stroke engine. Since whole electric demand at sailing is covered by shaft generator, operation hour of D/G is reduced. Fuel oil consumption is also improved, because SFOC for 2 stroke engines is better than 4 stroke engines.
Shore Power 	Alternative to use of D/G Note | GHG including CO_2 from shore is not accounted.	During vessel in port, whole electric demand is supplied from shore side. GHG emission for shore power is not counted on GHG index for vessel in FuelEU. So, GHG from D/G at port operation is totally no count for GHG emission
Exhaust Gas Recirculation (EGR)  Source: MAN ES	Applicable only for M/E	The EGR system works through drawing around 30 to 50% of the engine's exhaust gas into the EGR receiver, where it passes through a pre spray to lower its temperature, before passing through a cooler spray. After passing through a water-mist catcher, the gas then goes through a blower to increase pressure back up to scavenging air pressure, before being fed back into the compressor and the engine. This process improves the stability of the combustion process by eliminating the chance of lean mixtures formation and thus reducing methane slip.

Figure 16: Vessel-level methane emission reduction solution assumptions.

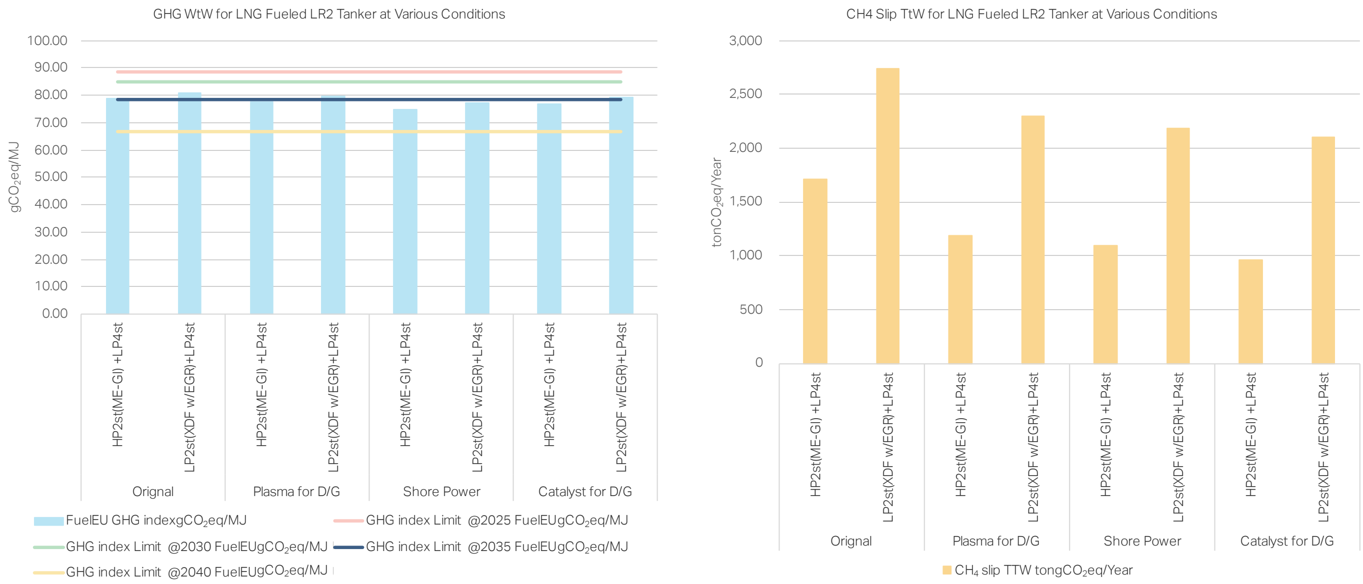


Figure 17: LR2 tanker WTW GHG emissions for emission reduction measures.

For both ships and all engine arrangements, the effect of implementing different emission reduction measures was calculated by estimating the total WTW GHG emissions. The results of these calculations are shown in Figure 17 for the LR2 tanker and Figure 18 for the LNG carrier. For each vessel and engine configuration, the GHG emissions and yearly methane slip are shown for the original configurations after adopting a selection of emission reduction measures. We have also included FuelEU GHG intensity index limits for 2025, 2030, 2035, and 2040 to show how the studied methane emission reduction solutions can help vessel owners achieve compliance. A full version of the figures, including all the investigated emission reduction measures, can be found in the Appendix.

This analysis allows for both an assessment of regulatory compliance and a comparison between methane emission reduction technologies and solutions that can be used to reduce emissions and achieve compliance. For the two vessels studied and both ME configurations, the emission levels before emission reduction measures are implemented are already below the 2025 and 2030 FuelEU GHG intensity index limits. However, they are very close to or exceed the 2035 limits. For reference, the FuelEU level for HFO is 91.6 gCO_2eq/MJ.

As this is a CO_2eq methodology, there are multiple ways to reduce emissions to comply with the regulation, including using alternative fuels or onboard emission reduction technologies and solutions. However, it is important to highlight that energy efficiency initiatives to reduce the vessel's total energy demand do not impact the FuelEU index levels as it is a GHG intensity metric that measures emissions per unit of energy used by the ship. As a result, energy efficiency initiatives would result in lower

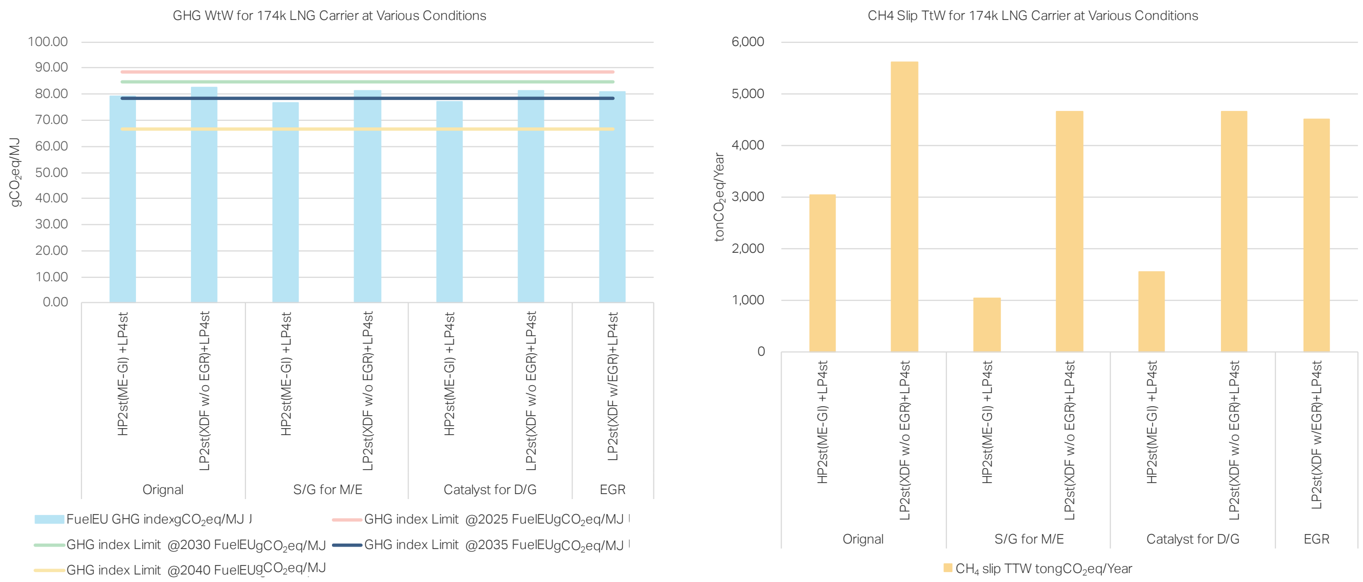


Figure 18: LNG carrier WTW GHG emissions for emission reduction measures.

absolute emissions, but also lower energy consumed, so the GHG intensity index would remain unchanged.

As shown in Figure 17 and Figure 18, there are several options for reducing emissions to achieve compliance in 2035 and 2040 using onboard emission reduction technologies and solutions. For the LR2 tanker with an HP2st ME, PRS with only the LP4st AEs could reduce emissions in line with 2035 FuelEU limits. However, for the LP2st ME configuration, PRS must be applied to both the ME and AEs for compliance to be achieved. Shore power also effectively eliminated auxiliary loads and thus the methane slip produced by LP4st engines.

For LNG carriers, using a shaft generator can significantly reduce methane slip onboard by reducing LP4st engine use. 2035 FuelEU compliance can be achieved by applying a shaft generator on an LNG carrier powered by an HP2st engine. A similar result can also be expected with a catalyst system.

EGR can reduce methane slip onboard vessels fitted with an LP2st engine and is set to become a standard piece of equipment with the latest LP2st engines post-2021. However, this solution alone cannot achieve 2035 Fuel EU compliance – a combination of methods is needed, such as a shaft generator with an LP2st fitted with an EGR and using shore power.

This study focused on onboard emission reduction technologies and solutions. Still, ultimately, the decision on how to achieve compliance must include considerations like the techno-economics of onboard emission reduction, price, and availability of alternative fuels, and the flexibility and timing of when that decision needs to be made.

9 Techno-economic analysis

When determining the best way to achieve regulatory compliance or reach a specified emission level, the economics are equally crucial as the emission reduction potential. We estimated the CAPEX and OPEX (including fuel costs) for each emission reduction technology, solution, and applicable combination (see Table 5). We also calculated the GHG abatement cost for each solution in \$/ton CO_2eq for a 10- and 20-year period. The abatement cost of onboard technologies should not be evaluated in isolation but together with all options for achieving an emission reduction target so that the most cost-effective solution can be identified. As a result, we also included the GHG abatement cost of using a 20% blend of bio-methane for comparative purposes and an indicator of relative cost-efficiency. However, the availability and price of bio-methane are not clear or established. Therefore, relying on this option only presents its own risks and uncertainties that would need to be considered separately.

It should be noted that the techno-economic analysis does not directly aim to compare the two dominant engine technologies but rather to provide an overview of the available solutions for each type of engine.

GHG unit price is the GHG abatement cost based on Equation 2.

Equation 2: GHG unit price formula

$$\text{GHG unit price} = \frac{CAPEX + OPEX(incl.\,fuel\ cost)\ for\ 20\ years}{Reduction\ amount\ of\ WTW\ GHG\ emissions}$$

The assumptions associated with the calculated CAPEX and OPEX figures include:

- CAPEX is on newbuilding base
- LNG Fuel price is estimated at $610/ton
- Electric cost for shore power is estimated at $0.2/kWh
- Shore power is considered renewable energy (GHG zero emission), and CAPEX + OPEX for shore power supply facility in port is omitted.

Table 5: CAPEX and OPEX for emission reduction measures

Measure	Ship Type	Configuration	CAPEX M$	OPEX K$/Year
Plasma for ME	LR2 Tanker	HP2st(ME-GI) +LP4st	3.4	266
	LNGC	HP2st(ME-GI) +LP4st	7.2	422
	LR2 Tanker	LP2st(XDF w/EGR)+LP4st	3.4	247
	LNGC	LP2st(XDF w/o EGR)+LP4st	7.2	435
Plasma for D/G	LR2 Tanker	HP2st(ME-GI) +LP4st	1.0	26
	LNGC	HP2st(ME-GI) +LP4st	2.7	134
	LR2 Tanker	LP2st(XDF w/EGR)+LP4st	1.0	24
	LNGC	LP2st(XDF w/o EGR)+LP4st	2.7	102
Catalyst for D/G	LR2 Tanker	HP2st(ME-GI) +LP4st	0.2	50
	LNGC	HP2st(ME-GI) +LP4st	0.6	200
	LR2 Tanker	LP2st(XDF w/EGR)+LP4st	0.2	50
	LNGC	LP2st(XDF w/o EGR)+LP4st	0.6	200
S/G for M/E	LR2 Tanker	HP2st(ME-GI) +LP4st	1.2	-90
	LNGC	HP2st(ME-GI) +LP4st	4.5	-436
	LR2 Tanker	LP2st(XDF w/EGR)+LP4st	1.2	-37
	LNGC	LP2st(XDF w/o EGR)+LP4st	4.5	-264
Shore Power	LR2 Tanker	HP2st(ME-GI) +LP4st	0.2	500
	LNGC	HP2st(ME-GI) +LP4st	0.8	646
	LR2 Tanker	LP2st(XDF w/EGR)+LP4st	0.2	467
	LNGC	LP2st(XDF w/o EGR)+LP4st	0.8	519
EGR for M/E	LNGC	LP2st(XDF w/EGR)+LP4st	2.8	-50

- Bio-methane price is $1,136/ton, and its WTT GHG emissions are –41.04gCO2eq/MJ[14]
- PRS & Catalyst CAPEX and OPEX are preliminary estimations.

Note that the CAPEX and OPEX are positive in most cases. However, for the shaft generator and EGR, the OPEX is negative. This is due to the fuel savings associated with reduced fuel consumption the technologies provide, in addition to emission reduction.

The GHG abatement cost based on the estimated CAPEX and OPEX can be used with the expected emission reduction potential to assess which solutions should be applied based on a specific vessel, newbuild or retrofit, baseline engine technology, and emission reduction targets. The most optimal solution varies by scenario, particularly for reducing emissions of newbuilds vs. retrofitting existing vessels. Based on our integration studies, we concluded that shaft generators and EGR are not retrofittable and are only suitable for newbuilds due to engine room space limitations. MOC and PRS, on the other hand, can be retrofitted. It is also possible to retrofit shore power in most cases; however, this was not directly studied for this paper. It's important to note that shore power may not be readily available at all ports resulting in unrealized emission reduction even if the capability is installed on the vessel.

GHG cost abatement graphs provide a simple tool to evaluate your emission reduction options given a particular target to balance the need to achieve a certain emission level while also considering the cost-efficiency of emission reduction measures. GHG abatement cost graphs were generated for the two case study vessels and baseline engine technologies. Note that the LR2 tanker with the LP2st engine has an EGR included in the baseline, while the LNGC LP2st engine does not have an EGR. GHG abatement costs over a 20-year period are used within the report. For reference, the 10-year period graphs can be found in the Appendix.

Figure 19 shows the GHG cost abatement graphs for HP2st ME configurations, which provides both the emission reduction potential and GHG abatement cost of various emission reduction technologies, solutions, and combinations. Two main objectives can be evaluated using such figures: 1) maximize emission reduction by minimizing GHG emissions or achieving a desired reduction target, and 2) minimize the associated GHG abatement cost. The ideal or *utopia* point on the graphs is in the bottom left side (zero GHG emissions at zero GHG abatement cost), a point that is not achievable. When comparing solutions, one is considered *dominated* if another solution has both lower GHG emissions and GHG abatement cost. For example, in Figure 19b, the plasma for D/G solution is dominated by all others and should not be considered a valid solution. The red horizontal lines indicate the original vessel's emissions without any methane emission reduction.

With the HP2st main engine baseline, the most efficient solutions (see Figure 19) are related to reducing the use of the LP4st auxiliary engines, including the installation of a shaft generator and the use of shore power. For a retrofit scenario, using a catalyst or a shore power connection are efficient options. For the LNGC vessel with increased auxiliary power demands compared to the LR2 tanker, the shaft generator becomes more efficient with lower GHG emissions and GHG abatement costs. This is reflected in the latest LNGC newbuild design trend of incorporating shaft generator systems.

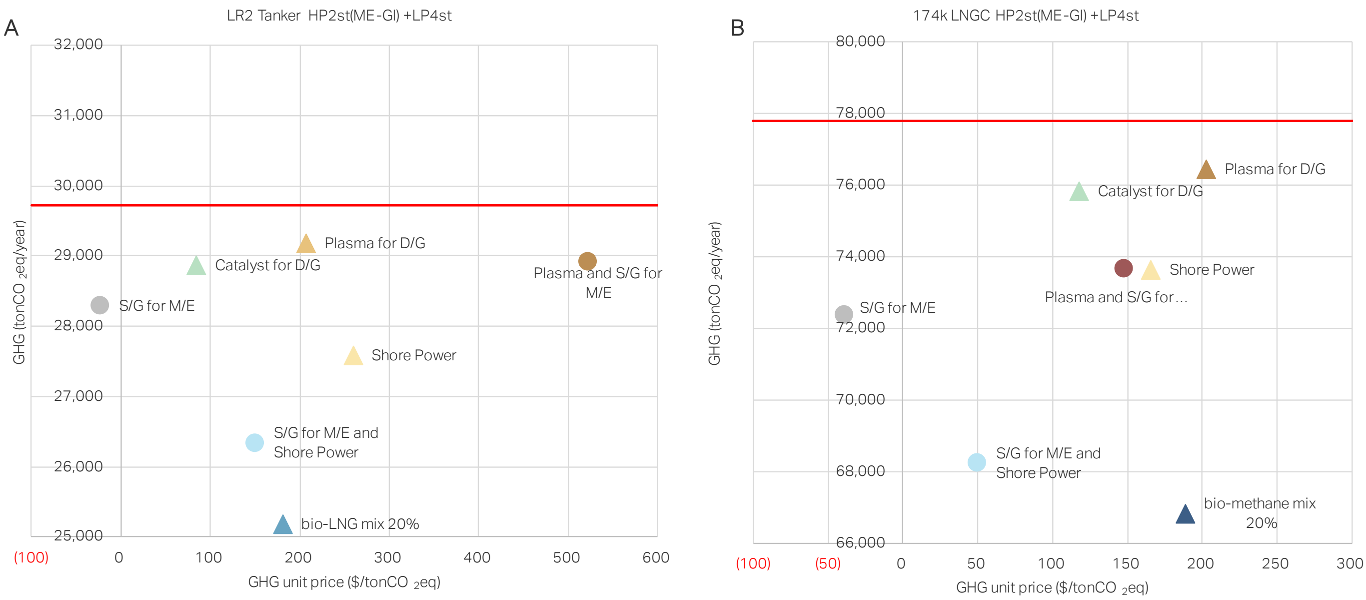


Figure 19: GHG cost abatement graphs for HP2st ME configurations.

[14] MMMCZCS Industry Transition Strategy 2021

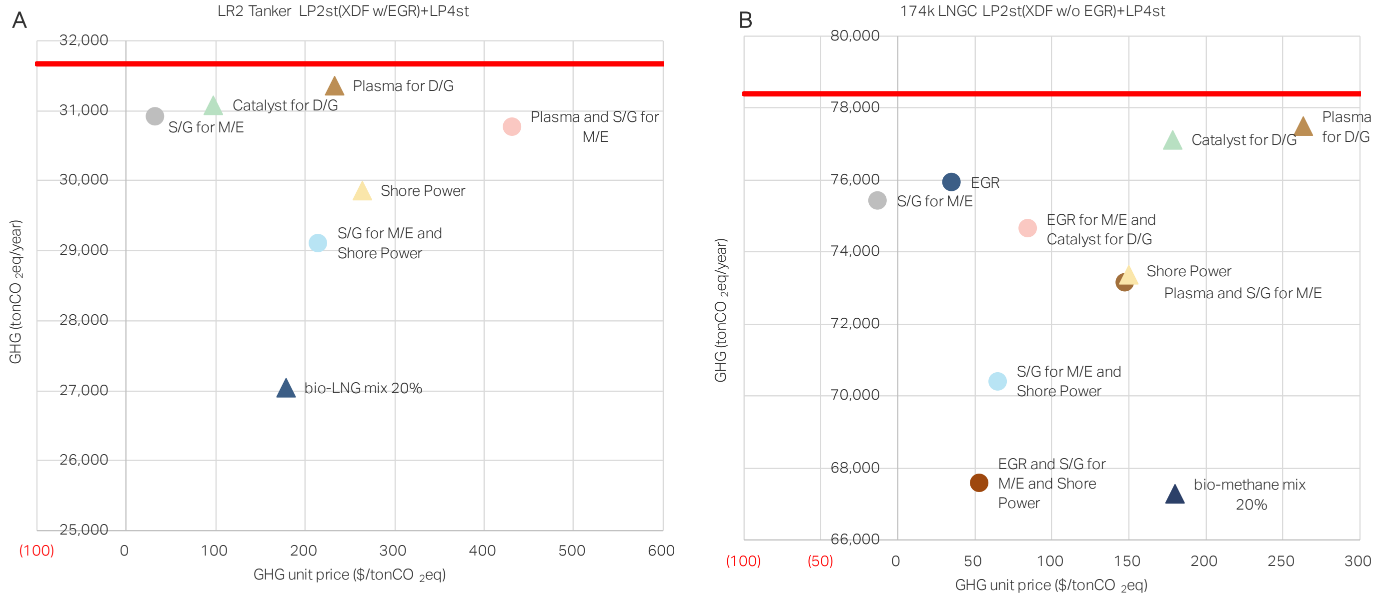


Figure 20: GHG cost abatement graphs for LP2st ME configurations.

With the LP2st main engine baseline, the most efficient solutions (see Figure 20) are again related to reducing the use of the LP4st auxiliary engines, including installation of a shaft generator and use of shore power, except for the LNGC case where an EGR is not installed. For newbuild designs, an EGR is now becoming a standard equipment supplied with the engine. For a retrofit, installing a catalyst can also be an efficient way to reduce GHG emissions.

Based on the overall techno-economic analysis, onboard methane emission reduction technologies can provide a cost-effective way to reduce methane emissions. Onboard methane emission reduction technologies are also cost competitive with the use of alternative fuels like bio-methane in reducing overall GHG emissions of a vessel up to a certain point. For a newbuild, in addition to the selection of the baseline main engine technology, system solutions like shaft generators and preparation for shore power are recommended as they provide meaningful emission reduction at low abatement costs. Higher abatement costs should be expected for retrofits, as well as more limited options. Installation of methane catalysts on LP4st auxiliary engines present an efficient way to reduce emissions in retrofits.

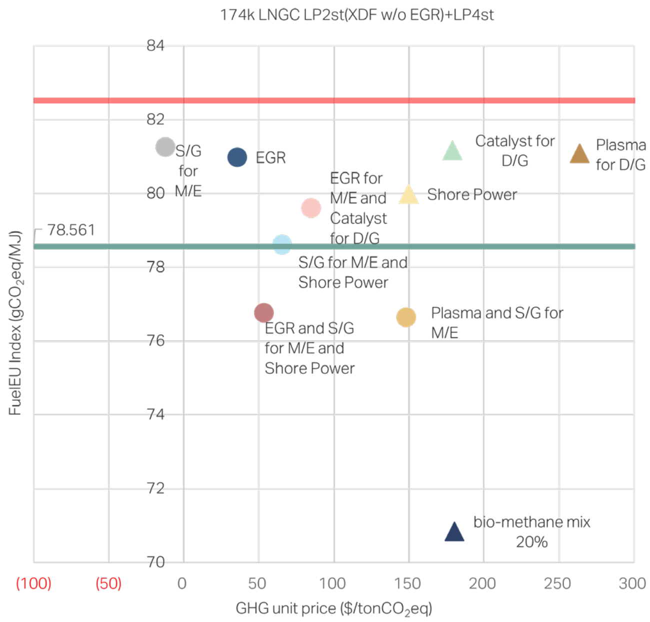


Figure 21: FuelEU GHG cost abatement graph.

An alternative GHG abatement cost graph can be generated if the objective is solely to fulfill a certain regulatory requirement. Figure 21 provides an example of such a graph using the required FuelEU level in 2035. The red line indicates the baseline vessel emission level, and the green line is the Fuel EU 2035 requirement level. All measures below the green line comply. In this case, the most cost-efficient compliant option is the combination of EGR, shaft generator, and shore power.

10 Conclusions

Methane emission reduction can be an efficient way to reduce a vessel's overall CO_2-eq emissions, allowing compliance with upcoming regulations and increasing the viability and competitiveness of methane-based alternative fuel pathways.

Based on our working group's results, the following conclusions have been made:

- **A vessel's total methane emissions should be considered:** While the main source of onboard vessel methane emissions is methane slip from main and auxiliary internal combustion engines, total methane emissions of a vessel is highly dependent on a vessel's operations, system dimensioning, machinery configurations and connected technologies. In addition to selecting baseline engine and potential after-treatment technologies, system solutions can significantly reduce onboard vessel methane emissions.

- Cost-efficient onboard vessel methane emission reduction is possible but limited for existing vessels: For the vessels studied, onboard methane emissions can be cost-efficiently reduced by 40-80% for a newbuild and 20-50% for an existing vessel through the selection of baseline engine technologies and the use of after-treatment technologies and system solutions. These reductions translate to onboard methane emissions being reduced from 7-14% of total tank-to-wake GHG emissions to 2-8% for a newbuild and 4-12% for an existing vessel. Ship owners should carefully consider onboard methane emission reduction at the newbuild phase to avoid potential costly modifications later in the vessel's lifetime. While it is technically feasible to further reduce onboard vessel methane emissions beyond these levels, utilizing other options like the use of low-emission fuels could be more cost-efficient if further GHG emission reductions are required.
- Reducing onboard vessel methane emissions are needed to increase viability of electro- and bio-methane fuel pathways: Reducing onboard vessel methane emissions to these cost-efficient levels increases the longer-term viability of the electro- and bio-methane fuel pathways, however, it is still unclear if upstream well-to-tank fugitive emissions can be reduced to acceptable levels. Using the FuelEU methodology and cost-efficient onboard methane emission reduction measures, GHG WTW emissions can be reduced to 5-9 gCO_2eq/MJ using 100% electro-methane and hydrothermal liquefaction (HTL) Oil as a pilot fuel (a 90-95% decrease relative to heavy fuel oil).
- Proposed FuelEU for Maritime limits are not strict enough to activate onboard vessel methane emission reduction: For the vessels studied, GHG emission levels are already compliant with the 2025 and 2030 FuelEU GHG intensity index limits without introducing any onboard vessel methane emission reduction measures. This is due to LNG's lower CO_2 emission factor used within its 100-year GWP methodology. If a CO_2-eq regulation with the proposed FuelEU limits is introduced, no emission reduction actions would be needed until 2035.
- Regulation is required for widespread adoption of onboard vessel methane emission reduction technologies and solutions: Without strong incentives or regulatory requirements to reduce methane emissions, there is limited commitment from ship owners to adopt methane emission reduction technologies and solutions. There are ongoing discussions at the IMO to include methane into its LCA methodology, a CO_2-eq approach like FuelEU. There is also the possibility that methane is regulated in a more direct way using a vessel's Technical File like NO_X emissions. This type of regulation could more directly target methane slip levels and the need to reduce them onboard the vessel either for newbuilds or existing vessels if retroactive.

To properly assess the viability of methane-based alternative fuel pathways like electro- and bio-methane, the ability to reduce upstream well-to-tank fugitive emissions needs to be fully understood. Upstream fugitive emissions are not covered in this paper but are currently being studied at the MMMCZCS to enable a complete viability assessment of the methane-based fuel pathways. The MMMCZCS also plans to study onboard vessel emissions in operation where factors like dynamics engine loads and sea states can influence methane emission levels.

Despite the slow progress to incentivize or require LNG-fueled vessels to limit their methane emissions, there is significant international social pressure to reduce emissions of GHGs, particularly methane. From the Global Methane Pledge (COP26) to the US' Inflation Reduction Act of 2022, growing worldwide concern is strongly pushing for GHG reductions to limit the increase in the global average temperature to well below 2°C above pre-industrial levels. It is expected that this social pressure will lead to definitive action by stakeholders across all industries.

11 Related projects and future development areas

In addition to the assessment of onboard methane emission reduction, the MMMCZCS is investigating biogenic routes to produce methane. Liquified methane of biogenic origin can be produced with the same specifications as LNG. The two products are indistinguishable and liquified bio-methane has a 100% "drop-in" potential. The MMMCZCS is currently studying whether biogas (renewable gas) is one of the contenders to supply net zero carbon fuels to shipping. In a project running in the second half of 2022, and partnering with numerous third parties representing technology, energy producers, consulting firms, we will clarify biomass availability, LCA aspects, cost of manufacturing and strategies to boost the industry relevant for shipping.

Onboard emission measurement is a general topic that is currently being studied further to better understand actual onboard emissions including operational factors like dynamic engine loads and heavy sea states. Onboard emission monitoring is also being considered as a potential tool for emission regulation compliance assurance and enforcement.

Appendix

Ship Integration Study Operating Profile

Item	Unit	LP2st + LP4st
Ship Type	-	LNG Carrier
Capacity	m3	174,000
Loa x B x D	m3	293 x 46 x 26
ME Type	-	6 Cyl 62 Bore (DF) without EGR
ME Power	kW	12,540 x 2
Diesel Generator Type	-	6 Cyl 34 Bore (DF)
Diesel Generator Power	kW	2,880 x 4

Item		Normal sea going	Maneuvering	Unloading	Loading	Port
Actual	Electric Load	2,430	2,530	5,830	3,600	2,750
	Generator in service	2 sets	2 sets	4sets	2 sets	2 sets
	Load Factor	44%	46%	53%	65%	50%

Note: In normal operation exclude Unloading, only two Gensets are used. There is enough margin for GE capacity.

Calculation Model Vessel Details

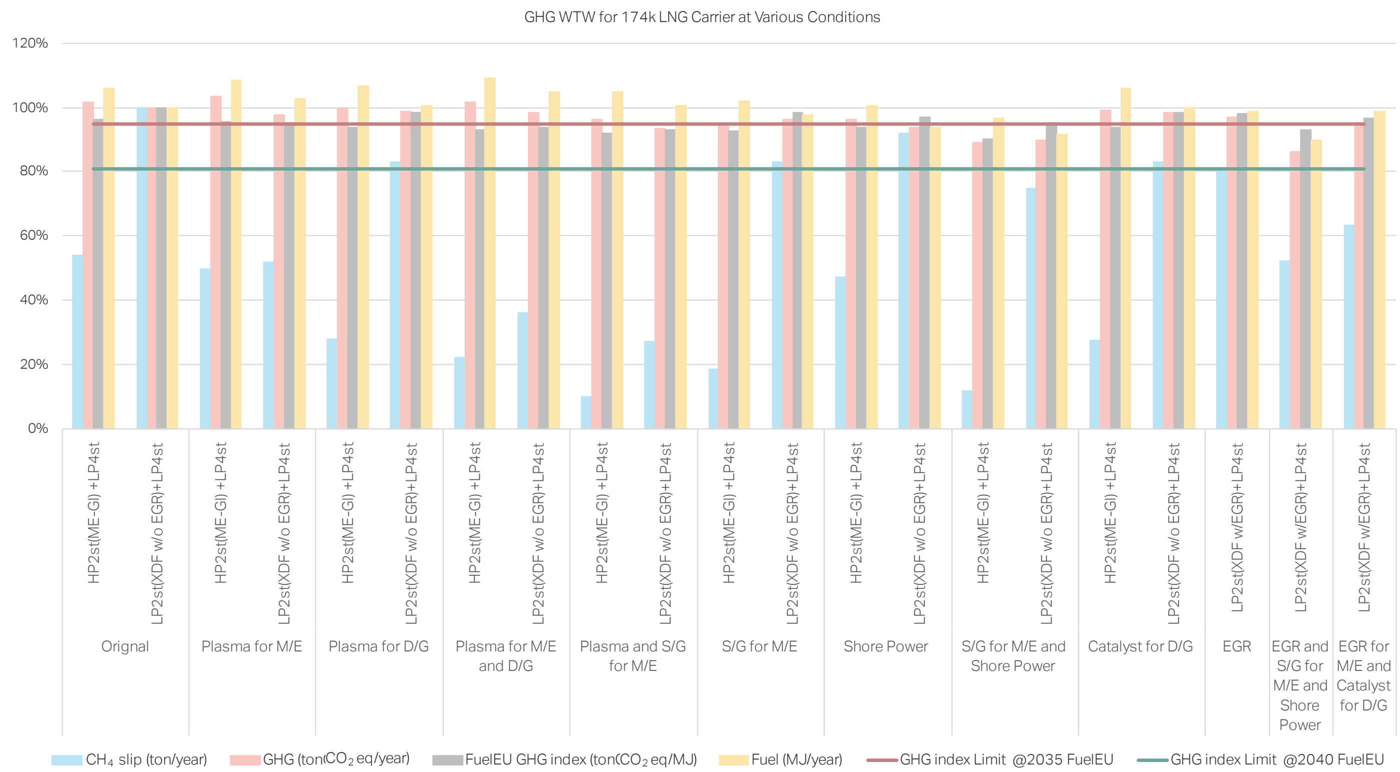
LNG Fueled LR2 Case

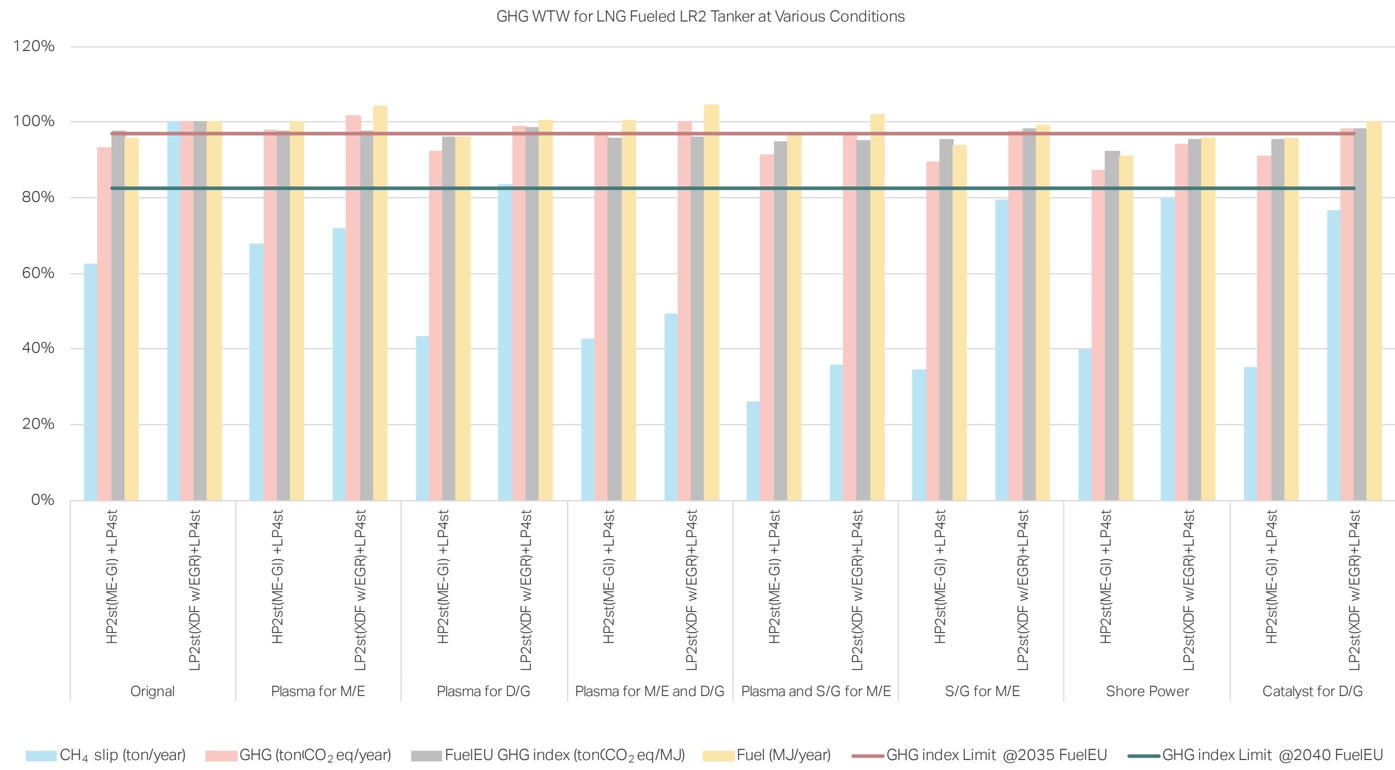
Item	Unit	HP2st+LP4st	LP2st+LP4st
Main Engine (hereafter ME) Type	-	6 Cyl 60 Bore (DF)	6 Cyl 62 Bore (DF) with EGR
ME Q'ty	sets	1	1
ME Power	kW	12,000	12,000
Diesel Generator Type	-	8 Cyl 20 Bore (DF)	6 Cyl 20 Bore (DF)
Diesel Generator Q'ty	sets	3	3
Diesel Generator Power	kW	1200	1000
Average ME Load at Sailing	kW	6,878 (57%) Pilot : 2.5% by MJ	6,878 (57%) Pilot : 0.6% by MJ
Average D/G Load at Sailing	kW	950kW (79%x1set) Pilot : 3.2% by MJ	825kW (83%x1sets) Pilot : 3.1% by MJ
Days at Sailing	days	225	225
Average D/G Load at Port	kW	735kW (61%x1set) Pilot : 3.7% by MJ	660kW (66%x1sets) Pilot : 3.8% by MJ
Days at Port	days	90	90
Average D/G Load at Loading	kW	1350kW (56%x2sets) Pilot : 3.9% by MJ	1275kW (64%x2sets) Pilot : 3.7% by MJ
Days at Loading	days	30	30
Average D/G Load at Unloading	kW	2250kW (63%x3sets) Pilot : 3.8% by MJ	2175kW (73%x3sets) Pilot : 3.5% by MJ
Days at Unloading	days	20	20
Boiler Fuel Consumption	ton/year	1,025 (LNG)	1,025 (LNG)
Purged CH_4 to combustion unit	ton//ear	6.7	6.7
Purged CH_4 to vent	ton/year	0.45	0.45

174k LNG carrier Case

Item	Unit	HP2st+ LP4st	LP2st+LP4st
ME Type	-	5 Cyl 70 Bore (DF)	5 Cyl 72 Bore (DF) without EGR
ME Q'ty	sets	2	2
ME Power	kW	12,590 x 2	11,350 x 2
Diesel Generator (hereafter D/G) Type	-	6 Cyl 34 Bore (DF) + 8 Cyl 34 Bore (DF)	6 Cyl 35 Bore (DF) + 8 Cyl 35 Bore (DF)
D/G Q'ty	sets	2+2	2+2
D/G Power	kW	2,880 x 2 + 3,840 x 2	2,880 x 2 + 3,840 x 2
Average ME Load at Sailing	kW	12,000 (48%) Pilot : 7.9% by MJ	12,500 (55%) Pilot : 0.7% by MJ
Average D/G Load at Sailing	kW	4,200 (73%) 2xSmall Pilot : 1.6% by MJ	3,000 (78%) 1xLarge Pilot : 2.2% by MJ
Days at Sailing	days	216	202
Average ME Load at Maneuvering	kW	3,700 (15%) Pilot : 13.4% by MJ	3,400 (15%) Pilot : 1.6% by MJ
Average D/G Load at Maneuvering	kW	2,700 (40%) 1xSmall+1xLarge Pilot : 1.3% by MJ	2,700 (40%) 1xSmall+1xLarge Pilot : 1.3% by MJ
Days at Maneuvering	days	7	9
Average D/G Load at Loading	kW	5,000 (87%) 2xSmall Pilot : 0.8% by MJ	4,800 (83%) 2xSmall Pilot : 0.8% by MJ
Days at Loading	days	14	17
Average D/G Load at Unloading	kW	7,400 (77%) 2xSmall + 1xLarge Pilot : 1.4% by MJ	7,300 (76%)2xSmall + 1xLarge Pilot : 1.4% by MJ
Days at Unloading	days	14	17
Boiler Fuel Consumption	ton/year	100 (LSFO)	120 (LSFO)
Purged CH_4 to combustion unit	ton//ear	169.1	169.1
Purged CH_4 to vent	ton/year	0.45	0.45

Additional calculation model results




GHG WTW for LNG Fueled LR2 Tanker at Various Conditions
120%
100%
80%
60%
40%
20%
0%
HP2st(ME-GI) +LP4st
LP2st(XDF w/EGR)+LP4st
Orignal
Plasma for M/E
Plasma for D/G
Plasma for M/E and D/G
Plasma and S/G for M/E
S/G for M/E
Shore Power
Catalyst for D/G
CH4 slip (ton/year)
GHG (tonCO2 eq/year)
FuelEU GHG index (tonCO2 eq/MJ)
Fuel (MJ/year)
GHG index Limit @2035 FuelEU
GHG index Limit @2040 FuelEU

GHG Abatement Cost Graphs (over a 10-year period)