Tackling Methane Slip in Shipping

Insights into options for regulation and quantification

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

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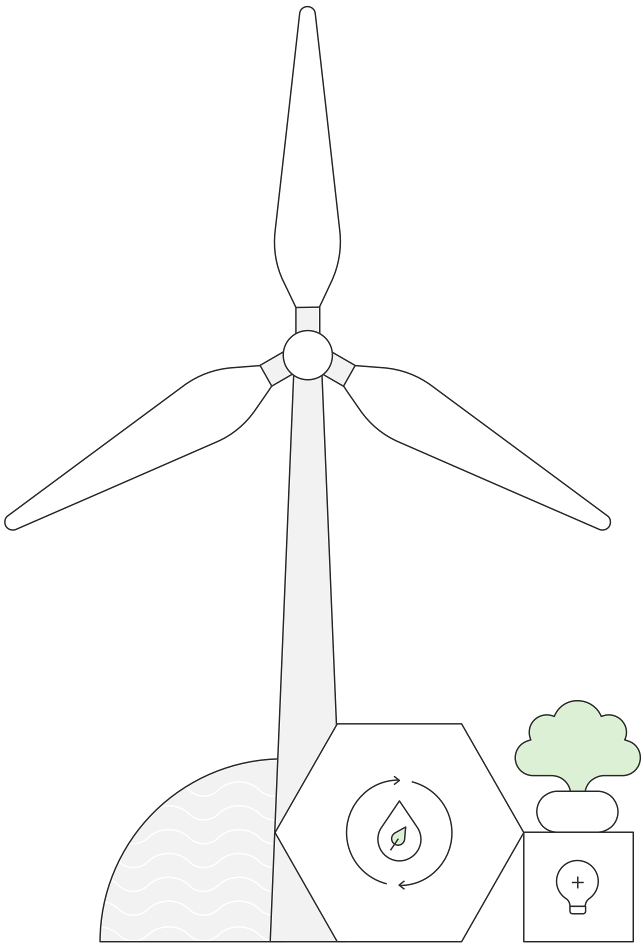


Executive summary

Liquefied natural gas (LNG) has increased in popularity as a maritime fuel due to its associated environmental benefits. While the tank-to-wake (TTW) carbon dioxide (CO_2) emissions from the complete combustion of methane are nearly 30% lower* than those from diesel for the same energy, methane slip emissions during combustion and fuel production may pose an obstacle for methane-based pathways to reach zero emissions. To make methane-based fuel pathways a viable solution for net-zero shipping, methane emissions during the whole life cycle need to be addressed.

Looking to the coming decades, the growing methane-fueled fleet will drive up the consumption of LNG and other methane-based fuels, while the expected switch to sustainable bio- and e-LNG will reduce this fleet's overall CO_2-equivalent greenhouse gas (GHG) emissions on a well-to-wake (WTW) basis.[1] At the same time, if no mitigation actions are taken, methane slip will remain and even increase as the methane-fueled fleet grows. Therefore, methane slip from shipping will continue to contribute to global warming if not controlled. As such, this paper focuses on TTW methane slip emissions from engine combustion.

Past research at the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS)[2] has demonstrated that current regulations that include methane, such as CO_2-equivalent fuel standards (e.g., FuelEU Maritime), will have a limited effect on reducing onboard methane emissions in the short to mid term. Furthermore, the default methane slip value concept does not provide a direct incentive to engine makers, shipowners, or shipping operators to proactively reduce methane slip.

Our research has indicated that, considering the expected growth trajectory for the methane-fueled fleet, methane slip will contribute significantly to GHG emissions from shipping. The industry needs effective and relevant regulations that will drive the implementation of solutions that minimize methane slip. To support the development of effective regulation of methane slip, this report summarizes analysis and insights into two key areas:

1. Impact of possible regulatory measures on methane emissions from methane as a shipping fuel towards 2050

In this analysis, we modeled eight different scenarios to assess methane slip mitigation strategies based on different ambition levels, incorporating various regulatory and technological measures. This section aims to inform regulators on the potential effectiveness of various approaches to reducing methane slip and, consequently, decreasing overall emissions from the marine fleet.

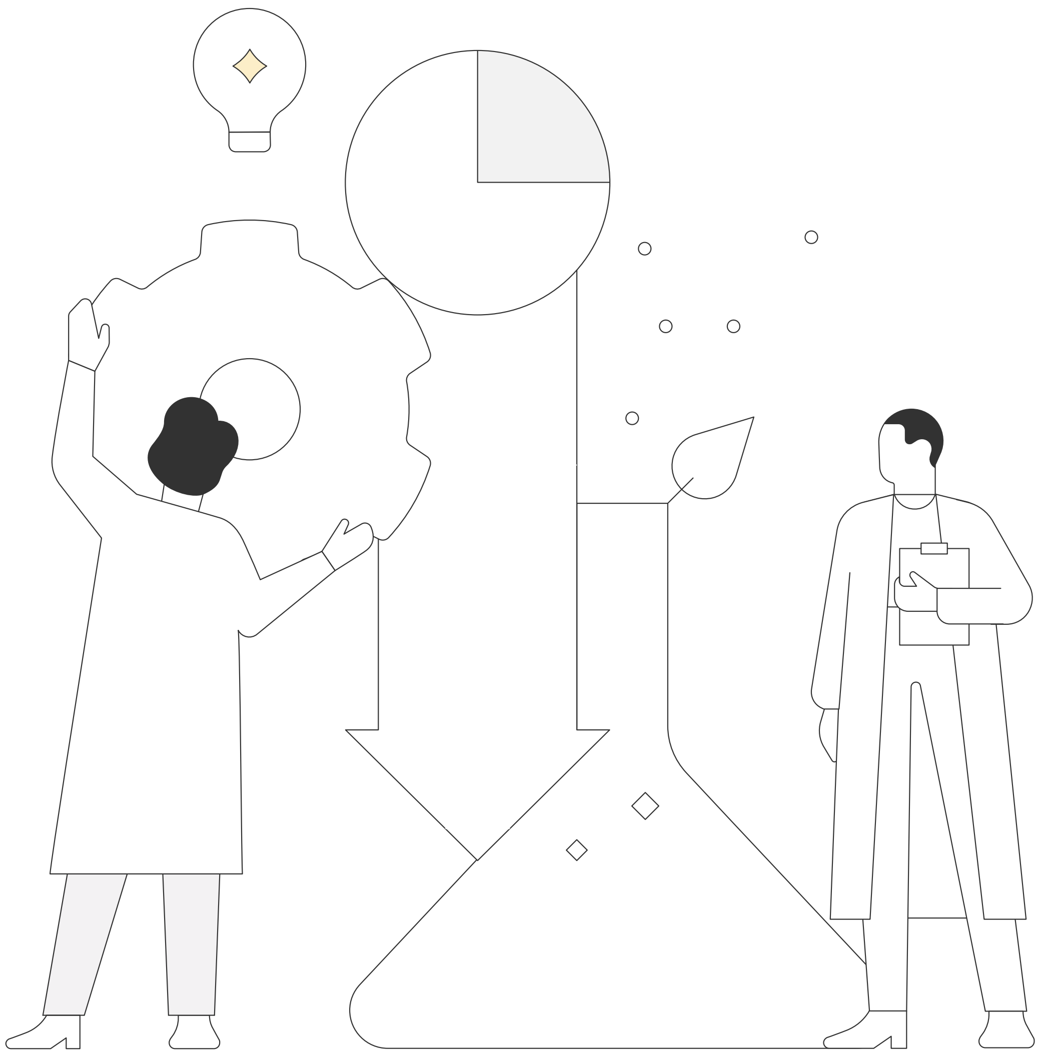
Notably, our analysis reveals that early implementation of methane slip regulations for newbuild vessels could achieve reductions in methane slip similar to those from retroactive measures. We therefore highlight the early regulation of newbuilds as a cost-effective method for meaningful reduction of methane slip, emphasizing the urgency and economic efficiency of early regulatory action to ensure the qualification of the sustainable methane-based fuel pathway with a near-term uptake.

* Calculation based on the formula 1 ÷ LHV x Cf. For methane: 1 ÷ (50 MJ / kg) × 2.75 = 0.055; for MGO: 1 ÷ (42.7 MJ / kg) × 3,206 = 0.075 ; 1 − 0.055 ÷ 0.075 = 27%.

2. Quantifying methane slip from engines on a ship level

We applied four different quantification approaches to calculate methane slip using real operational data from vessels in different shipping segments. Our analysis indicates that a test cycle average quantification approach based on the International Maritime Organization's (IMO) NO_x Technical Code can provide a relatively accurate estimate of real-life methane slip without requiring overly burdensome data collection. Further, unlike the default value approach (e.g., as currently applied in the FuelEU Maritime regulation), this quantification approach would incentivize engine manufacturers to strive for slip reduction and thereby contribute to prompt reduction of GHG emissions in the shipping industry.

Based on these insights, we conclude this report with a set of recommendations and guiding actions by regulators, equipment manufacturers, and shipowners and operators, as well as some suggestions for further technical research. Specifically, we propose that the regulatory community consider measures targeting onboard methane slip at a ship level in the short term. This should ideally be achieved through the adoption of the test cycle average quantification method outlined in this report. Furthermore, we encourage equipment manufacturers to standardize the integration of methane slip reduction technologies in their product designs, while also focusing on the adaptability of these technologies for retrofit on existing vessels. For shipowners and operators, selecting fuel and engine technology with an emphasis on mitigating methane emissions is critical. Such proactive measures will contribute to the reduction of methane emissions, and at the same time mitigate the risk of incurring significant costs due to future regulations.



01 Introduction

In light of the urgent need to deploy low-carbon energy solutions at a significant scale across shipping and other industries, methane has emerged as a critical transitional fuel within this decade. Nevertheless, methane emissions need to be regulated and managed for the long-term viability of a sustainable methane fuel pathway.[3]

Methane is recognized as the second-largest contributor to global warming after carbon dioxide (CO_2) for the period 2010-2019.[4] Methane's global warming potential (GWP) is 29.8 times greater than that of CO_2 over a 100-year timescale and 82.5 times higher on a 20-year timescale.[4] Estimates suggest that methane emissions have already caused approximately 0.5°C of warming since pre-industrial times.[4] Over the last decade, the concentration of methane emissions in the atmosphere has increased by approximately 6%, and methane's contribution to climate change has been nearly tantamount to that of CO_2.[4, 5] In an effort to keep 1.5°C of warming within reach, the Global Methane Pledge signed in 2021 commits signatory countries to reducing their methane emissions by at least 30% by 2030 compared with 2020.[6] However, such absolute reductions compared to 2020 will be extremely challenging for the shipping sector to reach while liquefied natural gas (LNG) is still being introduced to the market.

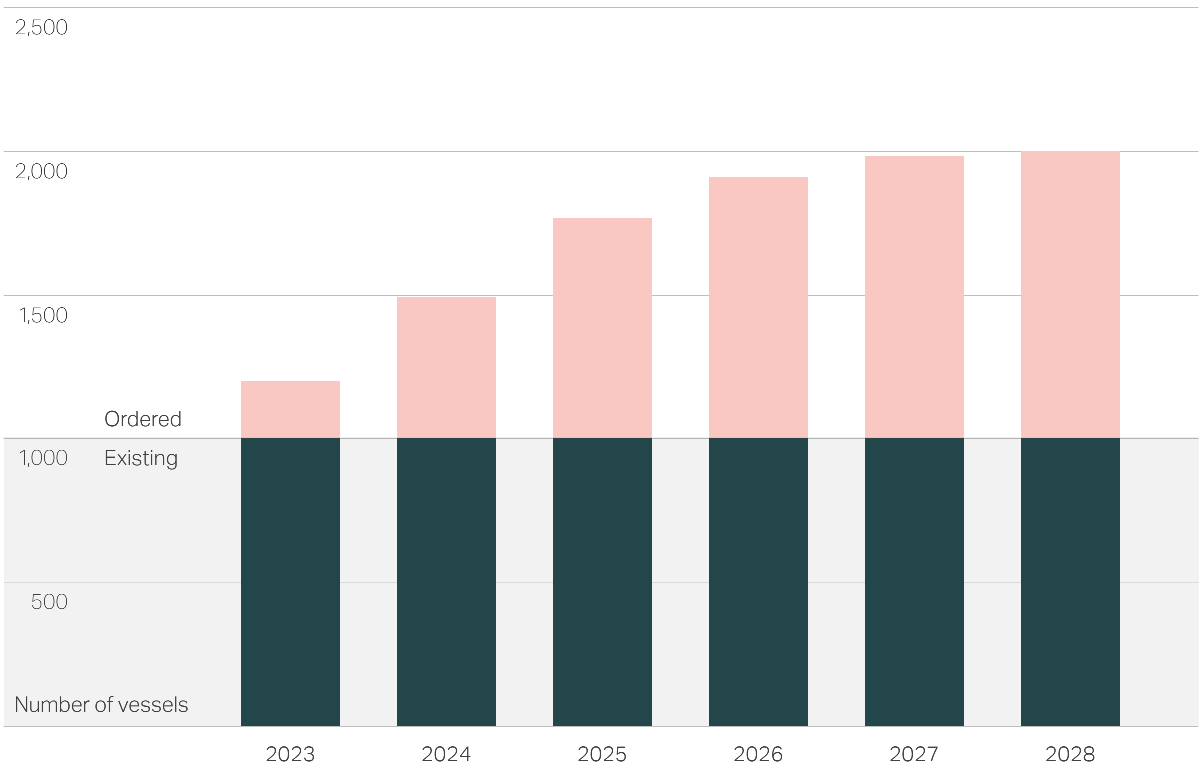
LNG has recently seen increased popularity as a maritime fuel due to its environmental benefits. LNG is mainly composed of methane, which entails a higher hydrogen-to-carbon ratio and energy content compared to liquid fuels like heavy fuel oil and marine diesel or gas oil. A high hydrogen-to-carbon ratio yields lower CO_2 emissions.[7] In addition, using LNG contributes towards reducing emissions of local air pollutants like nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter, including black carbon, compared to conventional fuels.[8] These low-emissions properties render LNG an attractive fuel for ships that operate in Emission Control Areas, where ships must comply with stringent air quality standards.

However, methane's high GWP, especially within short timescales, means that even low levels of methane emissions may negate the climate benefits of reduced CO_2 emissions from LNG over conventional maritime fuels. Methane emissions emerge over the entire supply chain. On board vessels, they take the form of either combustion and direct methane slip (unburned methane escaping to the atmosphere) in main and auxiliary combustion engines, or non-engine-related methane emissions (operational, fugitive, and emergency releases).[2]

In this situation, we need to consider shipping's total greenhouse gas (GHG) emissions from a well-to-wake (WTW) perspective, rather than concentrating solely on CO_2 and on tank-to-wake (TTW) emissions from the combustion process only. Therefore, the industry must identify sources of methane emissions, determine acceptable levels, and address both fugitive emissions in the supply chain and slip on board vessels to allow methane-based fuels to form a part of the future fuel landscape in shipping.

Despite the anticipated introduction of renewable bio-methane and e-methane, which can act as drop-in fuels for fossil LNG, methane slip is expected to remain an important source of GHG emissions from methane-fueled ships unless action is taken to address it. According to data from Clarksons Research, more than 1,280 methane-fueled vessels are expected to be operating in 2028, with 836 ships in the newbuild orderbook (Figure 1). This growing fleet and resulting methane consumption will increase methane's contribution to GHG emissions from shipping unless methane slip is reduced.

Figure 1: LNG fleet existing and newbuild orderbook based on data from Clarksons Research and DNV.[9, 10] Data were accessed in late 2023.



1.1. Opportunities to reduce methane slip on board vessels

Different technologies are associated with varying levels of methane slip, and several measures are available to reduce methane slip.[2, 11] These measures include improvement of engine design (e.g., reduction of crevice volumes in the combustion chamber), after-treatment solutions, and operational measures.[12]

On an engine level, selecting a diesel cycle (high-pressure) instead of an Otto cycle (low-pressure) gas engine for a newbuild reduces methane slip by nearly a factor of 10, as indicated by emissions factors in FuelEU Maritime initiative.[13] However, the compression of gas from low to high pressure generally requires energy, and thus there might be some efficiency loss and increased CO_2 emissions associated with the switch to increased gas pressure. A recent study[8] suggests that methane slip from a four-stroke engine can be reduced by 50-65% at relatively high loads and up to 70% at low loads.

In addition to on-engine measures, after-treatment solutions such as methane catalysts are available.[2] A previous Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) publication[2] discussed opportunities for the reduction of onboard methane emissions using after-treatment solutions, and concluded that existing technologies can be used to reduce methane emissions in a cost-efficient manner by up to 80% for newbuilds and by up to 50% for retrofits. However, uptake of these technologies is not encouraged by current legislation, and shipowners are therefore not incentivized to use such technologies to reduce vessels' environmental impact. Further technical development would also increase the feasibility of reducing methane slip using after-treatment technologies. Therefore, the uptake of methane emissions reduction technologies will need to be encouraged by legislation specifically targeting methane slip.

Finally, operational opportunities to reduce methane slip include proper maintenance of the engine and avoiding gas operation at low load, as the increased methane slip in this situation significantly reduces the benefits achieved. Otto cycle engines also could switch from gas to fuel oil when at low load to avoid methane slip; such a fuel switch could be automated. In practice, this could mean an automatic shift to marine diesel or gas oil to reduce GHG emissions at, for example, below 25% of the engine's maximum continuous rating (MCR) or when the methane slip exceeds a certain threshold value.

1.2. Current regulatory landscape for methane slip

Early regulatory actions would cater for methane slip control at reasonable levels through to 2050. Figure 2 summarizes recent and upcoming regulatory developments regarding methane emissions from shipping. A previous submission to the International Maritime Organization's (IMO) Marine Environment Protection Committee (MEPC) by the Royal Institution of Naval Architects (RINA) (MEPC 79/INF.16) describes the different sources of onboard methane emissions and measures to reduce onboard methane slip.

While there are no IMO standards dealing with methane slip, the first steps towards TTW methane emissions reporting have been taken as part of the European Union's (EU) Fit for 55 program. This program addresses methane emissions reductions in the energy sector through the inclusion of CO_2, nitrous oxide (N_2O), and methane in the Monitoring, Reporting, and Verification system from 2024 onwards as part of the EU Emissions Trading Scheme (ETS) regulatory framework. Further, FuelEU Maritime aims to limit the carbon intensity of maritime fuels from a WTW perspective. Nevertheless, the proposed FuelEU limits for the maritime industry may not activate reduction of onboard methane emissions in the short term.[2] An alternative tool for regulation and reduction of onboard methane emissions could be direct limitations on methane slip, analogous to those currently regulating NO_x emissions in shipping.[14]

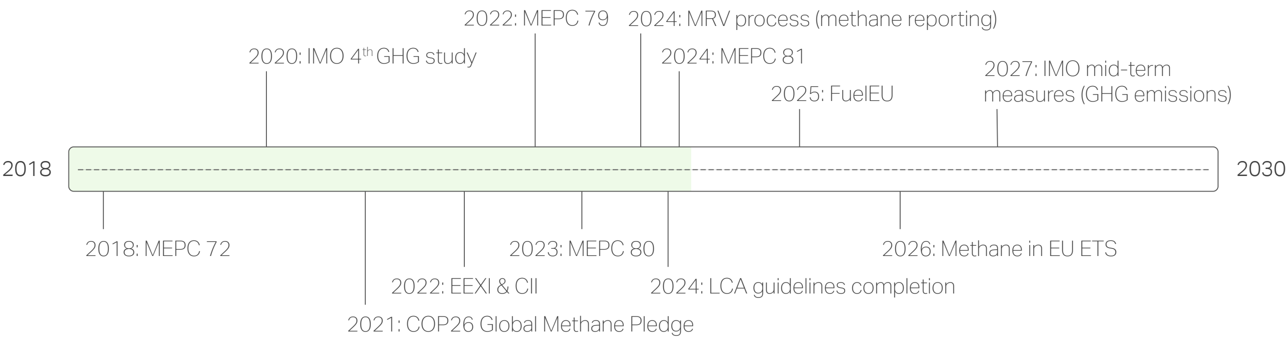
In parallel, the IMO is discussing the development of guidelines for life-cycle assessment (LCA) of GHG emissions from marine fuels and a possible GHG Fuel Standard. While the IMO's LCA framework and guidelines are expected to be finalized by 2025, the mid-term GHG reduction measures currently on the MEPC agenda will likely also include methane emissions. Furthermore, we can expect signatories to the Global Methane Pledge, including the United States and the EU, to develop regulations to cut methane emissions in the near term. Irrespective of the eventual form(s) of relevant regulation, it is important to establish realistic values for methane emissions when investigating mitigation measures.

1.3. About this project

Against this backdrop, this report from the MMMCZCS delves into the regulation and quantification of methane emissions in the shipping industry. Our key findings are arranged into two main areas of insight:

Insight 1: Our first deep dive addresses methane emissions from shipping towards 2050. We model the industry-level impact of different possible mitigation

Figure 2: Timeline of regulatory measures relevant to methane emissions.



MEPC = Marine Environment Protection Committee
IMO = International Maritime Organization
GHG = Greenhouse gas
EEXI = Energy Efficiency Existing Ship Index
CII = Carbon Intensity Indicator
MRV = Monitoring, Reporting & Verification system
LCA = Life-cycle analysis
EU ETS = European Union Emissions Trading Scheme

measures on methane slip levels. This section sheds light on **how and when regulatory efforts could accelerate the transition,** helping policymakers devise tangible strategies for methane slip mitigation.

Insight 2: The key question addressed in our second deep dive is: **what is the impact of the quantification approach on measurement of ship-level methane emissions?** Methane slip values depend on engine design and operational conditions, e.g., gas-injection method, engine size, and engine load. Hence, technical variations are difficult to capture when methane slip is estimated using default values, as in the current FuelEU Maritime regulation. This section presents four different approaches for quantifying onboard methane emissions values and discusses their potential suitability as part of a future ship-level regulatory measure.

The insights presented in this report have also been the topic of two submissions to the IMO MEPC's 81st session (MEPC 81), namely MEPC 81/7/10 and MEPC 81-INF.25.

02 Insight 1: Methane slip regulation potential

To understand the industry-level impact of possible approaches to regulating methane slip, we modeled the effects of several regulatory pathways based on available emissions reduction technology. Our analysis included a baseline scenario plus seven alternative methane slip mitigation scenarios, described in Table 1. The scenarios were defined so as to model the impacts both of different regulatory approaches and of technological improvements over time. Some of the mitigation scenarios model specific regulatory limits or target levels for methane slip (Scenarios 2-4), while others are agnostic to the specific form of regulation (Scenarios 1a-c, 5); however, even in the latter category of scenarios, it is implicit that some regulation or other incentive is in place to drive the uptake and improvement of methane slip reduction technologies (i.e., none of our scenarios model only voluntary uptake of methane slip reduction technologies). Similarly to the existing regulation of NO_x emissions, we did not consider non-compliance penalties as an opportunity for vessels to exceed emissions limits (i.e., if specific regulatory limits are in place, all vessels comply through meeting the limit on an engine level, not through penalties).

Table 1: Description of methane slip mitigation scenarios used to model impacts of regulatory approaches and technological improvement on methane slip from shipping towards 2050.

#	Scenario description	Activation	Application (newbuild or retroactive*)	Regulatory approach to methane slip
0	**Baseline scenario:** No specific regulatory limits for methane slip levels. This model includes existing regulations (e.g., FuelEU, EU ETS, CII) but not pledged regulations – i.e., IMO mid-term measures expected to be in effect from 2027. Does not model uptake of methane slip reduction technologies (e.g., catalysts). Models the effect of projected uptake of alternative fuels and energy efficiency technology alone.	Active	Retroactive	Per existing regulations
1a	**Newbuild to 95% reduction by 2050:** Applied to baseline scenario. Does not assume any specific regulatory limits for methane slip levels. Assumes that technological improvement will be able to offer a 95% reduction in engine-level methane slip by 2050. The scenario is technology-neutral and models a linear annual improvement in methane slip reduction from 0% in 2025 to 95% in 2050.	2025	Newbuild	Not specified
1b	**Catalyst for newbuilds:** Applied to baseline scenario. Does not assume any specific regulatory limits for methane slip levels. In this case, catalyst technology with 57-70% methane slip reduction efficiency will be available in 2030 and with 74-90% efficiency after 2035. The technology is installed on all newbuilds. Methane slip reduction is modeled in a stepwise manner.	2030	Newbuild	Not specified
1c	**Scenario 1b delayed by 5 years:** The same as 1b but delayed by five years (e.g., either due to delay in regulatory action or delay in introduction of catalyst technology).	2035	Newbuild	Not specified
2	**Newbuild reduction by 2050 & retroactive 2030 and 2040:** Applied to Scenario 1a. Models the same technological development as in 1a, while adding specific regulatory limitation of engine-level methane slip to 1.5% by 2030 and 0.9% by 2040.	2030	Retroactive	Specific regulatory limit for methane slip levels
3	**Methane slip peaking by 2035:** Applied to Scenario 1a. Models the same technological development as 1a, while adding a specific regulatory limitation of engine-level methane slip to 1% by 2035.	2035	Retroactive	Specific regulatory limit for methane slip levels
4	**Methane pledge:** Applied to baseline scenario, adding specific regulatory limits for methane slip compliant with the Global Methane Pledge (30% reduction by 2030) – i.e., a retroactive methane slip limit of 0.2% for all ships.	2030	Retroactive	Specific regulatory limit for methane slip levels
5	**Catalyst potential:** Applied to Scenario 1a. Does not assume any specific regulatory limits for methane slip levels. Models the same technological development as 1a, but assumes 100% uptake of EGR and after-treatment technology whenever the technology is available (including retrofitting). Specifically assumes that catalyst technology is introduced in two steps: first-generation technology in 2030 and second-generation after 2035 (see also Table 2). Accordingly, methane slip reduction is modeled in a stepwise manner. The scenario is intended to show the outer bound of technologically possible emissions reductions.	2030	Retroactive	Not specified

EU ETS = European Union Emissions Trading Scheme, CII = Carbon Intensity Indicator, EGR = exhaust gas recirculation.

* Retroactive application here means that the described mitigation measure(s) apply to both newbuilds and vessels already in operation.

The first scenario (0), which forms a baseline case for the fleet fuel consumption projection, was modeled using the NavigaTE integrated assessment model developed by the MMMCZCS.[15] The remaining scenarios are not calculated in NavigaTE but derived using the number of projected dual-fuel methane vessels from Scenario 0. This means that the analysis presented here omits any dynamic effects of the incremental cost of mitigation options on the size of the projected dual-fuel methane fleet.

In our scenarios, we estimated the split of fuel consumption for main and auxiliary engines based on partner data and input from other MMMCZCS projects. We used this fuel consumption split between different engine technologies to derive a segment-specific average methane slip factor.

Engine and after-treatment technology efficiencies were modeled separately for different engine technologies (low-pressure four-stroke (LP4st), low-pressure two-stroke (LP2st), and high-pressure two-stroke (HP2st)).

To allow sufficient time for regulatory adoption before implementation, we assumed that the scenarios would be activated after 2025. The IMO GHG fuel standard will most likely include the GHG effects of methane slip and is expected to enter into force in 2027 at the earliest. If the IMO were to regulate methane slip explicitly, new regulations would have to be developed, with 2028 being the earliest possible year for entry into force.

In most of our scenarios, we assumed a slightly longer timeline to implementation (i.e., 2030 or 2035) for regulatory measures. These timelines also provide ample time for technology development, to ensure commercial availability and long-term performance of slip reduction technology.

In this report, methane slip % is defined as a ratio of unburned (slipped) fuel to injected fuel – excluding possible fugitive emissions. Furthermore, all scenarios considered entail a set of modeling assumptions as follows:

- Two percent of the existing shipowners will act even without the presence of methane slip legislation. This implies that upon availability of novel methane slip reduction technology, 2% of the newbuild and existing fleet will include this technology.

- The installed catalyst technology is used only to comply with the scenario limit values. Hence, even in the case that catalyst technology would be able to reduce methane emissions much further than required by the applied regulation, it will be only used to the degree needed to comply with the required performance levels (apart from Scenario 5).

- In the event of the introduction of retroactive regulation, newbuilds will start to adapt to the new limitation two years in advance, e.g., by installing a catalyst; 30% of the newbuilds will incorporate measures to comply two years before the introduction of the retroactive limits. One year before the introduction of the limit, 60% of the newbuilds are expected to comply. All retroactively applicable limits considered in the scenarios require the existing fleet to install and utilize appropriate methane slip reduction measures (e.g., a catalyst) for the years following enforcement.

- The scenarios are based on technology-neutral considerations, except for Scenarios 1b, 1c, and 5. Two technology introduction phases are assumed – see tables below for assumed levels of methane slip at the engine level (Table 2) and ship level (Table 3) for the first- and second-generation engine and catalyst technologies.

Table 2: Assumed engine-level methane slip and technology efficiency values.

	Methane slip level			Engine/catalyst/other after-treatment technology efficiency	
	Original	Newbuilding with generation 1 technology*	Newbuilding with generation 2 technology**	1st generation NB/retrofit	2nd generation NB/retrofit
HP2st	0.20%	0.20%	0.20%	58%/58%	74%/74%
LP2st	1.70%	0.90%	0.36%	55%/25%	83%/83%
LP4st	3.10%	0.93%	0.31%	70%/70%	90%/90%

EU ETS = European Union Emissions Trading Scheme, CII = Carbon Intensity Indicator, EGR = exhaust gas recirculation.

* Remark 47% reduction (exhaust gas recirculation etc.) is applied for LP2st, and 70% reduction (after-treatment etc.) is applied for LP4st.
** Additional 60% reduction is applied for LP2st and reduction for LP4st is improved to 90% from 70%.

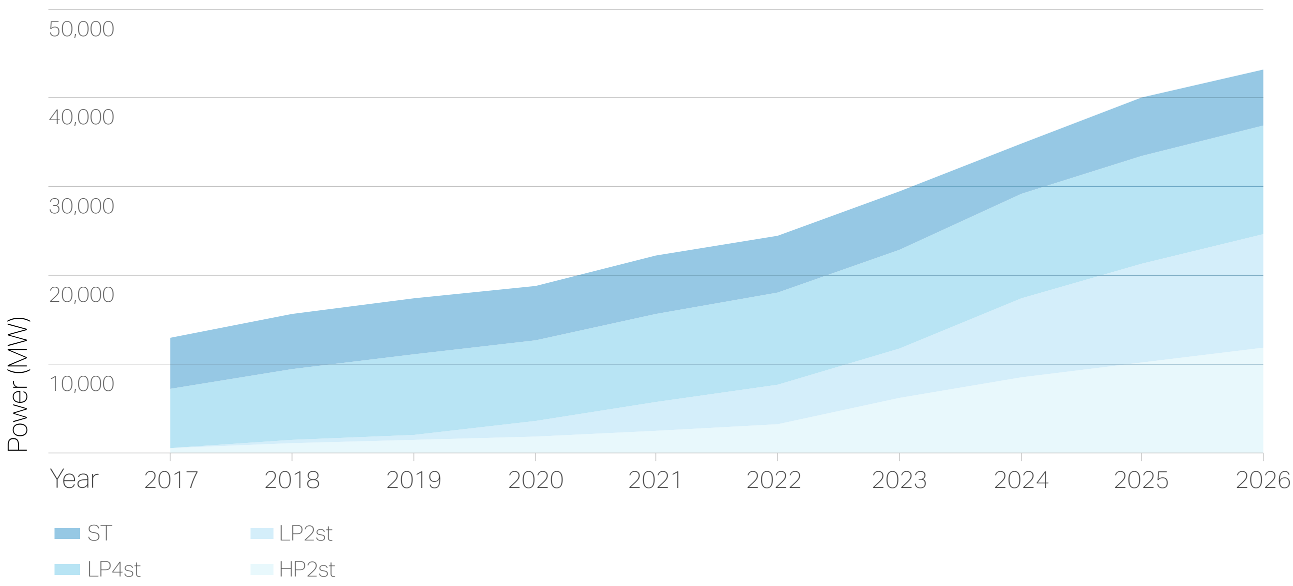
Table 3: Assumed vessel-level methane slip values.

	Original	Newbuilding before after-treatment technology is available (% difference with respect to original value)	Newbuilding with generation 1 technology (% difference with respect to original value)	Newbuilding with generation 2 technology (% difference with respect to original value)
HP2st + LP4st	0.88%	0.88% (0%)	0.37% (-58%)	0.23% (-74%)
LP2st + LP4st	2.03%	1.41% (-30%)	0.91% (-55%)	0.35% (-83%)
LP4st	3.10%	3.10% (0%)	0.93% (-70%)	0.31% (-90%)

Additional assumptions: main engine is operated at average 75% load for 200 days/year; generator engine is operated at average 10% of 100% power of main engine for 365 days/year. HP2st = high-pressure two-stroke, LP2st = low-pressure two-stroke, LP4st = low-pressure two-stroke.

The number of two-stroke dual-fuel LNG engines in our modeling is commensurate with the known increase in the number of existing and ordered LNG-fueled ships. Two-stroke engines account for an increased proportion of the power used by LNG-fueled ships and are expected to become a dominant technology among gas engines for certain deep-sea shipping segments (Figure 3). Four-stroke engines are still used in ferries and cruise ships but are largely being replaced by two-stroke engines in newbuild vessels (e.g., for LNG carriers). On the other hand, steam turbines are being phased out, and their number will gradually decrease as vessels are scrapped. Therefore, we did not consider steam turbines further in our modeling.

Figure 3: Total power of dual-fuel engines installed on LNG-fueled ships over time. Data from Clarkson Research.



ST = steam turbine, LP4st = low-pressure four-stroke, LP2st = low-pressure two-stroke, HP2st = high-pressure two-stroke.

Figure 4 presents an overview of the total annual methane slip on a TTW basis calculated for our eight different scenarios between 2024 and 2050. All scenarios are independent of the share of the renewable bio- and e-methane in the methane fuel mix, as the contribution of the slipped methane to global warming is the same regardless of its origin. Figure 4A presents the results for scenarios that are agnostic to the specific form of regulation (Scenarios 1a-c, 5), while Figure 4B shows the scenarios that include specific regulatory limits for methane slip (Scenarios 2-4). Figure 5 benchmarks cumulative methane slip emissions in the different scenarios compared to the baseline.

Our modeling suggests that, without specific action, annual methane slip emissions will increase from 0.2 million tonnes in 2024 to more than 1.4 million tonnes in 2050 (Scenario 0). All seven mitigation scenarios show sizeable reductions in annual and cumulative methane slip in 2050 compared to the baseline (Scenario 0).

A key message from our results is the importance of early regulatory action. For example, the difference in cumulative emissions between Scenarios 1b and 1c (Figure 5) clearly emphasizes the positive impact of early introduction of emissions limits for newbuilds. In fact, early introduction of limits for newbuilds (Scenario 1b) can yield reductions in cumulative methane slip emissions comparable to those from the application of retroactive measures (Scenarios 2 and 3). On the other hand, a delay in enforcing a newbuild-only regulation by five years translates to an additional 0.24 million tonnes of absolute methane emissions between 2030 and 2035 (Scenario 1c versus 1b).

Scenario 5 describes the greatest technologically possible reductions in methane slip, based on our assumptions regarding performance and availability of exhaust gas recirculation (EGR) and catalyst technologies (Table 2 and Table 3). This scenario assumes 100% EGR and catalyst uptake and in turn applies these technologies retroactively to every ship at every technological development step. Scenario 5 results in an absolute annual emissions reduction of 85% in 2050 compared to the baseline, and a 76% reduction in cumulative terms. As immediate and universal adoption of methane slip reduction technologies is not a realistic scenario, this result helps to define the possible range of ambition that regulatory efforts can operate within.

Figures 4 and 5 show that the specific and retroactive emissions limits introduced in Scenarios 2 and 3 provide notable reductions in annual and cumulative methane slip compared to our baseline scenario. In particular, Scenario 2 results in a 71% reduction in methane slip to 0.39 million tonnes in 2050 (56% reduction in cumulative emissions), whereas Scenario 3 delivers a reduction of approximately 66% to 0.47 million tonnes in 2050 (51% reduction in cumulative emissions). That being said, we consider that applying retroactive regulation to existing vessels is both technically challenging and expensive to implement compared to newbuild pathways such as Scenarios 1b and 1c.

Finally, Scenario 4 is based on the target outlined in the Global Methane Pledge (i.e., to "reduce global methane emissions by at least 30 per cent from 2020 levels by 2030").[6] Based on our analysis, meeting shipping's share of this target (Scenario 4) would bring about a 62% reduction in absolute TTW methane slip emissions from shipping by 2050, and an 81% reduction in cumulative terms, compared to the baseline. Notably, Scenario 4 generally achieves greater methane slip reductions (annual and cumulative) than Scenario 5, which is intended to model the upper bound of what we expect to be possible through technological improvement plus universal adoption of technological slip reduction solutions. Therefore, due to the forecast increase in the number of methane-fueled ships (Figure 1), we expect that significant additional efforts or new technological advancements will be warranted if the industry is to reach the targets of the Pledge.

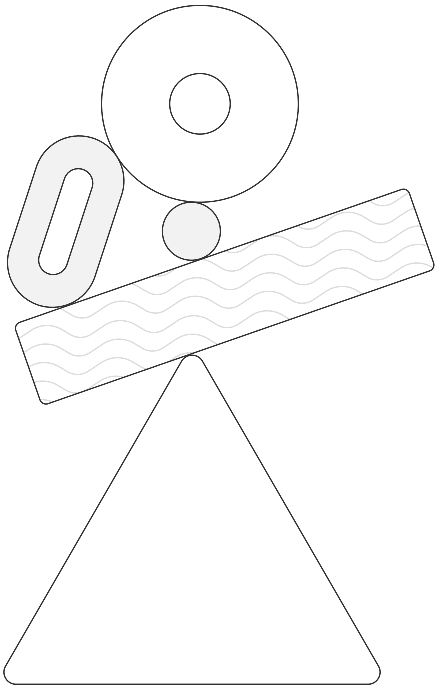
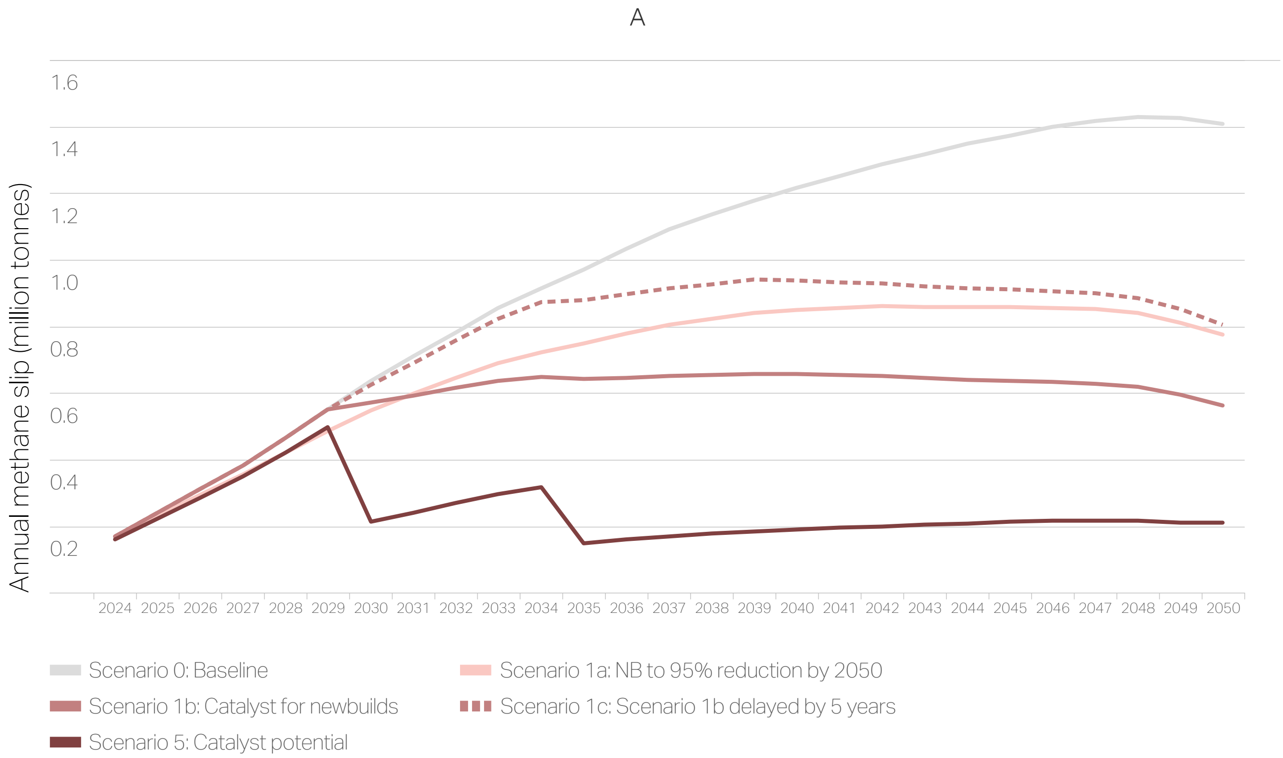


Figure 4: Annual tank-to-wake (TTW) methane slip projections for different scenarios based on techno-economic modeling for: (A) scenarios agnostic to the specific form of methane slip regulation; (B) scenarios with regulation imposing specific limits on methane slip from shipping.

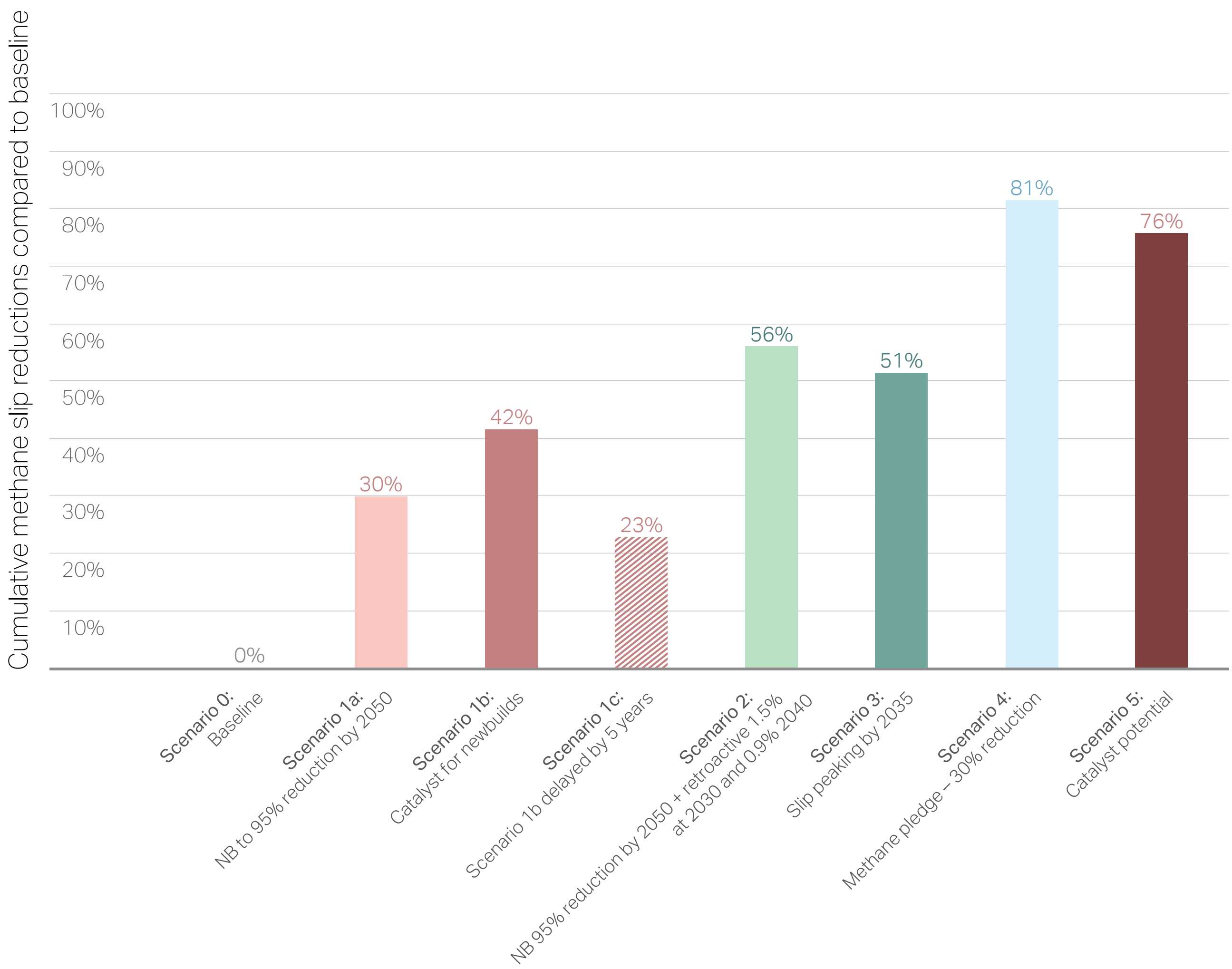


Although the use of renewable fuels is expected to reduce the overall GHG emissions from shipping, increased use of methane-based fuels will lead to more methane slip. This increase in methane emissions could offset the reductions in WTW CO_2 emissions. Therefore, in the future, methane slip will be a paramount contributor to WTW GHG emissions for methane-based fuels.

Several technical and operational options for methane regulation could be considered to support methane slip reduction efforts. These options include, but are not limited to:

- Requiring engine switchover from methane gas mode to fuel oil at low engine loads where methane slip exceeds a CO_2-equivalent threshold.
- Methane slip is dependent on factors such as engine type, size, and power level of operation. Acknowledging this, control measures could, for instance, be based on the operational speed of the engine – similar to those established for NO_x in the NO_x Technical Code.[14] Measures could include specific baseline and Tier mitigation level, e.g. of low load-point contribution using the weighted cycle approach for a weighted methane slip value.
- Regulatory measures should be technology-neutral and should not differentiate between engine types or shipping segments: however, regulation may refer to the “best available technology” in such a way as to leave space for technological competition.

Figure 5: Cumulative methane slip reduction to 2050 in mitigation scenarios compared to baseline scenario.



Insight 1 conclusions:

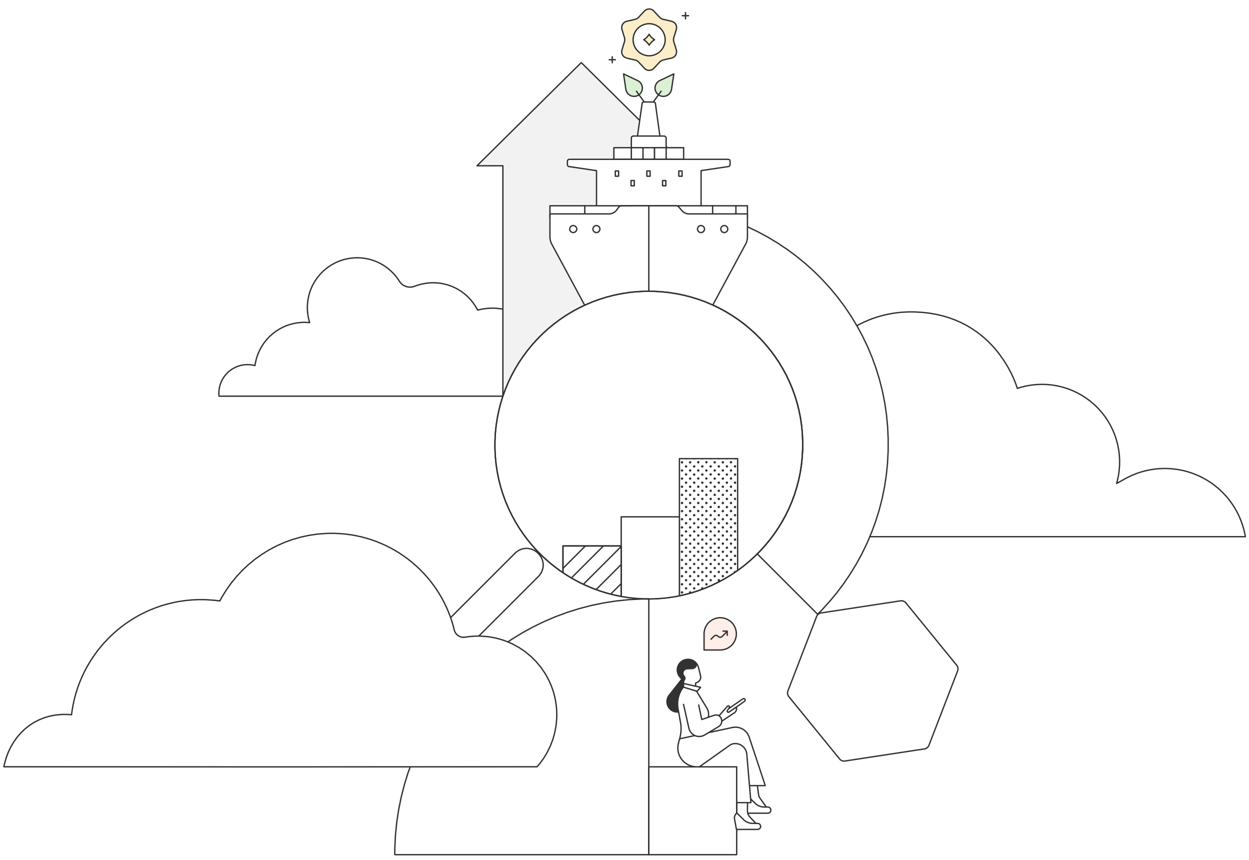
- Methane emissions from shipping are projected to increase due to growth of the methane-fueled fleet, even with the advent of renewable methane fuels.

- Current regulations that include methane, such as CO_2-equivalent fuel standards (e.g., FuelEU), are not sufficient to reduce onboard methane emissions in the short to mid term.

- Relying on the gradual future uptake of mitigation technologies by newbuild vessels (Scenario 1a – 95% by 2050) will likely result in 45% reduction of methane slip levels by 2050 on a fleet level compared to the baseline (Scenario 0); however, more stringent regulatory measures would reduce methane slip even further (by 60-73% e.g., Scenarios 1b, 2, and 3).

- Early regulation of methane slip from newbuilds (Scenario 1b) seems to result in a comparable level of methane slip reduction as that obtained with some retroactive measures (Scenarios 2 and 3). However, a delayed introduction of regulation targeting newbuilds only (Scenario 1c) appears to be less effective in reducing methane slip than gradual uptake of technology in the absence of specific regulatory limits (Scenario 1a). This implies that the later regulations are introduced, the more stringent and broadly applied they will need to be.

- Technically feasible pathways to reduce methane emissions in shipping exist[2] and can be applied through specific regulatory measures that would deliver a large impact on methane slip reduction.

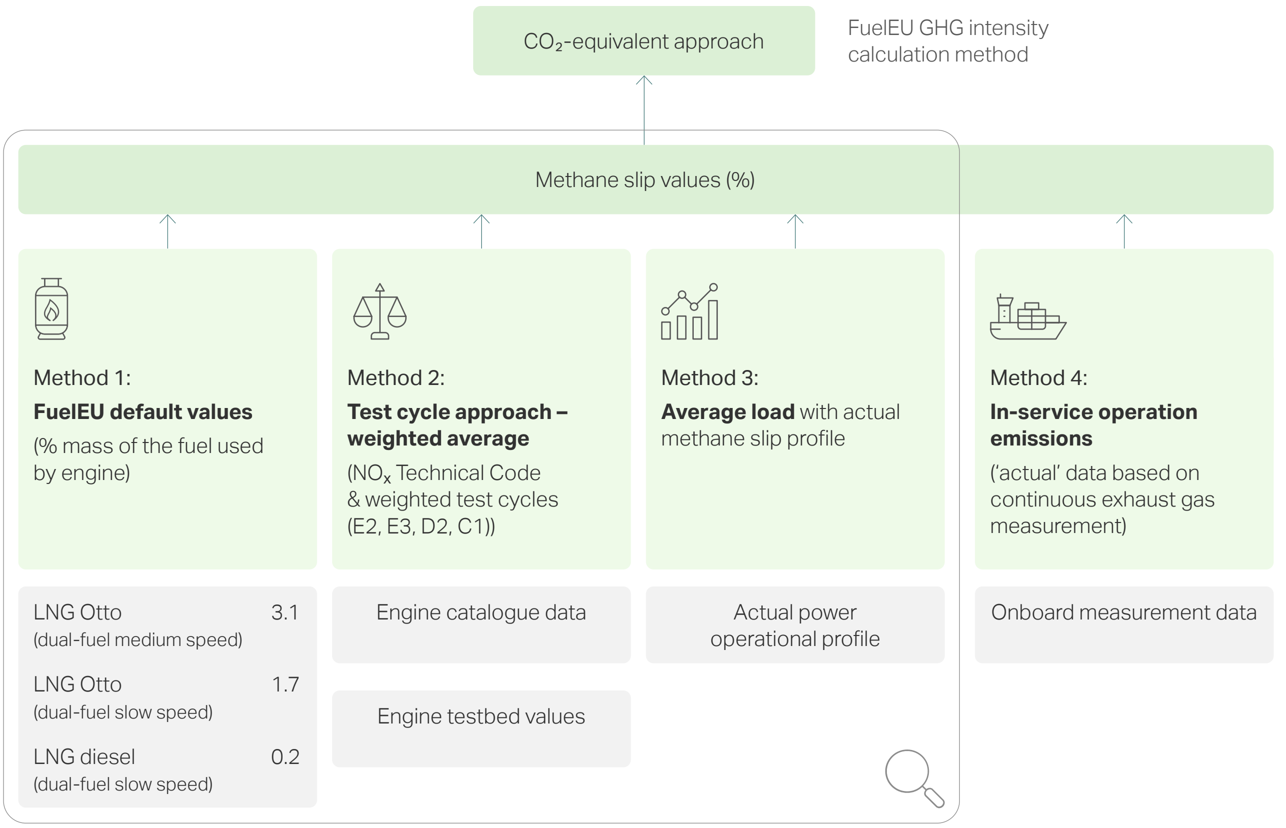


03
Insight 2: Quantification of methane emissions

To effectively regulate methane emissions in shipping, we need to be able to properly quantify these emissions. Regardless of the exact format of any regulatory action, accurate quantification is essential for successful emissions reduction. Selecting a quantification method can involve trade-offs between qualities such as accuracy, granularity, ease of measurement, and more. For example, CO_2-equivalent methodologies that use default methane slip values have the advantage of simplicity, but they do not incentivize engine makers nor shipowners and operators to reduce methane slip.

Therefore, in this section we focus on comparing four different methods for methane slip quantification: (1) default emission values, (2) test cycle approach – weighted average, (3) average load with actual methane slip profiles, and (4) in-service operation emissions – continuous measurement. The four methods are summarized in Figure 6 and described in more detail in the upcoming paragraphs.

Figure 6: Overview of methane slip quantification methods compared in this analysis.



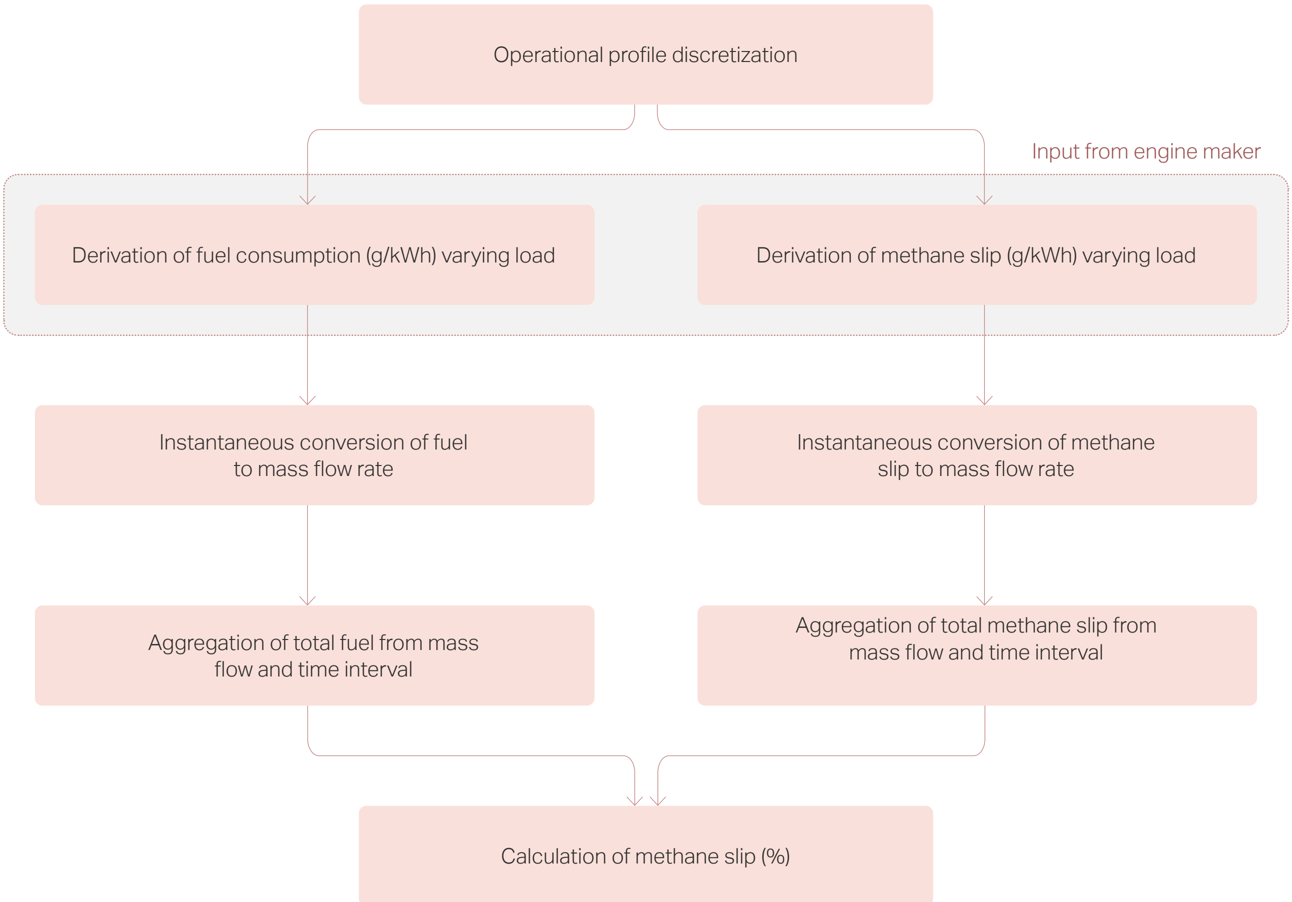
1 **Default emission values (FuelEU):** All engines are modeled using default methane slip values from the FuelEU Maritime regulation.[13] Ship-level methane slip is calculated as the sum of methane emissions from each engine. Of note, the FuelEU default values include fugitive emissions, which have not otherwise been examined in this study due to a lack of available information.

2 **Test cycle approach — weighted average:** All engines are modeled with the E2/D2/E3 test cycle[14] weighted slip. The ship-level methane slip is calculated using the methane consumption of each engine.

3 **Average load with actual methane slip profile:** Engines are modeled with the methane slip from the engine's average load (energy-based average over the actual operational profile). Methane slip is estimated at an average load based on the slip profile known as a function of engine load (from IMO test bed cycles). Ship-level methane slip is calculated as the sum of methane slip emissions from each engine using the total methane consumption of the ship. Of note, implementing this method in regulation would require agreement on the best way to calculate average engine load.

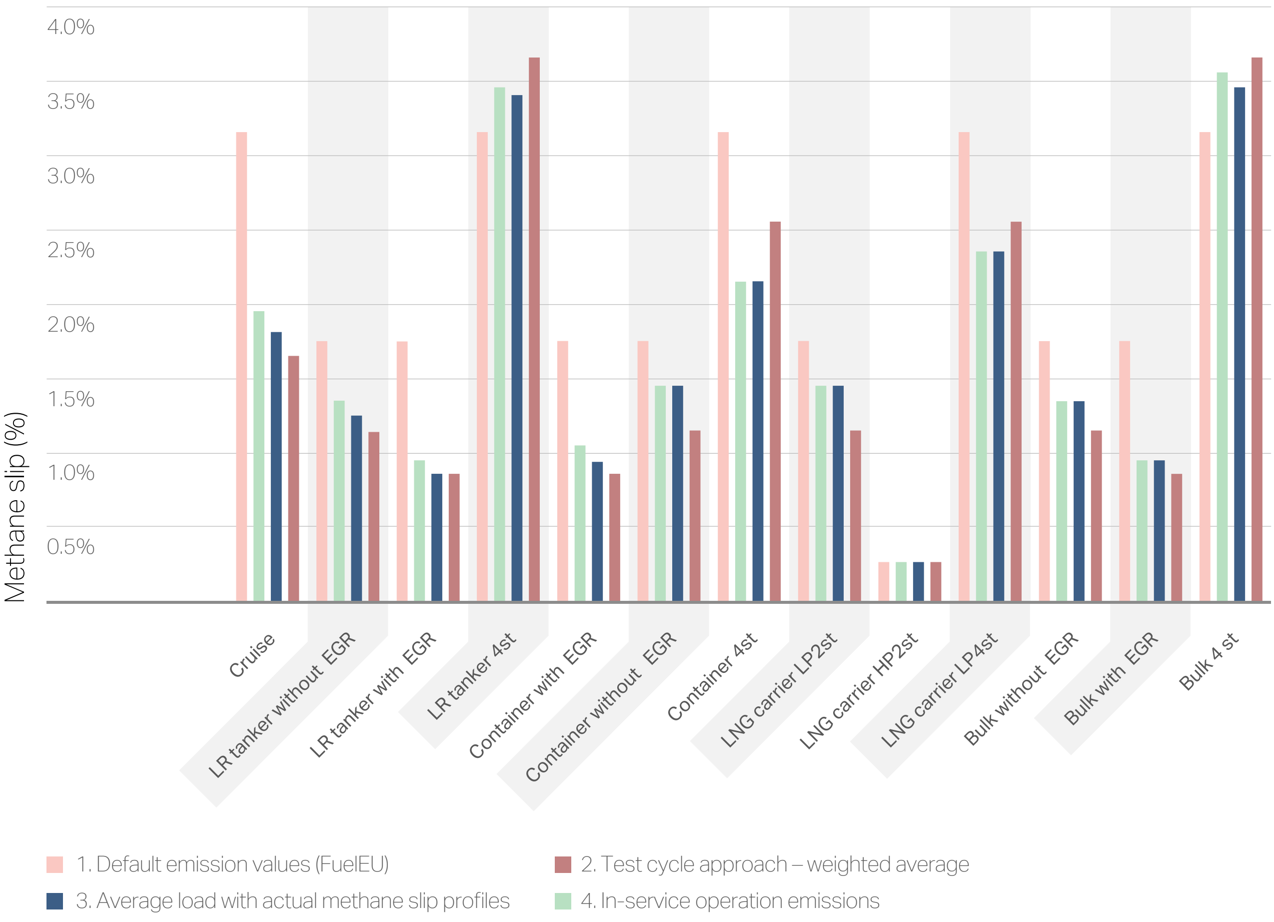
4 **In-service operation emissions — continuous measurement:** The amount of methane slip is calculated using the engines' methane slip profile obtained in the shop test, combined with the actual operational profile on gas firing. The result of this calculation is assumed to be equal to the onboard measurement result. The methane profile measured in the shop test shall be a function of engine load. Ship-level methane slip is calculated as the sum of methane slip emissions from each engine, based on their operational profile. Figure 7 illustrates the key elements of this calculation methodology. This quantification method is expected to provide accurate results and so serves as a baseline for comparison of the other methods in our analysis. While this method can be considered the most accurate, it also requires more effort and information than the other three.

Figure 7: Schematic of methane slip calculation using the 'in-service operation emissions – continuous measurement' quantification method.



We calculated segment-specific ship-level methane slip values based on the operational data of actual ships provided by MMMCZCS partners. For this assessment, we considered vessels from five segments, namely a medium-sized cruise vessel, a long-range tanker, a container vessel, an LNG carrier, and a bulk carrier. The operational data received included separate data for main and auxiliary engines. We assumed that the operational profile remains unchanged, since most data came from ships operating on diesel/residual fuel. The operational profiles of the main and auxiliary engines from each segment, together with the fuel consumption and methane slip data received from engine manufacturers for two-stroke and four-stroke engines, served as input to the calculation of the segment-specific methane slip with the different methods. A comparison of the methane slip calculations is shown in Figure 8.

Figure 8: Ship-level methane slip (%) quantified with different approaches for different shipping segments, based on actual operational profiles.



EGR = exhaust gas recirculation technology, 4st = four-stroke, 2st = two-stroke, LP = low-pressure, HP = high-pressure.

The results presented in Figure 8 indicate the following:

- The default emission values based on FuelEU (Method 1) typically provide the least accurate results. While the FuelEU default values account for fugitive methane emissions as well as slip, the other methods do not. However, we considered that the contribution of fugitive emissions would be only a small fraction of the overall emissions.

- The 'test cycle' approach based on IMO test cycles (Method 2) seems to provide a relatively accurate quantification of the methane slip, although the indicated slip calculated with this method is frequently lower than the actual operational slip (Method 4). It is likely that this situation might be improved by including lower load conditions (below 25% MCR) in the test cycle or by assigning a higher weighting value to lower load conditions.

- Quantification of methane slip based on the 'average load' approach (Method 3) resulted in calculated emission levels similar to those from continuous measurement of actual slip during operation (Method 4). This appears to apply to all shi1pping segments. Continuous measurements can in principle be used to ascertain methane emissions levels during operation.

- Methane emissions on a ship level can be quantified relatively accurately without the need to perform continuous measurements on board, provided that the engine operational profile and methane slip characteristics are known.

Another consideration is whether engine- or ship-level quantification would be preferable from a regulatory perspective. Establishing a regulatory scheme on a ship level would incentivize both engine design measures and operational procedures that mitigate methane slip. This approach would allow for greater flexibility, such as the ability to use integrated technical solutions that may be more affordable to apply at a vessel level than on an engine level.

Overall, the methods compared in this study offer feasible options for quantifying onboard methane slip as part of a regulatory scheme.

Insight 2 conclusions:

- The 'average load' approach (Method 3) can provide accurate estimates of methane slip. However, regulatory implementation of this method would require agreement on how to calculate average engine load.

- The 'test cycle approach – weighted average' method based on the IMO NO_x Technical Code (Method 2) can provide a relatively accurate estimate of real-life onboard methane slip. This method also has the advantage of being simple to implement with existing regulatory practices.

- Accordingly, we support frameworks that include methane emissions within CO_2-equivalent inventory *and* oblige measurement of methane emissions during factory tests using a weighted cycle approach in line with the NO_x Technical Code.

- In the longer term, the industry could explore options for updating regulations to incorporate other quantification approaches.

04
Recommendations

Overall, further attention from a regulatory perspective is imperative to manage methane slip and thereby ensure that methane can qualify as a sustainable maritime fuel. TTW GHG emissions, including methane slip, will be encompassed by the regulatory frameworks of FuelEU Maritime, the EU ETS, and potentially within a future GHG Fuel Standard under the IMO's mid-term measures. These regulations will evaluate GHG emissions on a life-cycle basis, highlighting the critical role of regulatory bodies in fostering the adoption of methane slip reduction technologies and LCA certification.

In light of the anticipated growth of the methane-fueled fleet in the coming years, our analysis underscores the pressing need for urgent regulatory action to curtail methane slip in shipping. For example, our modeling suggests that early implementation of regulations targeting only newbuild vessels can effect reductions in annual and cumulative methane slip comparable to those achieved with retroactive regulation. Of these two options, regulation targeting newbuilds only would likely be less expensive and less complicated to implement. However, our analysis also indicates that there is only a small window of a few years in which to enact such newbuild-targeted measures before this regulatory strategy loses much of its effectiveness in curbing methane slip. Given that a range of technical and operational solutions to reduce methane slip already exist, and that we expect to see further technological improvement towards 2050, the role of regulation in incentivizing timely uptake of these solutions is critical.

In addition, we expect that ambitious regulatory action and enforcement can create a virtuous effect by increasing demand for methane slip reduction technologies and thereby driving ongoing technological development of increasingly effective solutions. Technologies and engines designed to minimize methane slip have been available for years and continue to develop, yet their adoption has been limited due to higher costs and lack of regulatory incentives. Widespread adoption of low-methane-slip technologies among manufacturers is unlikely without regulatory mandates or significant incentives to offset the higher costs associated with these advanced technologies.

Mitigating methane slip requires equipment manufacturers and regulators to work in tandem. We therefore urge engine manufacturers to embed methane slip reduction technologies directly into their engine designs as standard features, rather than offering these innovations as add-ons. Manufacturers should also ensure that new “low-slip” designs are backward-compatible, allowing for retrofitting of older engine models or provision of upgrade kits. These measures will in turn extend assets’ operational lifetime and amplify the impact of methane emissions reduction efforts.

Furthermore, while this specific report has focused on control of methane slip, we wish to highlight that effective regulatory action must not only mandate reduction of methane slip but also set clear expectations for the sustainability credentials of methane-based fuels. By doing so, we can facilitate a near-term increase in the volume of sustainable energy sources available for maritime use.

This report has also detailed multiple methodologies for quantifying methane slip at both the engine and vessel level. Of the methods compared here, we consider that the ‘test cycle approach – weighted average’ method based on the NO_x Technical Code (‘Method 2’ in our analysis) offers a balance between accuracy and ease of implementation that is appropriate for regulatory use. We further suggest that incorporating methane emissions measurement into the Engine International Air Pollution Prevention (EIAPP) certification process during factory tests forms a practical approach to quantification of methane slip for regulatory purposes. Assessing key emissions metrics during EIAPP certification tests at designated points would make it feasible to accurately estimate a vessel's GHG emissions. This estimate could be based on the operational profile of the engine, or the amount of fuel consumed, offering a method to gauge ship-level emissions effectively. By setting ship-level regulatory limits in a manner akin to the NO_x Technical Code, with adjustments to account for emissions during low load operations, regulators can establish a robust framework that would encourage enhancements in engine design and the adoption of operational practices aimed at reducing methane slip.

Given the environmental and regulatory risks from methane slip, shipowners choosing methane as a fuel should follow best practices, install fuel and engine systems with minimum slip, and consider onboard methane emissions reduction technologies as soon as possible. Use of best practices will curb emissions from vessels and avoid potentially costly modifications later in the vessel’s lifetime when future methane regulations come into force. Furthermore, shipowners should assess the financial implications of non-compliance with GHG regulations to safeguard their investments. We call on shipowners to engage in prompt discussion with their equipment suppliers to address challenges pertaining to methane slip. Tackling these challenges early can secure a competitive edge for shipowners and operators in anticipation of forthcoming legislation targeting methane slip.

4.1 Gaps for further research

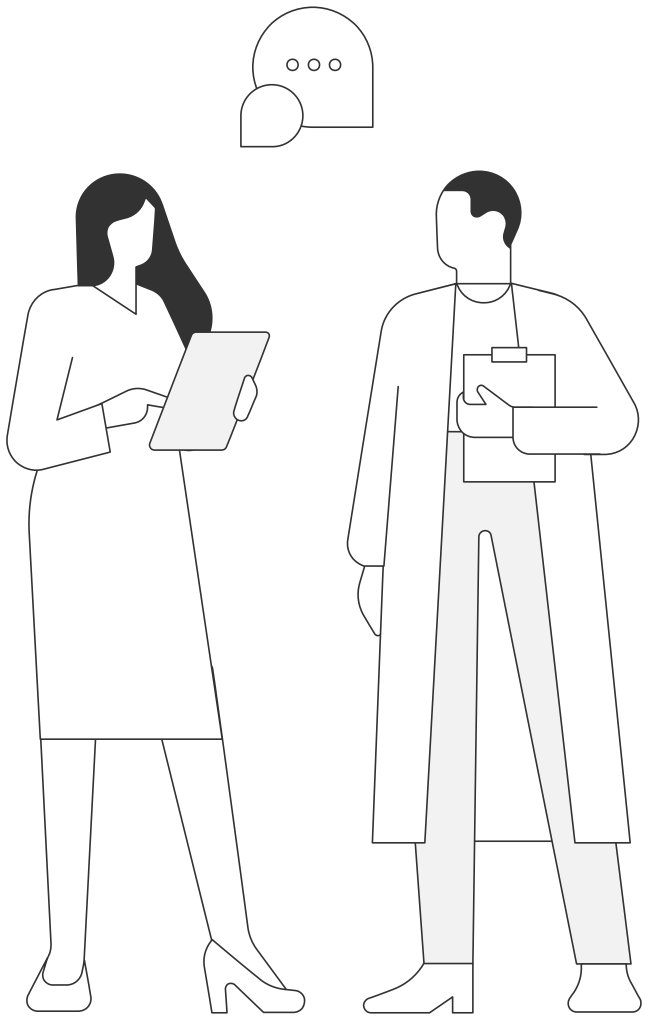
Finally, our analysis has identified key areas where further research is essential to enhance our understanding of how to best manage and quantify methane emissions:

- Regulatory framework development to verify the accuracy of onboard emissions measurements and benchmarking against engine test bed data.

- Assessment of test cycle weightings to more closely reflect actual operational profiles of vessels and to offer a better understanding of how engine tuning impacts methane emissions, assuming a fixed mechanical setup.

- Quantification of onboard methane emissions to better understand the characteristics and sources of non-slip methane emissions (e.g., fugitive emissions, operational releases) and further clarify the role of onboard emissions measurement from a regulatory and commercial perspective.

- Lastly, further consideration needs to be given holistically to the whole supply chain for LNG and other methane-based fuels, alongside certification processes. This will lead to a broader understanding of how methane slip emissions impact production facilities and other applications, in addition to onboard emissions.



05 The project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners. We would like to thank the following group members, who made major contributions to the work used as a basis for this report. Participants seconded to the MMMCZCS from a partner organization are marked with an asterisk (*).

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Abbreviations

CII	Carbon Intensity Indicator
CO_2	Carbon dioxide
EGR	Exhaust gas recirculation
EIAPP	Engine International Air Pollution Prevention
EU	European Union
EU ETS	European Union Emissions Trading Scheme
GHG	Greenhouse gas
GWP	Global warming potential
HP	High-pressure
HP2st	High-pressure two-stroke engine
IMO	International Maritime Organization
LCA	Life-cycle assessment
LNG	Liquefied natural gas
LP	Low-pressure
LP2st	Low-pressure two-stroke engine
LP4st	Low-pressure four-stroke engine
MCR	Maximum continuous rating
MEPC	Marine Environment Protection Committee
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
NO_x	Nitrogen oxides
N_2O	Nitrous oxide
SO_x	Sulfur oxides
TTW	Tank-to-wake
WTW	Well-to-wake

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