July 2024

Methane Abatement in Maritime Innovation Initiative

Report from **Safetytech Accelerator**

Safetytech Accelerator

Contents

About MAMII and Safetytech Accelerator

Launched in September 2022 and led by Safetytech Accelerator, the Methane Abatement in Maritime Innovation Initiative (MAMII) is a coalition of shipping industry leaders, innovators, and maritime stakeholders united in identifying, accelerating, and advocating technology solutions to measure and abate methane emissions on LNG-fuelled vessels.

We aim to reach methane-free maritime and bunkering supply chains and operations, minimise the environmental impact of LNG in shipping, and facilitate the transition to future fuel solutions.

Members include Capital Gas, Carnival Corporation & Plc, Celsius Tankers, Chevron, CMA CGM, CoolCo, JPMorgan, Knutsen Group, Lloyd's Register, Maran Gas Maritime, Mediterranean Shipping Company, Mitsui O.S.K. Lines, MISC, NYK Line, Seapeak, Seaspan Corporation, Shell, TMS Cardiff Gas, Total Energies, UK P&I Club, United Overseas Management.

The first fully dedicated technology accelerator focused on advancing innovation in safety-critical industries, Safetytech Accelerator exists to make the world safer and more sustainable through wider technology adoption.

Safetytech Accelerator was established by Lloyd's Register, one of the world leaders in professional services, compliance, and assurance in the maritime sector.

Safetytech Accelerator produced this report to share learnings from MAMII with all stakeholders concerned with methane emissions from shipping and recommend actions to accelerate the adoption of technology that can reduce or remove methane emissions.

Safetytech Accelerator is grateful to its partners for their funding and active engagement in the programme, and to Lloyd's Register, for its technical expertise and strategic view.

For more information, visit www.mamii.org and www.safetytechaccelerator.org.

As the world's third-largest LNG player, we are delighted to be joining the MAMII initiative and contributing our expertise in reducing the emissions all along the gas value chain.

It is key for TotalEnergies to further improve the environmental benefits of LNG as a marine fuel, already a major decarbonisation lever for the maritime industry."

Jerome Cousin
SVP Shipping, TotalEnergies

Foreword

After carbon, methane is the second most important greenhouse gas. Its emission profile is amplified by its potent nature, even though only small volumes of methane are emitted in maritime operations.

With the growth of the LNG-fuelled ship fleet, as well as the number of LNG carriers fuelled by LNG, critics have focused on methane emissions and methane slip, emissions deriving from incomplete or inefficient combustion.

Despite the availability of engine and LNG-handling technology which can mitigate this risk, methane emissions have been promoted as a counterargument to prevent shipowners from adopting a fuel which can deliver an improved greenhouse gas footprint and an unrivalled local pollution profile with multiple societal benefits.

Some past engine technologies presented significant methane slip values, and criticism has also focused on the upstream side and the entire bunkering supply chain, penalising the use of LNG as fuel in maritime operations.

MAMII has been formed as a maritime industry response to this question to scrutinise, quantify, and finally propose measures and actions to mitigate the risk from methane emissions in maritime operations.

In the last two years, we have completed a comprehensive series of analyses detailing the nature of methane emissions at every stage of the value chain.

We have conducted global technology surveys focusing on methane measurement, reporting and verification, as well as various abatement approaches, and we have initiated pilots to unveil and assess technology readiness.

Based on this wealth of knowledge shared between partners, we have crystalised a strategy to help focus the industry and the regulators.

With more than 20 major groups behind this initiative, we are calling on the entire industry to support our efforts. Our immediate priority target is to lead the standardisation of methane measurement through a unified protocol, which can also constitute the basis for IMO (International Maritime Organization) action.

We are collectively taking and aligning actions with other industry bodies, including SGMF (The Society for Gas as a Marine Fuel). We hope to instigate a series of pilots to expedite technology development and uptake in the maritime industry.

MAMII serves as a prime example of the maritime industry taking the transition challenge into its own hands. We are actively involved in every aspect, crafting a strategy and facilitating technology development based on scientific evidence and the industry's insights.

In this context, we urge regulators and policymakers to make technology-centric decisions that will drive the widespread adoption of relevant technologies. For the MAMII partners who recognise the significance of addressing niche but critical challenges like methane emissions, the only way forward is together.

Panos Mitrou, Chairman of MAMII
Global Gas Segment Director, Lloyd's Register

Introduction

Shipping generates an estimated 3% of global greenhouse gas emissions. Merchant ships burn 300 million metric tonnes of fossil fuels annually, emitting around a billion metric tonnes of carbon dioxide (CO_2) – the equivalent of Japan's yearly carbon emissions.

Following The Paris Agreement in 2015, the International Maritime Organisation (IMO) pledged to halve carbon emissions from shipping by 2030 and achieve carbon-neutral shipping by 2050.

The IMO repeated this pledge at the 2023 United Nations Climate Change Conference (COP28) and updated its targets: a 20% reduction in emissions by 2030 and a 70% reduction by 2040 (compared with 2008 levels), and net-zero emissions by 2050.

The shipping industry is making significant efforts to find an alternative fuel to help meet these targets, directing attention towards biofuels, hydrogen and hydrogen carriers, and nuclear propulsion.

However, multiple factors – ranging from supply reliability to health and safety concerns – have limited the adoption of these alternatives, and many shipping companies are shifting towards Liquified Natural Gas (LNG) as a transition fuel to help meet upcoming targets.

Comparing the current global fleet against new ship order books shows this shift. While less than 7% of the current global fleet (by tonnage) can use alternative fuels today, half (51%) of new ships being built will be able to operate on alternative fuels.

45% of ships ordered in 2023 embrace alternative fuels, with LNG now considered to be a mature, scalable and commercially viable fuel for the maritime industry.

LNG is understood to generate the same propulsion power as other marine fuels but with 23% less CO_2, significantly lower nitrogen oxide gases, and almost zero sulphur and particulates.

However, the environmental gains from using LNG are compromised when methane, its primary component, escapes into the atmosphere.

The International Energy Agency (IEA) estimates that fossil fuels produced 120 million metric tons of methane in 2023. These levels are currently too high to meet international climate targets.

Besides, methane emissions have a global warming impact that is far greater than that of CO_2 and a 75% reduction by 2030 is necessary to prevent dangerous levels of warming.

Over a 100-year period, one tonne of methane will warm the planet as much as 29 tonnes of CO_2. Thankfully, technology is now available to abate these methane emissions.

Methane emissions on ships primarily stem from methane slip, unburnt methane released through the exhaust. It is important to detect leaks quickly and repair them promptly.

LNG carriers have more complex pipework with valves and flanges due to transporting substantial LNG cargoes, heightening the chances of fugitive leaks and increasing the challenge of leak detection.

There are also operational leaks, including deliberate releases during refuelling or purging of the fuel line. Moreover, due to pressure risks, LNG carriers must flare off excess gas in emergencies.

Measuring Methane Slip

The industry needs more data to assess the level and impact of methane released by LNG-fuelled ships. Quantifying this will allow policymakers to evaluate and de-risk the use of this interim fuel.

Many different units and measures are employed in the literature to describe the quantity of methane slip and associated Global Warming Potential (GWP).

There can also be a discrepancy between the emission levels reported by engine manufacturers and those measured in the exhaust stack. Modern engines running at optimum load, typically 80%, are very efficient. If misused, however, the performance of the same engine can be very poor.

Older engines tend to have a bigger problem. Engine manufacturers measure their engines at the optimum load for fuel usage and emissions. However, there are operational reasons why engines only sometimes run at their most efficient levels, such as when manoeuvring within a port environment.

Shipping operators can measure methane slip more precisely (in methane parts-per-million) using technology to sample exhaust gas. Some operational leaks are structured events when the amount of methane released can be precisely calculated. Others can be channelled and measured with sensors.

Various technologies can now detect, measure, and abate methane emissions.

The Methane Abatement in Maritime Innovation Initiative (MAMII) exists to validate the credibility and accuracy of these solutions in real conditions, which will require consistent, universal guidelines for measuring methane.

MAMII is already taking action on these critical fronts by developing measurement guidance, lining up trials, and adapting the most promising solutions for use in a marine environment.

Conclusions

Safetytech Accelerator has identified a series of learnings and recommendations through MAMII. These conclusions are from analysis and acceleration activities with 20 maritime partners over a 15-month period and engagement with over 100 technology providers offering potential solutions.

- Regulation is a necessity to address methane emissions in the maritime industry. A robust and clear framework centred around technology will facilitate faster uptake of solutions. Ambition must be high and well-defined, with a target to minimise emissions, regardless of origin, throughout all maritime operations.
- The industry should demystify the 'black box' of well-to-tank emissions – upstream emissions released by producing and delivering fuel – as it is possible to define and mitigate methane emissions at this stage. A key objective should be to validate and certify the performance of LNG producers and bunkering suppliers and to work with those who demonstrate excellence.
- Methane slip is the critical component of methane emissions onboard ships. Methane-proof engine technology is available today, but further innovation is imperative. Beyond combustion slip abatement, the industry should consider other solutions, such as shaft generators, to avert emissions and expedite the uptake of solutions tackling fugitive emissions.
- There are a wide variety of solutions to detect and quantify methane emissions. A key objective now should be to validate the credibility and accuracy of these solutions in real conditions. The variation between testbed and onboard measurement regimes requires urgent consideration, as well as consistent, universal guidelines for measuring methane. MAMII is taking action on these fronts, developing measurement guidance and moving several high-potential solutions to trial and marine industry adoption.
- There are more potential solutions to the abatement problem than previously expected, ranging from combustion improvement and post-combustion treatment to hydrogen blending. Despite substantial projected progress in methane performance, the cost and complexity of abatement are key risks. As solutions progress towards maritime adoption, it is important to prioritise adoption incentives and regulations that encourage technology use.
- Integrating methane into regulatory schemes will support the viability of methane abatement technology development and uptake. It will also make methane performance a key design parameter for future ships, trigger the uptake of solutions for and conversion of existing engines, and substantially improve the methane footprint of the global maritime fleet.

Regulations & Methane Emissions from Ships

A key conclusion from MAMII is the importance of a technology-centric regulatory framework to incentivise and facilitate faster uptake of solutions. The programme explored existing methane requirements in IMO and European Union (EU) regulations and identified global methane-related initiatives in the maritime sector.

One of the key elements in quantifying the impact of methane emissions is Global Warming Potential (GWP), a measure of how much heat a greenhouse gas traps in the atmosphere over a specific time period after it is emitted to the atmosphere. This allows methane to be compared with CO_2.

According to IPCC AR6[1], methane's GWP over 20 years (GWP20) is 82.5, while over 100 years (GWP100), the score is 29.8. This means that, over a 20-year period, methane has 82.5 times the heat-trapping potential of an equivalent amount of CO_2. Over 100 years, it is likely to trap around 30 times more heat.

IMO & EU REGULATIONS

Whether regulations around methane and methane abatement are based on GWP over a 20 or 100-year timescale could make a significant difference. Methane has a higher GWP over 20 years compared to 100 years, reflecting its stronger short-term impact on global warming.

Focusing on the 20-year timescale highlights its more immediate climate impact, which is critical for making informed decisions about emissions reduction strategies and regulatory policies in the shipping industry.

The IMO life cycle assessment guidelines[2] on greenhouse gas emissions are calculated as CO_2e (CO_2 equivalent) using the GWP100 approach, although GWP20 will be used for comparisons. Several proposals to IMO's Marine Environmental Committee suggest using GWP20 instead of solely GWP100. EU regulation has not yet committed to GWP100 or GWP20.

Other regulations that refer to methane include:

- **EU MRV (Monitoring, Reporting, and Verification) Maritime Regulation[3]**: Starting January 2024, this requires reporting of greenhouse gas emissions, including methane, for all legs of voyages involving an EU port, as well as emissions in the port.
- **FuelEU Maritime:** Beginning in 2025, FuelEU Maritime is part of a range of measures designed to address maritime emissions. It builds on existing policies such as Regulation (EU) 2015/757 of the European Parliament[4], which established a system to monitor, report and verify CO_2 emissions from large ships using EU ports.
- **EU ETS (Emission Trading Systems):** Shipping companies now have to purchase and use emission allowances for each tonne of in-scope CO_2e emissions, including methane[5]. In 2025, companies must buy allowances covering 40% of their reported emissions from the previous year. This will increase to 70% of emissions reported in 2026 and 100% in 2027.
- **IMO CII (Carbon Intensity Indicator) and EEXI (Energy Efficiency Existing Ship Index):** The International Convention for the Prevention of Pollution from Ships has included CII and EEXI ratings since 2022[6]. A CII refresh planned for 2026 will likely bring methane emissions within the regulations. Methane may be also included in the EEDI (Energy Efficiency Design Index) and EEXI regulations.

[1] IPCC Sixth Assessment Report, 2021: The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity Supplementary Material
[2] International Maritime Organization, 2023: 2023 IMO Strategy on Reduction of GHG Emissions from Ships
[3] European Union, 2023: FAQ - Monitoring, reporting and verification of maritime transport emissions
[4] European Commission, 2021: Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive
[5] European Union, 2023: Reducing emissions from the shipping sector
[6] International Maritime Organization, 2022: Rules on ship carbon intensity and rating system enter into force

DIRECTIONS

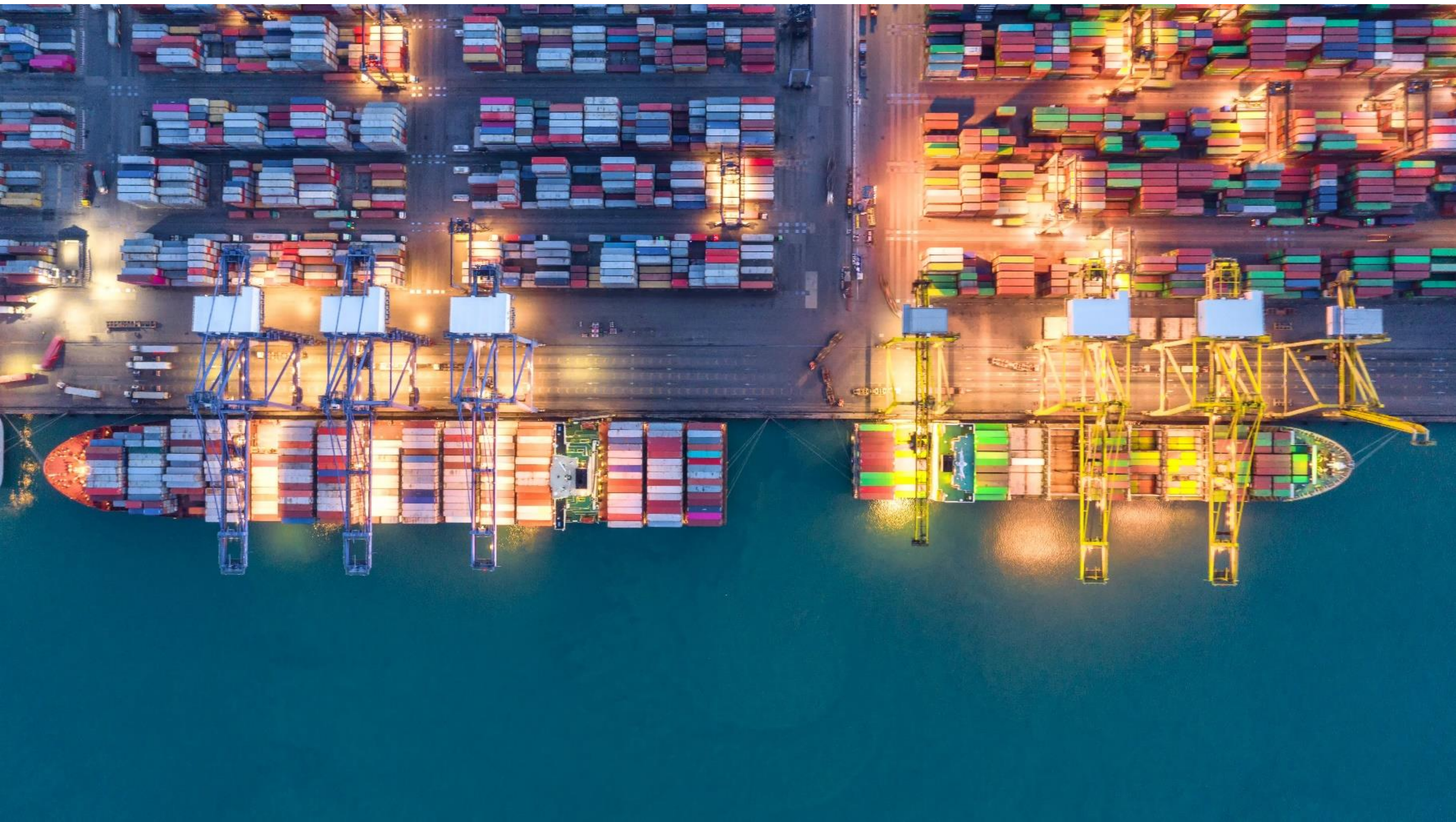
- It is vital that regulators implement a clear, robust, and focused regulatory framework as soon as possible to incentivise technology development and uptake.
- Regulators must eliminate any uncertainty to ensure that shipping companies are not discouraged from pursuing methane emissions reduction.
- The regulatory framework must be flexible and encourage the development and swift uptake of solutions that reduce emissions on existing ships and planned new builds.

Key Points for Ship Owners & Operators

New regulations are coming soon. The potential inclusion of methane in CII will present a significant challenge for ships without suitable abatement technology.

EU ETS and FuelEU Maritime regulations will provide the first incentives towards a methane abatement technology uptake.

The establishment of GWP20 over GWP100 intensifies the impact of methane emissions by roughly three times, further incentivising the adoption of methane abatement technology.



Well-to-Tank Methane Emissions

The ambition for methane abatement in maritime must be high, with a target of minimal emissions, irrespective of origin, throughout all maritime operations and the LNG supply chain. Supply-chain processes involved in obtaining, transporting, process and storing (bunkering) LNG are referred to as “well-to-tank”.

The natural gas sector is responsible for around 11% of global methane emissions. LNG accounts for nearly 40% of all gas traded internationally and around 4% of the global methane emissions.

Most LNG is used for electricity generation or industrial and residential use. Less than 1% of LNG methane emissions are currently attributable to shipping.

While well-to-tank methane emissions fall outside the maritime industry, they fall within the industry’s sphere of influence. Shipping companies must understand the total GWP of the LNG it consumes, and procure fuel with minimal, transparent, and verifiable emissions.

OUTCOMES

- MAMII examined the conventional LNG value chain of wells, pipelines, processing, liquefaction, transport, and storage.
- It found that a lot of work has been done in the LNG well-to-tank value chain and that the marine industry represents a small fraction of global methane process emissions.
- Emissions are becoming easier to measure accurately, with proven technologies such as sensor monitoring available to assess emissions in the well-to-tank part of the value chain.
- Certified gas initiatives are becoming more important to meet the growing demand for cleaner LNG shipments. These initiatives include:
    - The MiQ Standard, an independent framework for assessing methane emissions from the production of natural gas
    - The Oil and Gas Methane Partnership Gold Standard, an oil and gas reporting and mitigation programme from the United Nations Environment Programme
    - The GIIGNL (International Group of Liquefied Natural Gas Importers) framework, a verified statement of greenhouse gas intensity and emissions within the LNG value chain

DIRECTIONS

- The analysis provides confidence that well-to-tank emissions can be accurately assessed.
- Certification schemes contribute considerably to efforts to create methane-proof value chains.
- Incentives are crucial to stimulate the adoption of solutions for monitoring and mitigating these emissions.
- More work is required to ensure that technology used for floating production, storage and offloading vessels, floating LNG vessels, and floating regasification units is deployable.

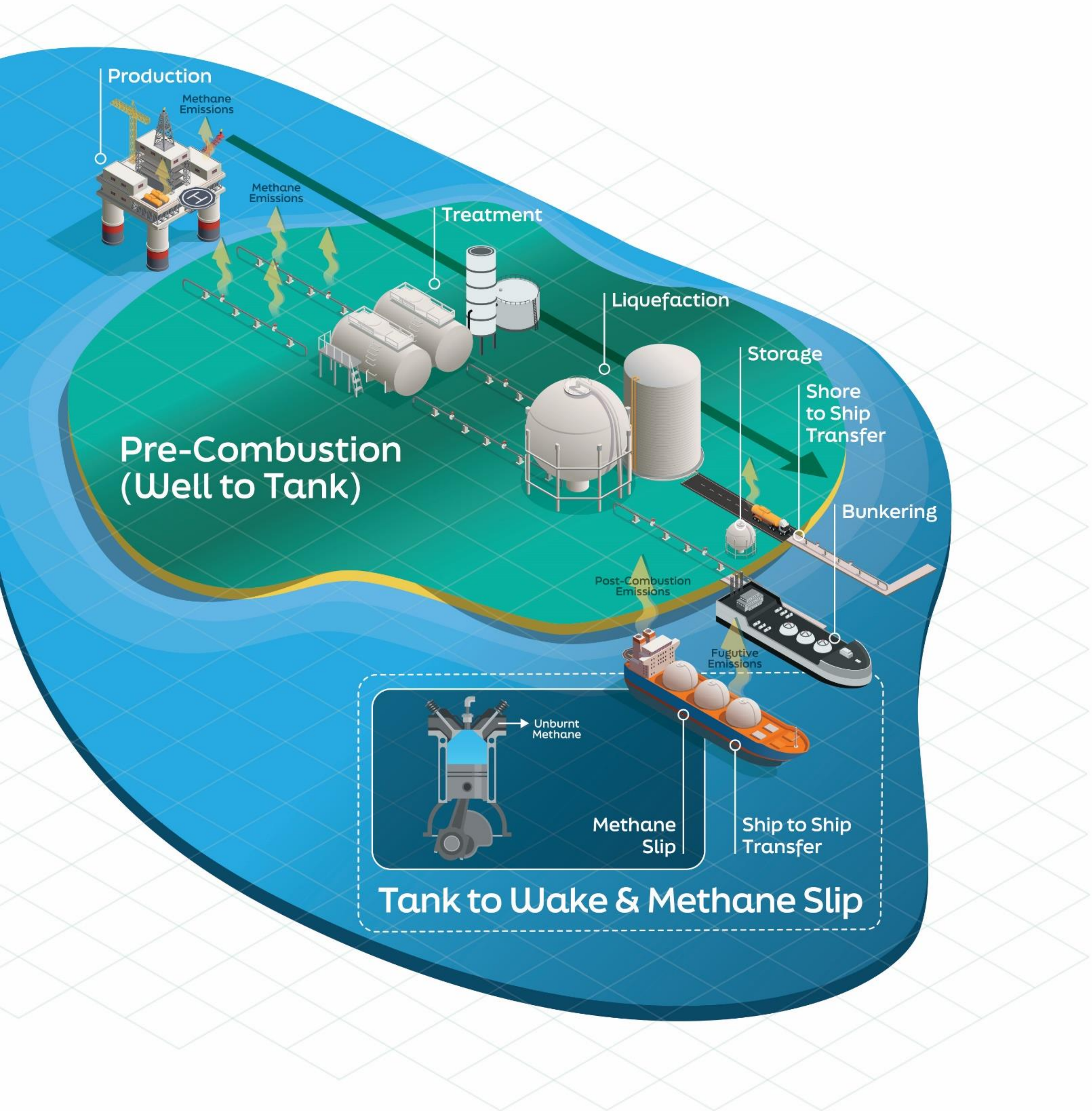
Key Points for Ship Owners & Operators

Several technologies, such as satellite surveillance and advanced sensor technology, are available to practically trace every methane molecule escaping from their installations.

The implementation of effective piping and compression arrangements can significantly minimise methane leaks.

Methane-proof upstream facilities will become increasingly common as more climate measures are adopted.

Consider LNG producers that successfully apply these measures and technologies and work with certification bodies to obtain greater visibility of methane performance.


Production
Methane Emissions
Methane Emissions
Treatment
Liquefaction
Storage
Shore to Ship Transfer
Pre-Combustion (Well to Tank)
Bunkering
Post-Combustion Emissions
Fugutive Emissions
Unburnt Methane
Methane Slip
Ship to Ship Transfer
Tank to Wake & Methane Slip

Tank-to-Wake Methane Emissions

MAMII has put substantial effort into the LNG value chain's tank-to-wake component, the emissions resulting from fuel use onboard a vessel. Methane emissions primarily come from the engine in the form of methane slip in the exhaust and the crankcase breather. They also come from operational activities such as purging lines and from fugitive or temporary leaks in pipework.

Many existing studies fail to consider the latest developments in the engines themselves and the ability of aftermarket solutions to abate methane

Variances can occur between measured methane emissions and testbed data offered by engine makers, and more up-to-date data is essential for understanding progress in engine technology and methane slip mechanisms.

Managing the engine loads during the various ship operations is particularly important to ensure optimum emissions management. Work is ongoing to identify technology to detect, measure and abate fugitive and operational emissions.

OUTCOMES

- Research shows methane slip remains the key component of onboard emissions and should continue to be the primary focus of methane abatement activities.
- While methane-proof engine technology exists for high-pressure two-stroke engines, other engine types present significant variance in methane performance.
- Despite progress, low-pressure two-stroke engines continue to emit methane at roughly 1g/kWh rates, but four-stroke engines are the main challenge.
- Auxiliary engine loads sometimes emit more methane than the main propulsion systems.

DIRECTIONS

- More informed decision-making around engine technology is necessary, with variations between testbed and onboard measurement regimes requiring urgent consideration and understanding.
- Despite recent progress, methane slip is the key component of onboard emissions. Engine manufacturers must continue exploring ways to improve performance and invest further in developing abatement solutions.
- The industry should focus further on non-engine interventions for averting methane slip, such as shaft generators and battery technology.
- Based on cost-benefit fundamentals and available technology, tackling fugitive leaks presents low-hanging fruit for reducing methane loss.

Key Points for Ship Owners & Operators

Exploring and adopting methane monitoring and abatement solutions on a cost-effective basis should be a key concern for the industry.

Consider using shaft generators instead of auxiliary engines while in mid-sea and technologies such as batteries and fuel cells for use near shore.

A clear distinction exists between engine methane slip at optimum combustion conditions and performance at transient or low-load combustion conditions. Consider alternative methods to avert sub-optimal engine conditions that exacerbate emissions.

Measurement Reporting & Verification

Irrespective of origin, accurate detection and quantification of onboard methane emissions is crucial. With more regulators integrating methane emissions into their schemes, methane measurement, reporting and verification solutions become vital.

While progress has been made around measuring methane slip on ships, some previous solutions have proven inconsistent when deployed across multiple operating conditions. Limited data and tools are available for analysis and there is yet to be a universally accepted method for measuring methane slip.

It is necessary to be able to monitor gas concentrations and volume precisely to quantify methane emissions accurately. It is possible to sample gas concentrations, while flow rates can be measured directly in the stack or calculated for the engine using parameters including fuel consumption and ambient conditions.

Key Points for Ship Owners & Operators

There is a variety of measurement technologies to address methane abatement challenges.

The absence of trials in real marine operating conditions and the lack of consistent universal measurement guidelines remain key challenges for addressing the performance of methane measurement, reporting and verification solutions.

Acting on these matters and expediting the uptake of credible detection and quantification onboard ships should be primary objectives.

OUTCOMES

- MAMII identified over 100 companies with methane measurement technologies, of which 25 had potential for maritime deployment.
- Solutions from SeaArctos, Green Instruments, Emsys Maritime, Daphne Technology, SailPlan, Everimpact, Tunable, and Servomex were shortlisted for further trials.
- The research shows that various technologies are available for detecting and quantifying methane emissions, although further testing of these technologies in real onboard conditions is required to independently determine the accuracy of those solutions.
- It is essential to develop and apply consistent universal measurement guidelines to mitigate the risk of discrepancies between methods and obtain a clear understanding of the solutions.

DIRECTIONS

- As methane emissions become regulated and monetised, credible detection and quantification become a key objective for the industry.
- A variety of technologies are currently available, each with the potential to detect and quantify methane emissions. It is important to trial and deploy these solutions in real marine operating conditions.
- Developing and applying a consistent universal measurement guideline is essential to benchmarking and understanding the potential of technologies.

Methane Abatement

Methane emissions are the second most important type of greenhouse gas emissions. For LNG-fuelled and LNG trading ships, they constitute a major risk. However, they also represent some of the lowest-hanging fruit for maritime industry climate alignment.

Multiple promising technologies have emerged, but they have yet to be available as established solutions to achieve complete methane abatement from maritime operations at scale. However, such technology can reduce methane slip to a negligible, if not zero, amount.

Despite progress in engine technology, abatement remains a key requirement for many engines with considerable methane slip, and the lack of methane integration in regulatory regimes means there is yet to be a business-critical incentive for the development and uptake of abatement solutions.

OUTCOMES

- MAMII identified more than 90 companies with methane abatement technologies. 17 of these had the potential for maritime deployment.
- Daphne Technology, Plenesys, Johnson Matthey, CDTi, SailPlan, and Rotoboost were shortlisted for imminent trials.
- There were three broad categories of abatement solutions:
    - Engine technologies to reduce methane slip
    - After-treatment solutions focused on mitigating the release of methane passed through the engine combustion process
    - Solutions that integrate various equipment classes to aid abatement efforts.
- Early trials and input from solution providers indicate methane abatement levels of between 30% and 70%, depending on the technology and deployment.

DIRECTIONS

- Regulators should incentivise onboard installation and use of methane abatement solutions.
- At current readiness levels, piloting and trialling onboard remains the key priority.
- Energy requirements and complexity of solutions are the key parameters when optimising what is currently available.

Key Points for Ship Owners & Operators

Shipping owners and operators could use a broad range of technologies for methane abatement. However, there are barriers to overcome relating to complexity, energy requirements, and adaptation to the needs of the maritime industry.

The optimal solutions will depend greatly on the types of engine technologies used. Factors such as exhaust gas temperature, hydrogen blending behaviour, and spark ignition may substantially affect performance.

Uptake of methane abatement at scale is unlikely without clear incentives and the regulatory framework that encourages the adoption of technology.

Cost Benefit Analysis

The gradual integration of methane emissions into regulatory schemes will establish a monetary value relating to their climate impact and create a clear and compelling business case for adopting methane abatement technologies.

MAMII conducted a comprehensive cost-benefit analysis of methane abatement technologies for maritime vessels. This analysis considered six scenarios based on three engine configurations and two trade routes: one from the Middle East to Europe, and a second from Australia to Japan.

MAMII developed ten models to assess the impact of abatement technologies on cost savings and CO_2e reduction. Fuel consumption assumptions for each engine configuration were based on LNG carriers of 174,000m^3 cargo capacity.

OUTCOMES

- Appropriate methane abatement technologies can lead to significant cost savings, reduced CO_2e emissions, and compliance with various environmental regulations.
- The choice of technology for different engine configurations can significantly affect cost savings and CO_2e emissions reduction.
- For ships with low-pressure two-stroke main engines and four-stroke auxiliary engines, implementing abatement technologies on both engines will deliver optimal cost savings and emissions reduction.
- Catalytic abatement technology has considerable potential for reducing emissions on four-stroke ships.
- Ships with high-pressure four-stroke main engines and four-stroke auxiliary engines would benefit financially from installing abatement technologies only on the auxiliary engines today.

DIRECTIONS

- Cost-benefit analysis suggests an exceptional climate case for methane abatement in the maritime industry.
- A technology-centric integration of methane in the CO2e regulatory framework would boost methane abatement uptake.
- Trialling solutions in a real maritime environment is essential to help technology companies understand how to price their innovations and improve the feasibility of deployments.

Key Points for Ship Owners & Operators

MAMII analysis showed that the choice of abatement technology for different engine configurations could significantly affect cost savings and CO_2e emissions reduction.

For ships with low-pressure two-stroke and low-pressure four-stroke engines, it is advisable to implement abatement technologies on both.

Due to their considerable abatement potential, it is recommended to implement catalytic abatement technologies in low-pressure four-stroke vessels.

Installing abatement technology on auxiliary engines for ships with both high-pressure two-stroke and low-pressure four-stroke engines will tackle the primary source of methane emissions.

Recommended Actions

The following actions are critical to reducing and removing the methane emissions issue from LNG use as a marine fuel:

METHANE REGULATION

- To incentivise technology development and uptake, regulators should implement a robust and focused regulatory framework as soon as possible.
- Clarity is of paramount importance. The ambition of this framework needs to be well-defined and areas of uncertainty mitigated.
- A flexible, technology-centric regulatory intervention will ensure a greater and swifter uptake of solutions.

WELL-TO-TANK

- MAMII's survey provides confidence that the total methane footprint can be assessed and mitigated.
- Climate incentives are vital for the adoption of solutions that will monitor and mitigate methane emissions across the well-to-tank value chain.
- The impact of methane performance certification schemes will contribute considerably to methane-proof value chains.

TANK-TO-WAKE

- Ship operators must ensure they are fully informed to make decisions around engine technology.
- Engine manufacturers should invest more effort in improving methane performance and developing abatement solutions.
- Ship operators should focus further on non-engine solutions for averting methane slip, such as shaft generators and batteries.
- Based on cost-benefit fundamentals and the technology available, fugitive leaks represent low-hanging fruit for reducing methane emissions.

METHANE ABATEMENT

- Regulators should incentivise the installation and use of methane abatement solutions on ships.
- Piloting and trialling onboard remain the key priorities at current technology readiness levels.
- Energy requirements and complexity of solutions are the key parameters in optimising what is currently available.

MEASUREMENT REPORTING & VERIFICATION

- As methane emissions are regulated and monetised, credible detection and quantification become key objectives for the industry.
- A variety of technologies are currently available to detect and quantify methane emissions. It is important now to trial these solutions in real operating conditions.
- Developing and applying a consistent universal measurement guideline is essential to benchmarking and understanding technology potential.

COST-BENEFIT ANALYSIS

- Cost-benefit fundamentals imply an exceptional climate case for methane abatement in the maritime.
- A technology-centric integration of methane in the CO2e regulatory framework can boost methane abatement uptake.
- Trialling versions of solutions tailored to maritime environments is essential to optimising cost parameters and improving feasibility.

Technology Overview

A range of promising methane measurement and abatement technologies are available for pilot studies today. However, they still need to be produced at a commercial scale and still require pilot studies and benchmarking to ensure their accuracy, effectiveness, and reliability in a marine environment.

METHANE SLIP MEASUREMENT TECHNOLOGIES

MAMII identified more than 100 companies with methane measurement technologies, with around 25 suitable for maritime deployment. Eight were investigated further.

For measurement to be useful in proving emissions and targeting abatement, measurement must be continuous, not just the result of inspection.

With the notable exception of Emsys Maritime, which has installations on hundreds of ships, the rest of the market is still playing catchup and has relatively few installations.

We found the following technologies to measure methane. They have been proven in agriculture, waste recycling and environmental monitoring industries.

- **Standoff Cameras:** These rely on infrared technology and are mostly used for fugitive leak detection rather than measurement.
- **Solid-State Sensors:** Solutions that use solid-state metal-oxide sensors are emerging but not currently well suited to maritime environments. They tend to be used in landfills and agricultural use cases.
- **Drones:** Service companies that use various sensor payloads on piloted drones for ad hoc methane measurements. This approach does not provide the continuous measurement recommended by MAMII.

- **Gas Chromatography:** This technology is typically used to measure methane concentration before entering the ship's engine.

- **Satellites:** The technology can detect and estimate the levels of methane emitted from certain sites, but accuracy needs higher for maritime use.

Laser-based technologies offer the speed and accuracy required by the maritime industry. The following technologies have already been deployed in maritime, often for solutions that measure sulphur oxides (SOx) and nitrogen oxides (NOx), but are also capable of being used for methane emissions.

They can be deployed either directly onto the exhaust stack or use a sample line to extract the gas to a remote instrument cabinet. Some solutions can use sample lines from several stacks into one single instrument to reduce costs.

- **NDIR Laser (Non-Dispersive Infrared):** Specifically designed to detect a single gas using a simple optical path, the response time for NDIR systems can be in milliseconds but tends to be averaged over seconds or minutes.

- **FTIR Laser (Fourier Transform Infrared Absorption Spectroscopy):** This technology can be tuned for different gases over a wide wavelength range but requires additional analytics to determine gas concentrations. Response times are in the order of seconds.

- **TDLS Laser (Tuneable Diode Laser Spectroscopy):** Wavelengths can be tuned for absorption by specific gases. It is highly accurate and offers fast response times. The technology provides the speed of NDIR and flexibility of FTIR.

Solutions based on these technologies will often use off-the-shelf components, but some manufacturers have developed their own key components, such as photon-detecting sensors.

Another technology to watch is Cavity Ring-Down Spectroscopy, which uses lasers to measure gas concentrations at parts per trillion. Although quick and accurate, this technology is expensive and requires complex installation.

METHANE SLIP ABATEMENT TECHNOLOGIES

We identified more than 90 companies with methane abatement technologies, 18 of which had the potential for maritime deployment. Seven were investigated further. MAMII partners are currently testing the following to reduce methane emissions:

- **Engine Redesign:** Manufacturers are continuously improving their engines to reduce methane emissions, with the following steps offering significant reductions:

  - Exhaust gas recirculation (EGR) sends cooled exhaust gas back to the engine so methane can further combust instead of escaping into the atmosphere.

  - Cryogenic valves improve efficiency by injecting liquid methane into the cylinder instead of gas.

  - Mixing input methane gas with hydrogen can reduce carbon content and methane slip. The hydrogen required for this process is derived from the ship's existing LNG tanks using thermos-catalytic decomposition. The carbon by-product can be captured and recycled.

- **Catalysts:** These can be installed in the exhaust stream, before or after the turbocharger, to convert methane into less harmful molecules. This technology is already well understood and deployed for SOx and NOx abatement. Once installed, they are usually low maintenance and have a lifespan of several thousand hours.

  - Installing catalysts before the turbocharger provides greater abatement due to higher exhaust temperatures. The downside is that engine modifications are necessary and installations must be done in partnership with engine manufacturers.

  - Installing catalysts after the turbocharger provides a lower level of abatement due to cooler exhaust temperatures. No engine modifications are necessary and installations are simpler.

  - If a ship has multiple engines, installing the catalyst at sea is sometimes possible by shutting down the affected engine. Single-engine ships must be in port for installation, although dry docks are not typically required.

- **Plasma:** This is an emerging technology for exhaust stacks where a plasma torch releases energetic electrons to interact with the exhaust to break up methane molecules. Electrical power is required, but plasma devices typically require low maintenance once installed.

- **Software:** Engine manufacturers are starting to provide software that informs crews when the engine is not operating at optimal load to reduce emissions. Independent software companies are also providing similar solutions.

- **Vapour Recovery:** Methane vented from LNG fuel tanks can be re-captured where regulations allow it. Methane is only vented from tanks in emergencies.

TECHNOLOGY FOR NEW BUILDS OR RETROFIT

A modern, well-designed engine that runs efficiently can have a very low methane emission. A combination of technologies can be added to improve performance.

They include monitoring to assess emissions in all conditions, solutions that enable ship operations to adjust behaviour to minimise emissions, using a single engine instead of two in tandem, and using cleaner alternatives for tasks such as electricity generation.

With nearly 1,000 LNG ships in service, it is critical to the environment that technology solutions are available to retrofit. Monitoring and abatement technologies must deal with larger amounts of methane for some more polluting older engines.

The technology needed for greener shipping already exists. With the right incentives, it can be industrialised and fitted onto ships relatively quickly.

To make this transition possible, investment is required from all stakeholders – ship owners and operators, venture capitalists, governments, and regulators. Their financial support is crucial in enabling the widespread adoption of these solutions and paving the way for a more sustainable shipping industry.

Technology Ecosystem

Everimpact

France: everimpact.com

Everimpact started as a real-time greenhouse gas monitoring platform for cities using satellites, sensors and AI. It has partnered with Mitsubishi and Wilhelmsen to launch a sensor-based continuous emissions measurement system (CEMS) for ships, now implemented on a Mitsubishi vessel.

Everimpact offers a gas analyser and a real-time platform for measuring greenhouse gas emissions from exhaust stacks. It uses a cabinet, safely deployed away from the stack, connected via a heated sample line.

Safetytech Accelerator evaluated more than 80 methane measurement technology companies. From this cohort, Everimpact was invited to produce a feasibility study in the summer of 2023 in partnership with MAMII anchor partners MOL and Shell.

Following a successful collaboration, Everimpact is now engaged in several pilots with anchor partners.

Green Instruments

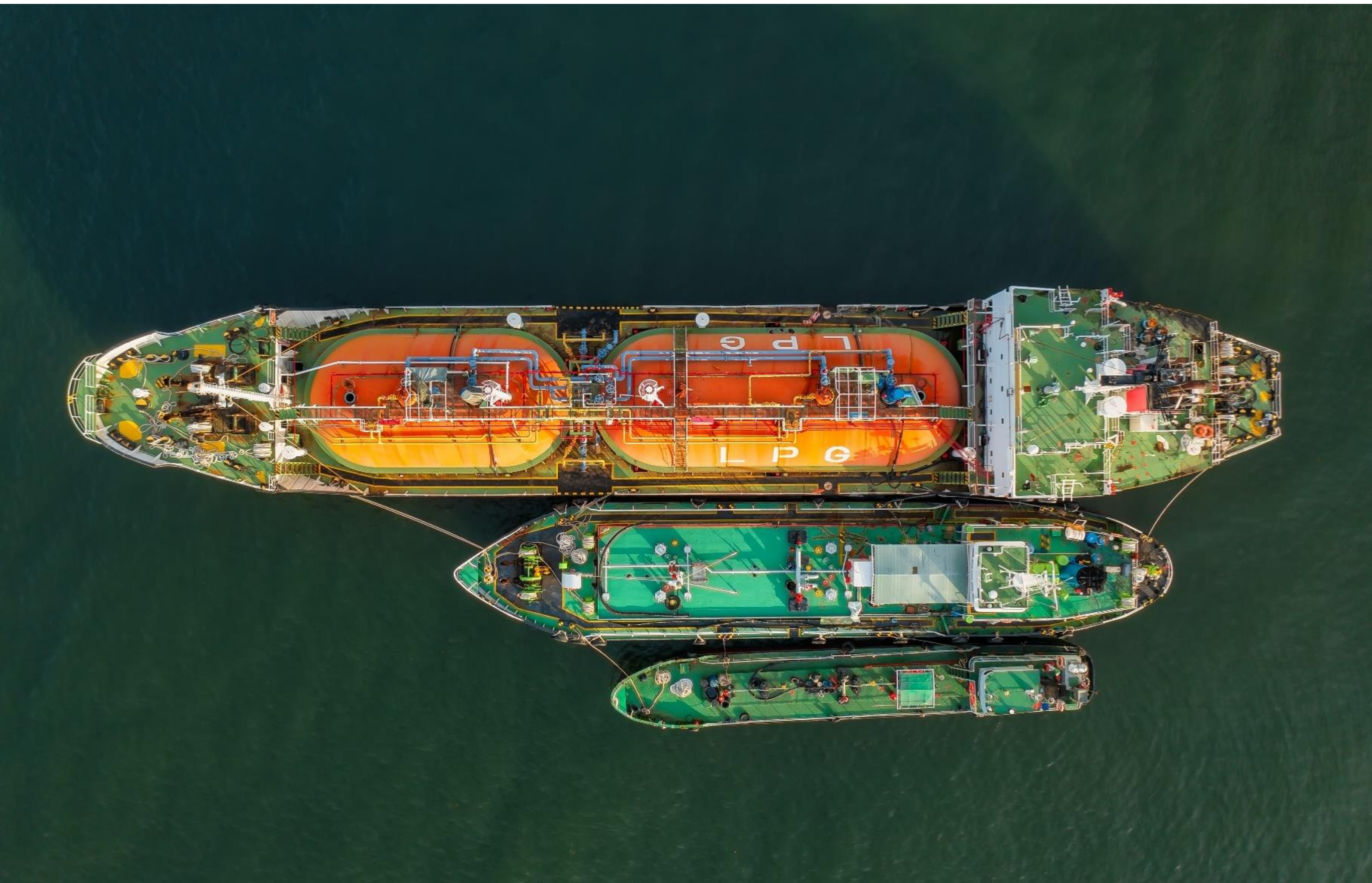
Denmark: greeninstruments.com

Green Instruments aims to address the need for accurate, crew-serviceable emissions monitoring on ships with its continuous monitoring system, the G7200 Multi Gas unit.

Green Instruments has already supplied over 300 continuous emissions measurement systems (CEMS) to the maritime industry, leveraging its proven technology and marine certifications.

Uniquely adapted for shipboard use, the unit can continuously measure methane and other emissions. It is designed to withstand humidity and contaminants common in exhaust streams.

Green Instruments was invited to do a feasibility study with Shell, which recommended an adapted, crew-serviceable CEMS system to monitor emissions in compliance with regulations continuously.



Emsys Maritime

United Kingdom: emsys-maritime.com

Emsys Maritime has developed a system specifically designed to measure and monitor various exhaust gases for the marine industry. It can calculate methane slip in g/kWh and CO2 equivalents in kg/tonnes, ensuring compliance with annual Selective Catalytic Reduction (SCR) spot checks.

The solution ensures emission control and can identify potential issues related to them. It has a compact, lightweight design enabling easy installation, has low maintenance requirements, and can be integrated with vessel automation systems.

Emsys Maritime was invited for a deep dive session to explore further their technology and its potential impact on enhancing safety and environmental sustainability in the maritime sector.

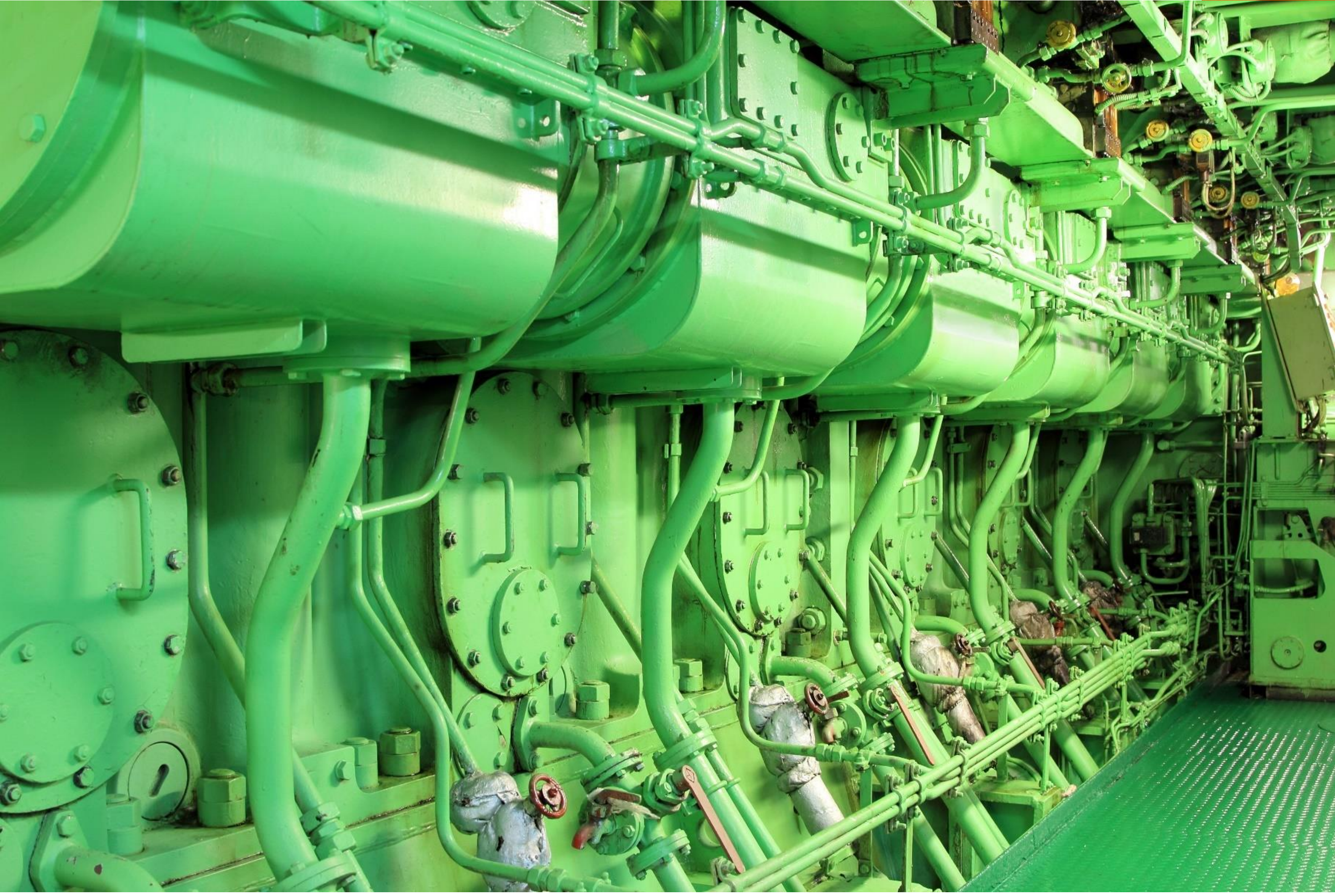
Plenesys

France: plenesys.com

Plenesys supports sustainability in marine transportation by using patented plasma torch systems to produce clean hydrogen reliably. Its plasma torches use industrial-grade alternating current to split exhaust methane into constituent hydrogen and carbon elements.

The design ensures durable, nonstop high-temperature operation that captures 100% of emission flows while requiring no downtime for electrode cooling. Beyond scrubbing maritime exhaust gases, the continuous cracking process exhibits potential for onsite hydrogen production as a reusable fuel source.

Plenesys was invited to do a feasibility study with Seapeak to utilise methane slippage from the exhaust stream more efficiently via conversion to hydrogen and integrate it into a cleaner blended engine fuel. Doing so curbs methane emissions in a cost-effective manner while also lowering net CO2 outputs.



CDTi Advanced Materials Inc.

USA: cdti.com

Invited to conduct a feasibility study for MSC Shipping and Capital Gas, CDTi brings over three decades of specialised experience in emissions reduction technologies.

CDTi proposed implementing its Lean Methane Oxidation Catalyst, a passive device installed within the exhaust flow of dual-fuel engines to curb methane slip. Its compact catalyst leverages noble metal chemistry to oxidise methane into carbon monoxide and water vapour.

CDTi can achieve substantial methane conversion rates with the proposed system at temperatures between 300-500°C. Additional testing will finalise parameters like space velocities and platinum group metal levels.

CDTi's adaptable, powder-proof solution can effectively control methane slip from internal combustion systems with minor retrofits, providing a reliable and efficient emissions reduction strategy.

Rotoboost

Norway: rotoboost.com

Rotoboost provides maritime vessels with an innovative system that enables the onsite production of clean hydrogen fuel through the thermo-catalytic decomposition of liquefied natural gas (LNG).

By leveraging the ship's existing LNG supply and minimal electrical input, hydrogen can be generated and blended directly back into the engines. Invited by Seapeak to undertake a feasibility study examining its vessels, Rotoboost confirmed strong potential to utilise the system to curb methane slip from the LNG-fueled engines.

Its analysis validated the capability for onsite decomposition of some of the ships' LNG to produce recyclable hydrogen for reintroduction as supplementary fuel. Initial predictions point to significant reductions in methane emissions and enhanced sustainability profiles from this form of LNG repurposing.

Daphne Technologies

Switzerland: daphnetech.com

Daphne Technologies SlipPure system for maritime vessels seeks to curb methane slip from dual-fuel engines by using plasma torch technology to split methane emissions into less harmful carbon and water vapour.

The system is installed within exhaust stacks and encompasses proprietary hardware for generating the plasma discharge and sensing equipment to quantify pre- and post-treatment slippage levels.

Daphne outlined multiple drivers spurring adoption from regulatory compliance to new carbon credit opportunities and tax incentives like the U.S. Inflation Reduction Act. For example, gas compression applications can mitigate penalties by reducing site emissions by over 75% using SlipPure.

Invited by MSC Shipping for a feasibility study, Daphne analysed engine data and vessel particulars to customise a SlipPure configuration that can curtail over 90% of methane slip.

Glossary of Terms

CII: Carbon Intensity Indicator measures the greenhouse gas emissions of a ship relative to the cargo carried and distance travelled. It is used to assess and regulate the environmental performance of maritime transport.

COP28: The 28th United Nations Climate Change Conference or Conference of the Parties. It is the world's highest decision-making body on climate issues.

EU MRV: A regulation by the European Union on maritime Monitoring, Reporting and Verification (EU 2015/757) applying to ships of 5,000 gross tonnage and above, regardless of their flag, that carry passengers or cargo for commercial purposes to or from ports in the European Economic Area

Exhaust Stack: An exhaust stack is a vertical pipe or chimney that directs combustion gases from an engine or boiler into the atmosphere, helping dissipate pollutants and efficiently manage heat emissions.

FLNG: Floating Liquefied Natural Gas refers to a ship or a floating platform equipped to produce and convert natural gas into LNG at sea.

FPSO: Floating Production Storage and Offloading is a type of vessel used in the offshore oil and gas industry to produce, process and store oil offshore until it can be offloaded onto a tanker or transported through a pipeline.

FSRU: Floating Storage and Regasification Unit is a specialised ship or floating platform equipped to store LNG and convert it back into gas form. They facilitate natural gas supply to regions without extensive gas infrastructure.

FSU: Floating Storage Unit is a vessel used primarily to store LNG or other hydrocarbons offshore.

GIIGNL: Groupe International des Importateurs de Gaz Naturel Liquéfié is an association of companies that import LNG and provides a framework for sharing best practices and promoting LNG safety and reliability.

GWP: Global Warming Potential.

IMO: The International Maritime Organisation is the United Nations specialised agency responsible for the safety and security of shipping and preventing marine and atmospheric pollution by ships.

Infrared Spectroscopy: Infrared spectroscopy is a technique that analyses how molecules absorb, emit, or reflect infrared light, revealing their chemical structure and composition.

LNG: Liquefied Natural Gas.

Methane Abatement: Methane abatement refers to the methods and technologies used to reduce methane emissions to mitigate climate change impacts.

Methane Slip: Methane slip refers to releasing unburned methane during combustion in LNG-fuelled engines, notably in marine applications. This occurs due to incomplete combustion or specific operating conditions, such as low load or during engine start-up and shutdown, significantly impacting greenhouse gas emissions.

MiQ: The fastest growing and most trusted methane emissions certification standard, a MiQ Certificate is a tradeable environmental attribute certificate evidencing the methane performance of natural gas production, processing and transport.

NOx: Nitrogen Oxides are reactive gases formed when burning fuel at high temperatures. They are significant air pollutants that contribute to smog, acid rain, and respiratory issues.

OGMP: Oil and Gas Methane Partnership is a voluntary initiative engaging oil and gas companies to reduce methane emissions through comprehensive reporting and implementing best practices in their operations.

PM: Particle matter refers to tiny particles and droplets in the air, such as dust, dirt, soot, and smoke, that can be inhaled and cause health problems. PM is a major component of air pollution.

SOx: Sulphur Oxides are gases primarily produced by burning fossil fuels. They are harmful pollutants that contribute to acid rain, respiratory problems, and environmental degradation.

Well-to-Tank: The energy supply chain, from extracting raw materials from the ground to delivering fuels into a fuel tank. This focuses on emissions and energy use during production and transportation.

Safetytech Accelerator

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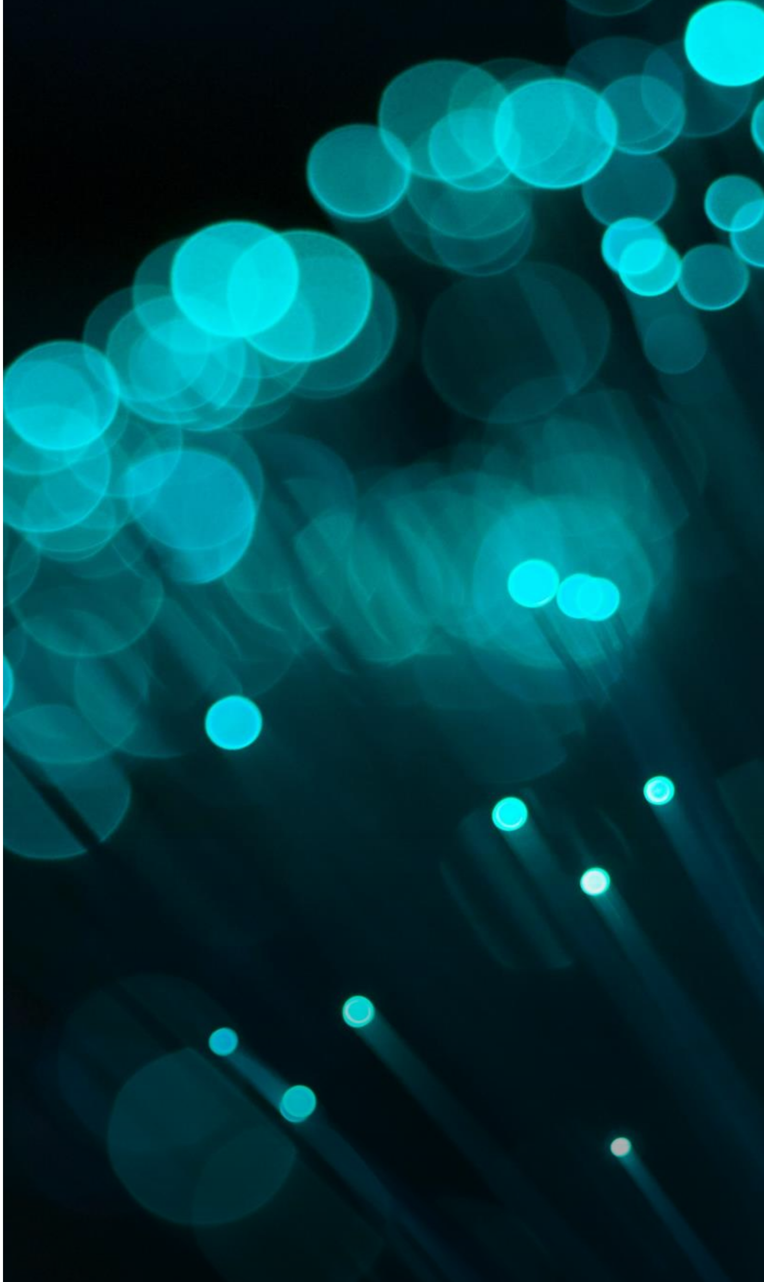

Partner with us

The Safetytech Accelerator seeks leading industry partners to join our mission to make the world safer and more sustainable through wider adoption of Safetytech.

Get in touch

For more information about the programme, including previous and ongoing safety and risk challenges, please visit:

www.safetytechaccelerator.org/contact