LNG PATHWAY - THE PRACTICAL AND REALISTIC ROUTE

SEA-LNG

A VIEW FROM THE BRIDGE

2024-2025

SEA-LNG.ORG

LNG PATHWAY – THE PRACTICAL AND REALISTIC ROUTE TO DECARBONISATION

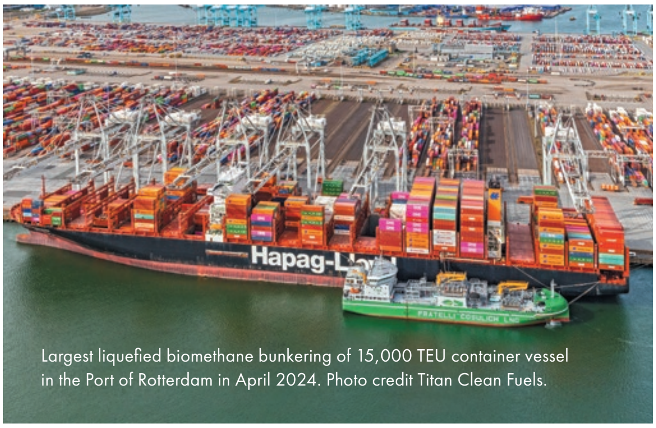
2024 saw a surge in growth in orders for new vessels that will utilise LNG and the pathway it offers to net-zero emissions. An additional 169 LNG dual-fuel vessels came into operation during 2024, and this was supported by rapid growth in supply infrastructure and the numbers of LNG bunkering vessels. The fuel demands from these vessels led to record volumes of LNG bunkered as a marine fuel.

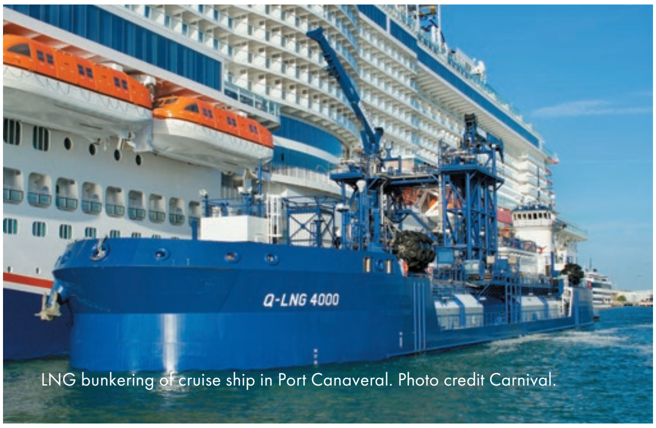
This growth was driven by the commercial and environmental benefits of LNG as a marine fuel and also the growing realisation that the LNG pathway offers the lowest cost of compliance with International Maritime Organization (IMO) and European Union (EU) greenhouse gas regulations. Methane slip, in the technologies where it remains an issue, is being addressed by a range of industry initiatives and technology providers.

In terms of the LNG pathway, liquefied biomethane is already commercially available and supplies of this low carbon fuel are growing strongly. The long-term decarbonisation trajectory for the industry established by the IMO and EU is incentivising investment in an ever-growing number of e-methane projects.

THE STATE OF PLAY FOR THE LNG PATHWAY

- **Around 6% of the global fleet by tonnage set to be fuelled by this clean marine fuel.**
- **Clean air benefits are significant and important: 95% reduction in NOx, negligible SOx and PM emissions.**
- **Reductions of up to 23% in Well-to-Wake greenhouse gas compared with traditional marine fuels.**
- **LNG bunkering available in 198 ports worldwide, with 61 LNG bunker vessels in operation.**
- **Liquefied biomethane already commercially available as a bunker fuel in 70 ports, worldwide.**
- **E-methane projects being developed in North America, South America, Australia, the Middle East, and Southeast Asia. First commercial availability as a bunker fuel in Europe in 2026.**


Largest liquefied biomethane bunkering of 15,000 TEU container vessel in the Port of Rotterdam in April 2024. Photo credit Titan Clean Fuels.



LNG bunkering of cruise ship in Port Canaveral. Photo credit Carnival.

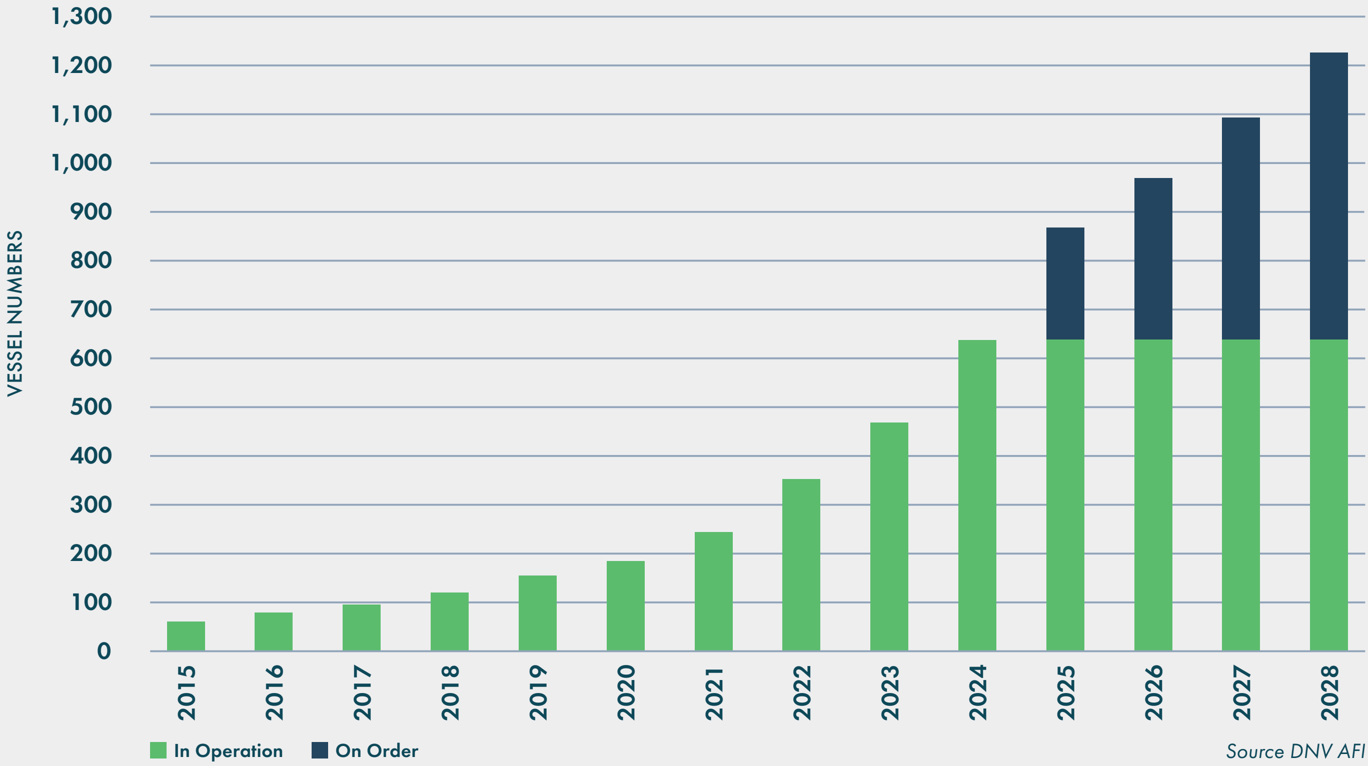
2024: THE YEAR OF GROWTH FOR LNG

Today, there are some 638 LNG-fuelled vessels in operation worldwide, an increase of more than one third over the past year. By the end of 2028, the order book data suggests that this number will have grown to more than 1,200. A near doubling in three years.

Once the LNG carrier fleet is included and taking the orderbook into account, vessels capable of utilising the LNG pathway currently represent about 4% of the global deep-sea fleet by numbers or over 6% when vessel deadweight tonnage (DWT) is considered. LNG-fuelled tonnage is dominated by the container sector, with almost 60% of total DWT in operation and on order. This is followed by the tanker sector (26%); the bulk sector (11%) and the car carrier sector (4%).

According to DNV, LNG dual-fuel vessels make up one third of the newbuild orderbook. Nearly half of all container vessels ordered in 2024 will be LNG dual-fuel, and over 90% of new orders for car carriers have been LNG dual-fuelled. In 2024 LNG dual-fuelled vessels accounted for 70% of alternative fuelled tonnage ordered, excluding LNG Carriers, up from 43% in 2023[1]. Additional new buildings in future years are expected to continue to favour the LNG pathway.

GROWTH OF LNG-FUELLED FLEET



Source DNV AFI

GLOBAL MARKET ADOPTION AND GROWTH

Almost every day brings new announcements of investments in LNG dual-fuel vessels. This is influenced by the practicality and immediate environmental impacts that the LNG pathway provides. LNG is a future-proof solution as the LNG pathway provides a seamless transition to liquefied biomethane and eventually renewable hydrogen-based liquefied e-methane.

The container segment which is the most fuel-intensive maritime sector is leading the uptake of LNG as a marine fuel. World leading container line and SEA-LNG member MSC will be taking delivery of 92 LNG dual-fuel vessels from 2025, while CMA CGM will take delivery of 34. Maersk has announced 62 owned and chartered LNG pathway capable vessels while Hapag-Lloyd has also signed a contract for 24 new LNG dual-fuelled container vessels. Many other owners are following these large operators.

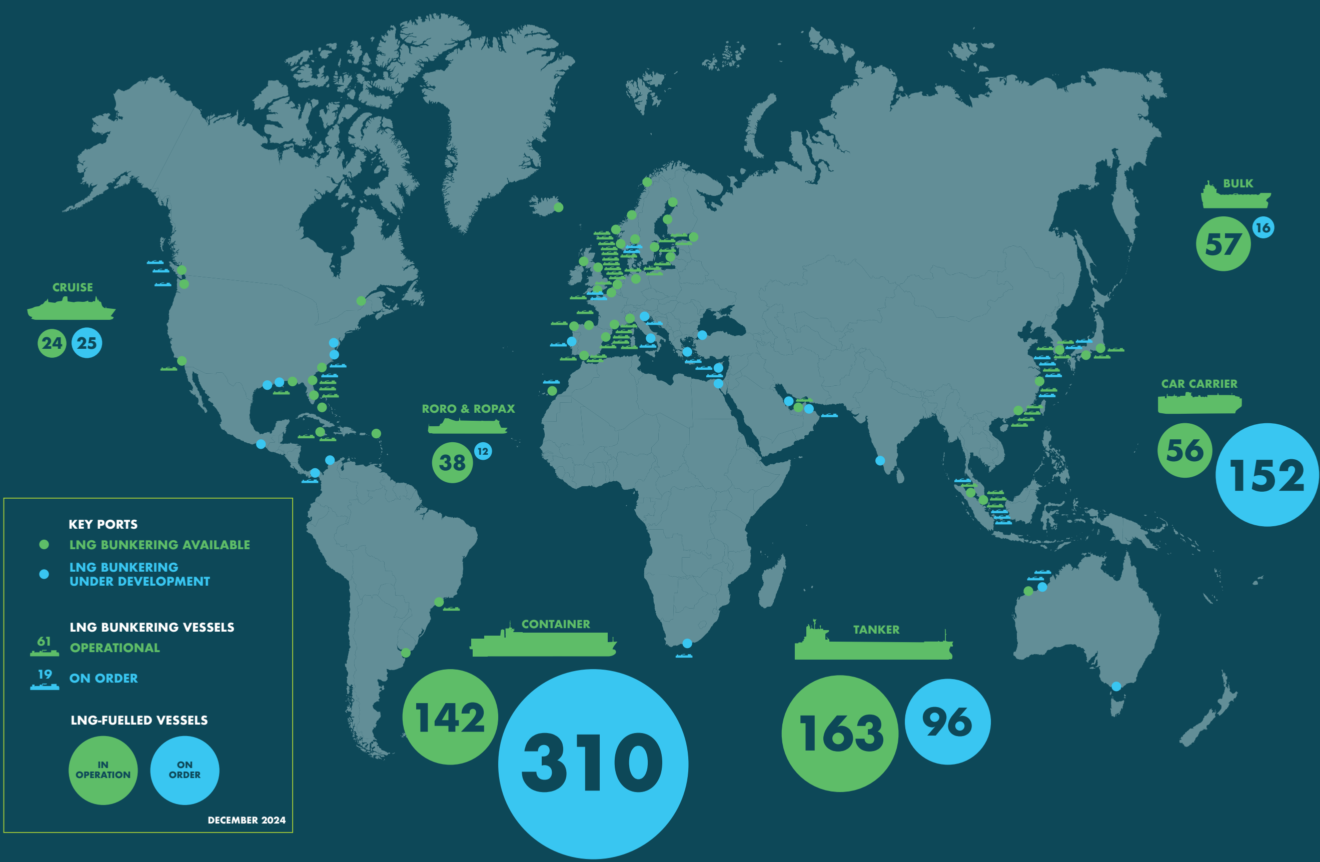
> **Shipping stakeholders are investing in LNG because it provides a low risk, incremental pathway for decarbonisation, starting now.**
>
> **Peter Keller, Chairman, SEA-LNG**

MSC MARIAGRAZIA bunkering LNG in Singapore in 2024.
Photo credit TotalEnergies.

LNG INFRASTRUCTURE DEVELOPMENTS

LNG bunker fuel availability continues to grow outside the traditional bunkering hubs. Clarksons reports[2] that LNG bunkers are currently available in some 198 ports around the world, with bunkering facilities planned for a further 78 ports. There are now more than 60 LNG bunkering vessels in operation in Europe, North America, Brazil, China, Singapore, Malaysia, Dubai, Japan and Korea with numbers having increased by 22% over the past year.

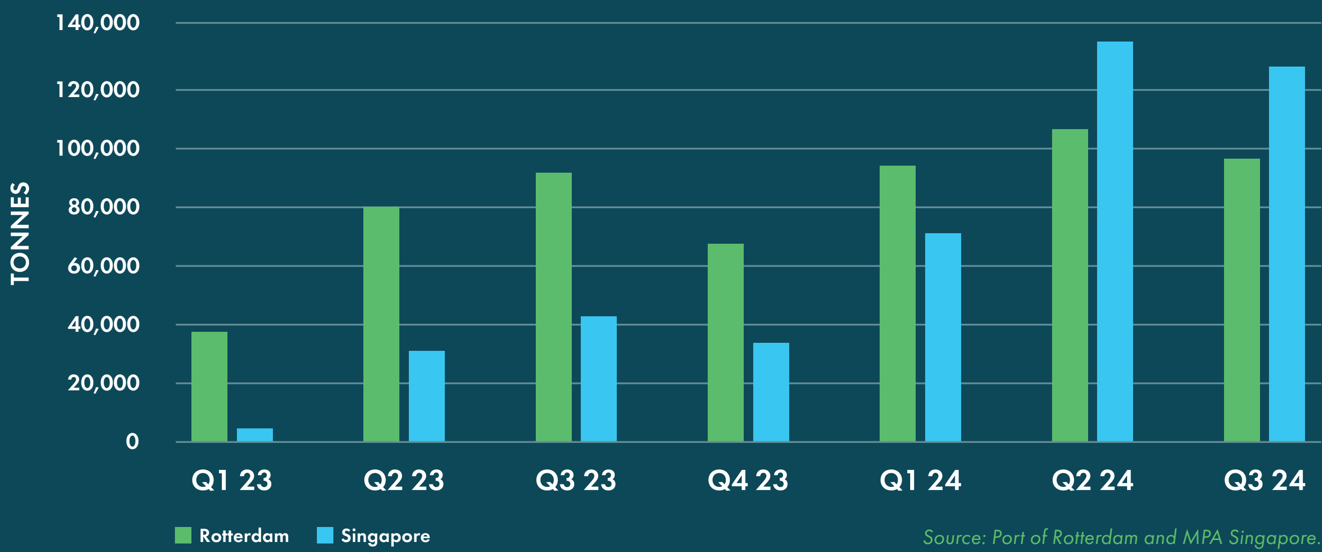
WORLDWIDE GROWTH IN LNG USE AND INFRASTRUCTURE



As more LNG-fuelled vessels have entered into operation, bunkering volumes have grown dramatically in key bunkering hubs. In the first three quarters of 2024, LNG bunkering volumes in Rotterdam grew by 44% to just over 300,000 tonnes compared to the same period in 2023. Singapore also saw a dramatic four-fold increase over the same period to almost 340,000 tonnes.

> **LNG is available today, at scale, and can reduce emissions today.**
>
> Melissa Williams, President, Shell Marine

QUARTERLY LNG BUNKER SALES: ROTTERDAM AND SINGAPORE



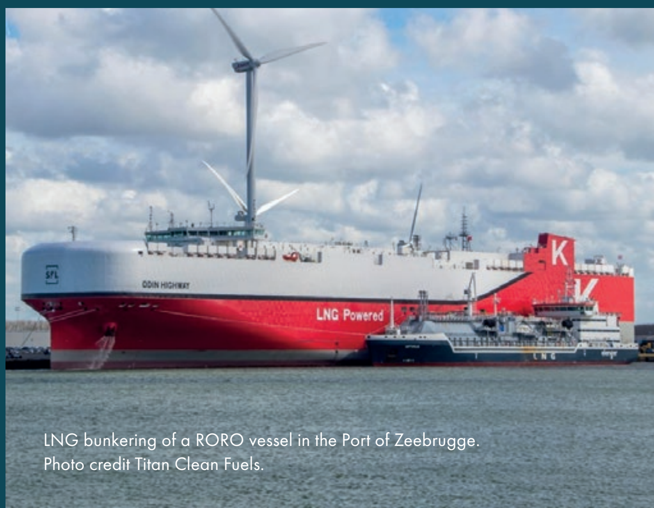
Source: Port of Rotterdam and MPA Singapore.

Amongst other notable infrastructure developments, the Maritime and Port Authority of Singapore (MPA) has launched an Expression of Interest (EOI) to explore both scalable solutions for sea-based LNG reloading to complement the existing onshore LNG bunkering storage and jetty capacities and the supply of e/bio-methane as marine fuel in the Port of Singapore.

In December 2024, Seaspan Energy successfully completed its first LNG ship-to-ship transfer to a containership in the Port of Long Beach. This operation marks the beginning of Seaspan's service offering on the West Coast of North America, with two LNG bunkering vessels to soon serve both the U.S. West Coast and Vancouver markets.

In early 2025, LNG bunkering will start in the Middle East, with bunker supplier, Monjasa chartering the 5,000 CBM Green Zeebrugge for operations in the UAE.

First SIMOPS LNG bunkering of a 15,000 TEU container vessel in the Port of Savannah in May 2024. Photo credit Georgia Ports Authority.



LNG bunkering of a RORO vessel in the Port of Zeebrugge. Photo credit Titan Clean Fuels.

The growing maturity of the LNG bunkering market is reinforced by the introduction of additional LNG bunker prices assessments by S&P Platts for Barcelona, China and the US East Coast.

S&P GLOBAL PLATTS LNG BUNKER PRICE ASSESSMENTS

As more and more LNG pathway capable deep-sea vessels come into operation the bunker fleet is continuing to grow to meet the need for clean, safe methane fuels.

Carnival MARDI GRAS bunkering LNG in the Port of Canaveral. Photo credit Carnival.

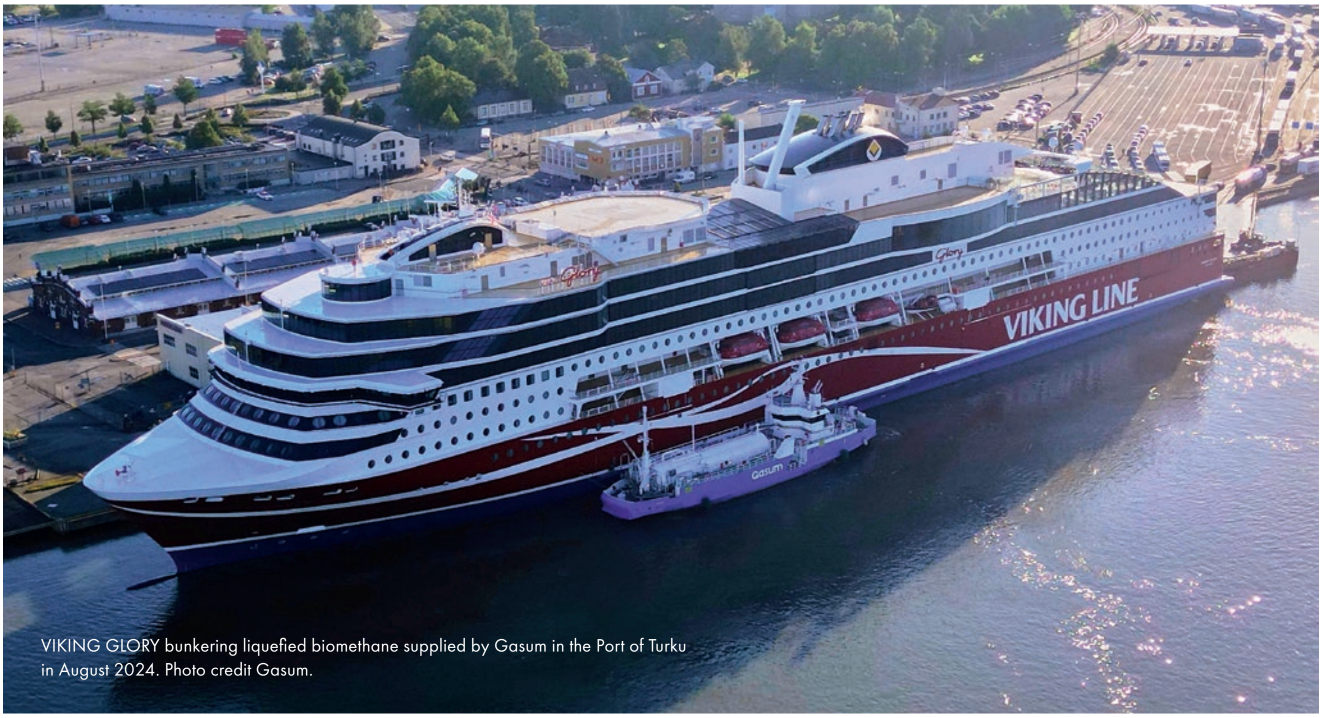
BIOMETHANE ADOPTION

Liquefied biomethane (otherwise referred to as LBM, or bio-LNG) is the next step along the LNG pathway to decarbonisation. Building on LNG's emissions reduction capabilities, the use of LBM as a marine fuel can reduce GHG emissions by an average of 80% compared to marine diesel on a full well-to-wake basis. It has the potential o meet about 13% of the energy requirements of the global shipping industry by 2050[2], even when demand from other industries is taken into account.

Biomethane is produced by the natural breakdown of biomaterial: unlike biomethanol, which requires an additional industrial process to convert biomethane to biomethanol. This means biomethanol is less energy efficient than biomethane and consequently is more expensive.

For biomethane to truly contribute to decarbonisation it must be made from sustainable biomass resources. These resources do not interfere with food, fodder, or fibre production.

When produced from anaerobic digestion of agricultural waste, such as manure, methane that would otherwise be released into the atmosphere is captured, resulting in negative emissions of up to -190% compared with diesel.



VIKING GLORY bunkering liquefied biomethane supplied by Gasum in the Port of Turku in August 2024. Photo credit Gasum.

The adaptability of liquefied biomethane is key to its adoption. Chemically biomethane is CH4, just like natural gas. It can be used seamlessly in ship engines which typically run on 'regular' LNG. It can be easily transported, stored and bunkered in ports with LNG infrastructure. There is no need for vast levels of investment and time to build new, specialised infrastructure.

Biomethane is readily available in growing volumes in Europe and the USA. In 2023, combined European biogas and biomethane production grew by 21% and reached 22 billion cubic meters (BCM), which represents 7% of EU gas consumption. In the US production of biomethane grew by 18% over the same period, reaching 2.6 BCM. Supply is growing globally with China and India also major producers.

SEA-LNG members are prepared to offer liquefied biomethane bunkers in some 70 ports in Asia, Europe and North America. In July 2024, German energy company, Uniper announced the start-up of liquefied biomethane production at the GATE terminal in Rotterdam, joining SEA-LNG members Gasum, Shell and Titan Clean Fuels as suppliers of liquefied biomethane at this key bunkering hub.

> **The LNG pathway for us is showing more immediate potential to support our net-zero strategy than methanol.**
>
> **Michele Francioni, Chief Energy Transition Officer, MSC**

Find out more information about biomethane on **page 24**.

GREEN CORRIDORS

Green corridors have long been seen as a way of catalysing the introduction of zero-emissions shipping technologies and fuels. This was first outlined in the 2021 Clydebank Declaration at COP 26 in Glasgow. The Rotterdam-Singapore Green and Digital Shipping Corridor (GDSC) is a prime example.

Since 2023, SEA-LNG has been leading the Methane Track for the Rotterdam-Singapore Corridor with the objectives of demonstrating the commercial credibility of liquefied biomethane as a scalable, low carbon fuel and helping to crystallise relevant maritime regulations in Europe and Singapore. Participants in this important endeavour include CMA CGM, Hapag-Lloyd, MSC, Shell, GATE terminal, SLNG, Port of Rotterdam and MPA.

In October 2024, the initiative conducted a successful pilot at the Port of Rotterdam for the bunkering of liquefied biomethane using a mass balanced chain of custody, when 100 tonnes of biomethane was supplied by SEA-LNG member Shell to the container ship, CMA CGM TIVOLI. The mass balanced chain of custody will be key for the commercial scaling of liquefied biomethane (and e-methane in the future) as a marine fuel. Mass balancing allows biomethane producers to sell fuel into existing natural gas grids and enables fuel customers to purchase this biomethane from the grid via a certificate. This approach is favoured by regulators as it is lower cost and simpler to scale as it uses existing gas and LNG infrastructure (further information on the different chains of custody can be found in the annex).

The purpose of the pilot was to test the compliance of the mass balance fuel certification process with EU regulations including EU ETS, FuelEU Maritime and Renewable Energy Directive III. Lessons learned are being developed and will be shared with the supply chain participants, regulators, certifiers and auditors.

Produced from waste-based feedstock, the liquefied biomethane used in this pilot provides a lower-emission alternative to conventional marine fuels. This initiative supports the GDSC's broader commitment to advancing the adoption of near-zero emission fuels along one of the world's busiest shipping trade routes.

A similar liquefied biomethane bunkering pilot is being developed at the other end of the Corridor, in Singapore, in 2025. The potential for liquefied e-methane pilots is also being explored.

The GDSC Methane Track is arguably the most advanced alternative fuel track of the more than 50 green corridor initiatives announced to date. It is providing lessons learned, not only for the commercial scaling of liquefied bio and e-methane but also other alternative fuels.

> **Today, we have an LNG pathway where we can make a difference.**
>
> **Bud Darr, Executive Vice-President Maritime Policy and Government Affairs, MSC**

LNG-powered MSC AZRA alongside Gioia Tauro in February 2024.
Photo credit MSC.

A 'FUTURE' FUEL OF TODAY

Biomethane *IS* a reality TODAY.

This year, Titan Clean Fuels and United European Car Carriers (UECC) announced they are collaborating on a series of major liquefied biomethane bunkering operations in the Port of Zeebrugge. Titan, a leading supplier of LNG in shipping, will bunker ISCC-EU certified mass balanced liquefied biomethane to all of UECC's LNG dual-fuel car carriers.

SEA-LNG member Gasum of Finland has also entered into a collaboration to expand adoption of the biomethane fuel. Gasum will supply leading container shipping company, Hapag-Lloyd's container vessels with liquefied biomethane for a two-year tender period.

Earlier in 2024, Hapag-Lloyd won the first tender issued by the Zero Emission Maritime Buyers Alliance (ZEMBA) for ocean shipping. The tender is based on waste-based biomethane which achieves at least a 90% reduction in GHG emissions. A notable advancement towards widespread adoption.

> **If you choose LNG, you have bio-LNG and then also the e-LNG path to walk on, which takes you from current status of burning LNG as a competitive fuel against any other alternatives in the market today, straight into the future and on par with the green ammonia or the green methanol through e-LNG.**
>
> **Jacob Granqvist, Vice-President Maritime, Gasum**

The final step in the LNG pathway is liquefied e-methane, otherwise known as e-LNG or renewable synthetic LNG.

Derived from renewable hydrogen, e-methane is compatible with existing LNG-fuelled vessels, transportation, storage and bunkering infrastructure. Much like biomethane, e-methane can essentially be 'plugged into' current LNG technology – giving it a head start against other synthetic fuels of 10+ years.

E-METHANE

Liquefied e-methane, also known as e-LNG, is chemically identical to LNG (liquefied natural gas, or CH4).

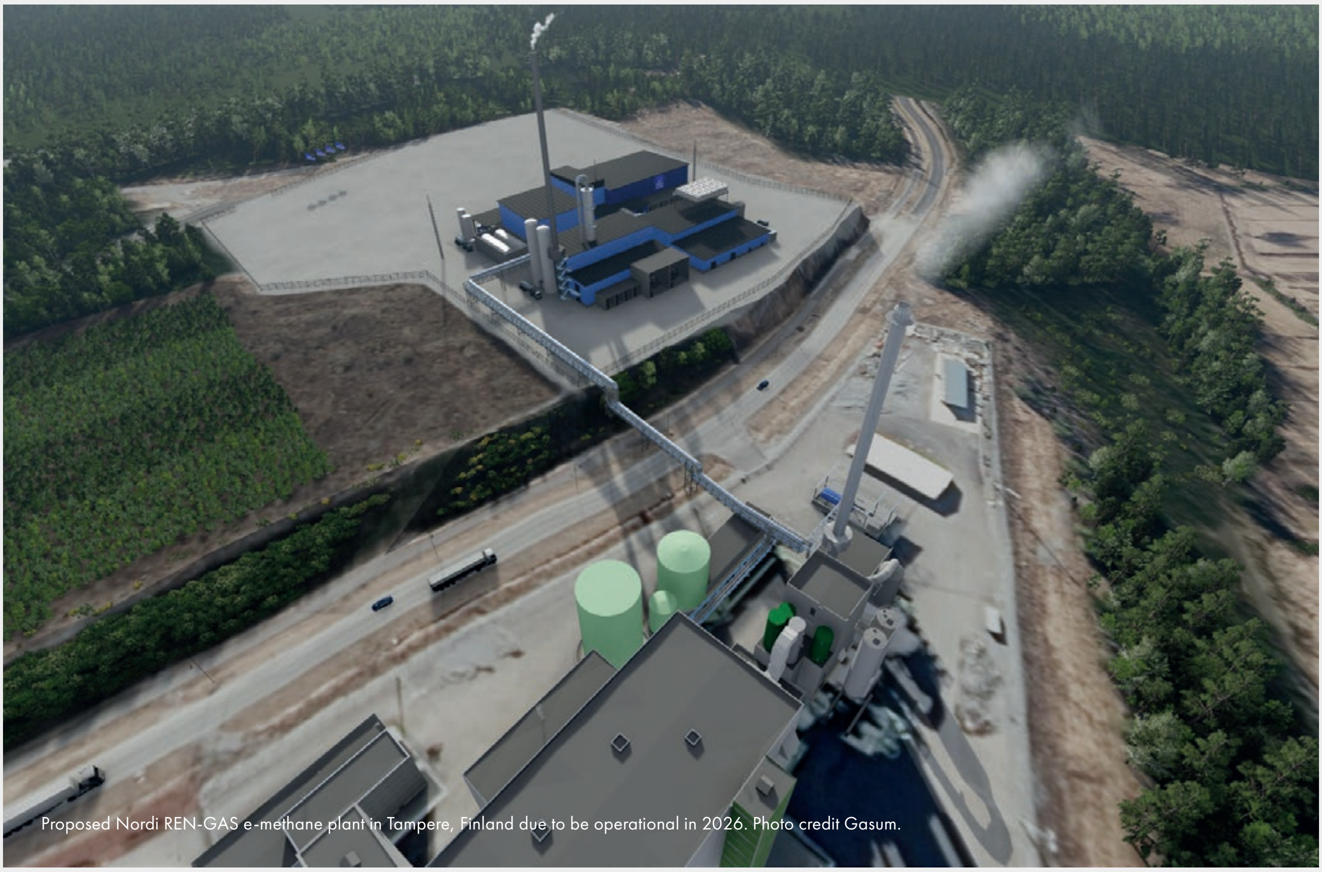
Similar to e-methanol and e-ammonia, it is an electro-fuel, or e-fuel, so called because it is produced from renewable electricity.

Liquefied e-methane is produced by combining hydrogen and carbon dioxide.

To be a zero-emission fuel, the hydrogen must be produced from electrolysis of water by renewable electricity, and carbon dioxide from biogenic sources, or captured directly from the atmosphere.

Liquefied e-methane can be used as a drop-in fuel in existing LNG dual fuel engines and delivered through existing LNG bunkering infrastructure with no additional investment.

E-methane production has grown twentyfold in eight years.



Proposed Nordi REN-GAS e-methane plant in Tampere, Finland due to be operational in 2026. Photo credit Gasum.

As with other electro-fuels, such as e-ammonia and e-methanol, the adoption of e-methane will depend on the scaling up of the renewable electricity and electrolysis capacity required to produce the common green hydrogen feedstock.

Recent analysis[4] from the European Biogas Association (EBA) shows that e-methane production in Europe is expanding rapidly with 35 operational plants currently available, 33 of which are fully renewable.

Germany leads the way with 14 facilities. Additionally, 20 new e-methane plants are either planned or under construction in Europe. Over the past eight years, e-methane production capacity in Europe has increased from 20 GWh per year to 449 GWh per year. EBA's projections indicate that by 2027, this capacity will reach nearly 3,000 GWh per year, equivalent to 0.27 BCM with Finland, Germany, and Denmark leading this rollout.

The nascent e-methane industry benefits from the demand from major gas utility customers looking to decarbonise their gas grids. For example, Japan's "Green Growth Strategy" explicitly states Japan's goal for supplying 1% of the country's gas demand with e-methane by 2030, increasing to 90% by 2050.

SEA-LNG members Osaka Gas, Shell and TotalEnergies are in the vanguard of these important developments working on a number of collaborative projects and feasibility studies in North America, South America, Australia, the Middle East, and Southeast Asia.

Liquefied e-methane has been successfully piloted in shipping. As with other e-fuels, it's currently only available in small volumes. However, bunker fuel suppliers have agreements with e-methane producers for commercial deliveries commencing next year. For example, in 2024, SEA-LNG member Gasum, announced[5] it will be distributing e-methane to both shipping and road transport companies as early as 2026. Working alongside Nordic Ren-Gas who will produce an amount of 160 GWh of renewable e-methane annually, Gasum will then procure and supply the fuel to both the maritime and road sectors.

> **It's also encouraging to see the high confidence levels in bio and synthetic LNG as important fuels in shipping's decarbonisation journey.**
>
> **GTT**

METHANE SLIP: INDUSTRY OVERCOMING THE CHALLENGE

One of the most commonly cited obstacles inhibiting the widespread adoption of LNG and its pathway is methane slip. While a legitimate historic concern, the industry has already made significant reductions in slip and estimates suggest it will not be an issue by the end of this decade.

2-stroke diesel cycle engines have essentially already eliminated methane slip. These types of engines account for ~75% of the LNG-fuelled vessel orderbook, and approximately 90% of the installed onboard power capacity.

For those low-pressure engine technologies where methane slip remains a challenge, manufacturers have already cut levels of slip from low-pressure 4-stroke engines by more than 85% over the past 25 years. This paints a promising picture for the coming years as shipping steams towards the IMO's net-zero targets.

> **LNG, with tightly controlled methane slip, delivers greenhouse gas savings today and has the potential to get to near zero through the LNG platform via biomethane and liquefied synthetic methane.**
>
> **Stelios Troulis, Energy Transition and Sustainability Director, Angelicoussis Group**

LNG bunkering of Newcastlemax bulker. Photo credit Titan Clean Fuels.

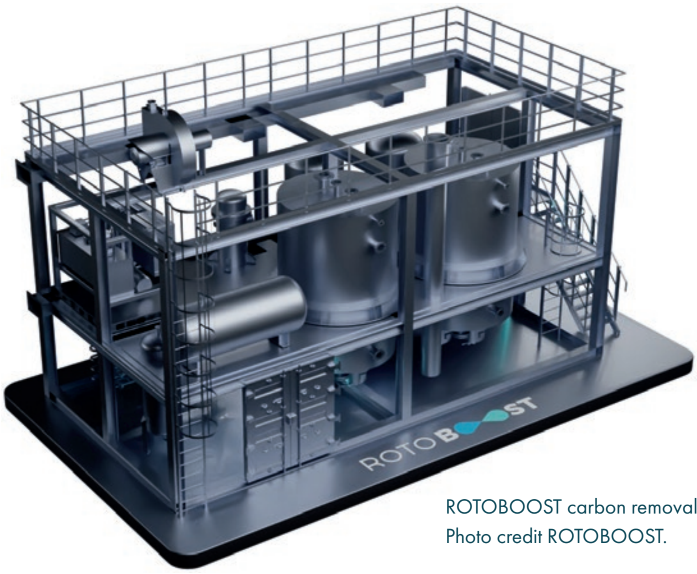
LNG bunkering of Aframax tanker. Photo credit Titan Clean Fuels.

INDUSTRY ADVANCEMENTS

2024 has seen considerable progress in addressing methane slip. The Methane Abatement in Maritime Innovation Initiative (MAMII) has begun a process of piloting exhaust stack methane measurement technologies, including from Green Instruments and Everimpact. MAMII has also called for regulators to implement a methane measurement, certification and validation protocol in a bid to eliminate the issue. They are actively partnering with governing bodies to make such a protocol a reality.

This example is only one of many. Consider Wärtsilä's ingenuity as a further example. As part of the EU-funded GREEN RAY project, the Finnish company piloted technologies on the AURORA BOTNIA RoPax ferry. The project successfully reduced methane slip by up to 56% in one of its most popular – and already emission-efficient – dual-fuel low pressure four-stroke engines.

One of our newest members, ROTOBOOST has also developed technology which easily can be equipped onboard LNG-fuelled vessels. The unique pre-combustion carbon removal system is based on Thermo-Catalytic Decomposition (TCD) and cracks the methane molecule into hydrogen and solid carbon.



ROTOBOOST carbon removal equipment.
Photo credit ROTOBOOST.

From here, the hydrogen is mixed into the methane fuel feed flow to the engines, directly contributing to lower methane and carbon dioxide emissions. While the solid carbon is captured and off-loaded finding its way to a large variety of industrial products.

Advances in addressing methane slip, in combination with biomethane and e-methane, provides a clear, effective, and viable long-term path towards net zero emissions. Shipowners and operators can be confident that the vessels ordered today are future-proofed for the next 25-30 years. Something which cannot be said for any other alternative fuel right now.

> **The combustion of LNG produces fewer air pollutants compared to liquid fuels and offers significant near-term emissions reductions. LNG can be gradually replaced by bio-LNG and eventually e-LNG or even be reformed to produce hydrogen onboard.**
>
> **Antonios Trakakis, Greece Marine Technical Support Director, RINA**

Find out more information about methane slip on **page 28**.

UPSTREAM METHANE EMISSIONS

The methane emissions associated with the production and transportation of LNG (so-called Well-to-Tank emissions) account for approximately 5% of the overall Well-to-Wake greenhouse gas emissions associated with the use of LNG as a marine fuel.

Natural gas producers have been making significant progress in reducing methane emissions through a range of voluntary initiatives such as the Oil and Gas Climate Initiative (OGCI) and the Oil and Gas Methane Partnership (OGMP) 2.0.

The OGCI member companies, which account for approximately one third of global oil and gas production, have collectively reduced their upstream methane emissions by 45% since 2017 to a level approaching half the current FuelEU Maritime Well-to-Tank default methane intensity level.

Methane certification is another voluntary initiative that is evolving rapidly as producers seek to differentiate themselves based on the methane emissions performance of their gas production. MiQ is the fastest growing methane certification organisation. Since its launch two years ago, it is already certifying 5% of the global gas market and 20% of US gas production. MiQ's target is to certify all natural gas production within this decade. In September 2024, MiQ announced[4] a pilot to certify a cargo of LNG being purchased by Uniper in Europe, from EQT Corporation, a leading US gas producer.

Methane emissions are also increasingly being regulated. For example, the EU Methane Regulation which came into force in 2024, imposes a range of measurement and other obligations on domestic oil and gas producers and importers. In the US, the IRA Methane Penalty, which also came into force in 2024, puts a fee on oil and gas producers' methane emissions. These and other regulations will help the industry achieve its goal of making slip a non-issue by the end of this decade.

REGULATORY DRIVERS AND THE COST OF COMPLIANCE

At the IMO in July 2023, the Marine Environment Protection Committee (MEPC 80) adopted a revised GHG Strategy which aims to significantly curb GHG emissions from international shipping.

The new targets include a 20% reduction in emissions by 2030, a 70% reduction by 2040 (compared to 2008 levels), and the ultimate goal of achieving net-zero emissions close to 2050. Separately, the EU has agreed to reduce the GHG intensity of fuels used by the shipping by sector by up to 80% by 2050.

These targets are being backed up with regulations. The IMO's Carbon Intensity Index, or CII, (effective from 2023), the inclusion of shipping into the EU's Emissions Trading System (ETS) in 2024 and FuelEU Maritime which comes into force in 2025 are putting immediate and growing pressure, as well as significant added costs on ship owners and operators in relation to their GHG emissions. The question of how to comply with these regulations with practical, safe and economically viable solutions is now front of mind for the industry.

Energy efficiency will be an important route to compliance in the short term. In June 2023, Clarksons estimated that energy-saving technologies had already been fitted on over 6,250 ships, accounting for about 27% of fleet tonnage. However, while all these innovations move the industry in a positive direction, to reach net-zero, the industry must move to carbon neutral, or so-called green fuels. Candidate green fuels for the deep-sea shipping industry currently include biofuels, and the LNG, ammonia and methanol fuel families. Ultimately, fuel choice will be driven by costs – not the costs in 2050 but the costs of complying with the incremental pathway to net-zero prescribed by regulations.

“

Enhancing dual-fuel technology to further reduce methane emissions will have a major impact on the long-term viability of LNG as a marine fuel.

Stefan Nysjö, Vice President, Power Supply, Wärtsilä Marine

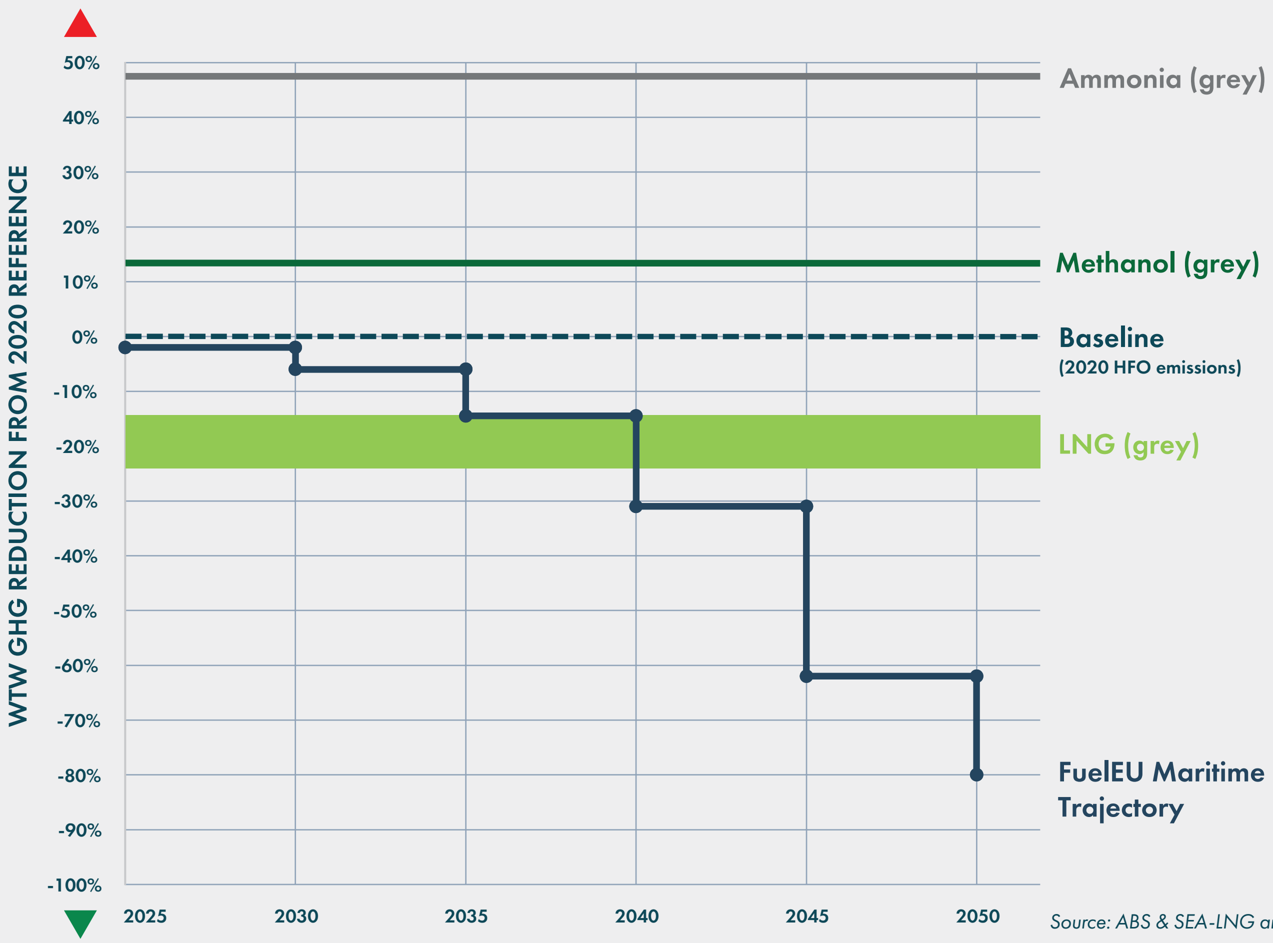
FUELEU MARITIME: ADVANCING DECARBONISATION

FuelEU Maritime (FEM) will be a key regulation in advancing shipping industry decarbonisation. It is a goal-based regulation designed to accelerate the maritime industry's decarbonisation through the adoption of renewable and low-carbon fuels and other technologies to reduce greenhouse gas (GHG) energy intensity of energy used onboard ships.

From January 2025 onwards, FEM will apply to EU and non-EU ships above 5,000 gross tonnage, and to all energy used on board in or between EU ports. It will also apply to 50% of energy used on voyages where the departure or arrival port is outside the EU.

GHG reduction targets are determined against a reference value reflecting the fleet average GHG intensity of energy used onboard by ships in 2020 as shown below.

LNG, METHANOL AND AMMONIA VS FuelEU MARITIME TRAJECTORY



Source: ABS & SEA-LNG analysis

When it comes to measuring GHG emissions, these are taken on a well-to-wake basis, and include emissions from other greenhouse gases, including methane and nitrous oxide.

Grey methanol and grey ammonia will not be compliant with this new regulation. Grey methanol is about 14% above the VLSFO baseline and grey ammonia, 47%. Both options will need to be blended with significant volumes of green versions of these fuels, simply to reach the GHG performance of VLSFO – let alone the decarbonisation pathway.

FuelEU Maritime creates a favourable environment for the LNG pathway. With the ability to achieve GHG emissions reductions by up to 23%, LNG-fuelled vessels are compliant until 2039. The use of liquefied biomethane and e-methane (the LNG pathway) can extend compliance through to 2050.

The regulation's pooling mechanism will create demand for biomethane, and e-methane. Both fuels offer overcompliance, and as such can generate credits which can be used by operators to ensure they meet GHG intensity limits for their fleets. Alternatively, they can be traded with other fleet operators, creating strong commercial incentives.

> **LNG is a relevant transition fuel for marine decarbonisation, and it will be around for quite a while.**
>
> **Johannes Lauterbach, Head of Business development & digitalization, MAN ES**

LNG-powered ISLA BELLA container vessel at sea. Photo credit TOTE Maritime.

THE COST OF COMPLIANCE

The costs of complying with current and anticipated future regulations is one of the biggest considerations for investors and fleet owners making newbuild decisions.

IMO AND EU DECARBONISATION REGULATIONS

REGULATOR	INSTRUMENT	APPLICATION	SCOPE	EMISSIONS	GEOGRAPHICAL COVERAGE	MECHANISM	IN FORCE
IMO	CII	Vessel	TtW	CO_2	Global	A,B,C,D & E vessel rating based on grams of CO_2 emitted per cargo-carrying capacity & nautical mile	Jan 2023
European Union	EU ETS	Vessel	TtW	CO_2 from 2024; CH_4 & N_2O from 2026	Intra-EU voyages and 50% of international voyages calling at EU ports	Emissions pricing	Jan 2024
	FuelEU Maritime	Fleet	WtW	CO_2, CH_4 & N_2O		GHG intensity limit for energy used on board ships	Jan 2025

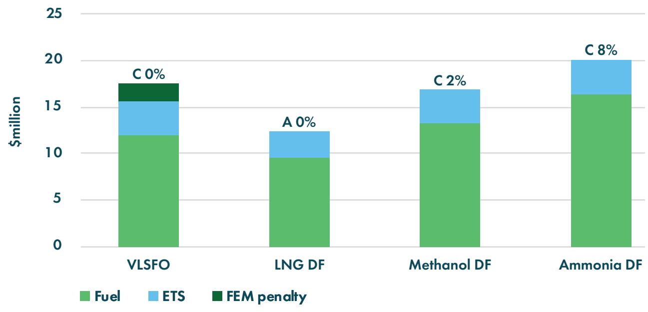
IMO and EU existing decarbonisation regulations vary in terms of application, scope, emissions, geographical coverage and mechanism. Some regulations are linked to whole lifecycle emissions of marine fuels from well to wake (WtW), while others only consider emissions onboard from the tank to wake (TtW). The emissions regulated include just carbon dioxide (CO2), or multiple GHG including methane (CH4) and Nitrous oxide (N2O). On top of these regulations, the IMO is looking to implement global Market-Based Mechanisms (MBMs) in relation to its revised Greenhouse Gas Strategy.

In analysing the impacts of these regulations, the industry needs to take into account the impact of local emissions regulations such as SECAs and NECAs which regulate SOX and NOX emissions, and the EU's Onshore Power Supply (OPS) mandates at core TEN-T (Trans-European Transport Network) European ports which start to come into effect from 2030 onwards.

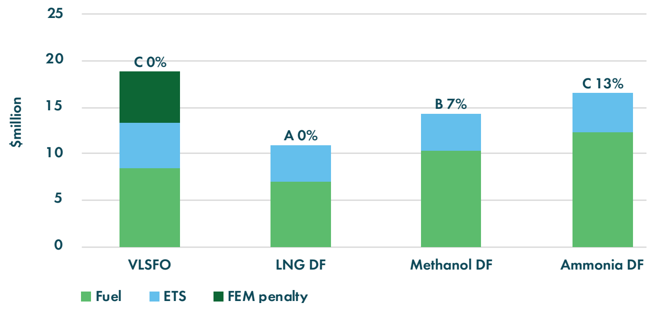
Towards the end of 2024 SEA-LNG undertook initial analysis of the costs of compliance of the LNG, methanol, and ammonia fuel pathways. We used Z-Joule's POOL.FM evaluation model on a hypothetical container fleet, operating on the Rotterdam-Singapore trade route, in the period 2025 to 2040. Fuel price assumptions were based on the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (MMMCZCS) Cost Calculator.

COMPARISON OF SINGLE VESSEL FUEL AND COMPLIANCE COSTS FOR 14,000 TEU CONTAINER VESSEL

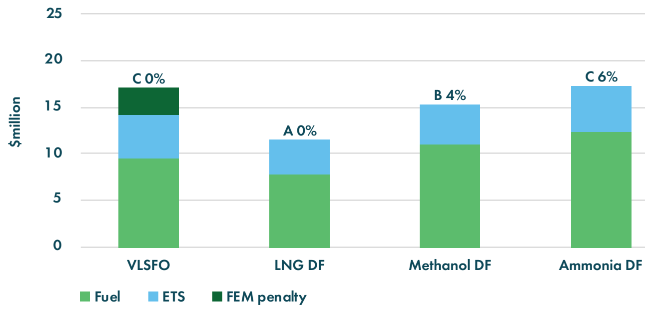
VESSEL FUEL PLUS COMPLIANCE COSTS 2025 (16KN)



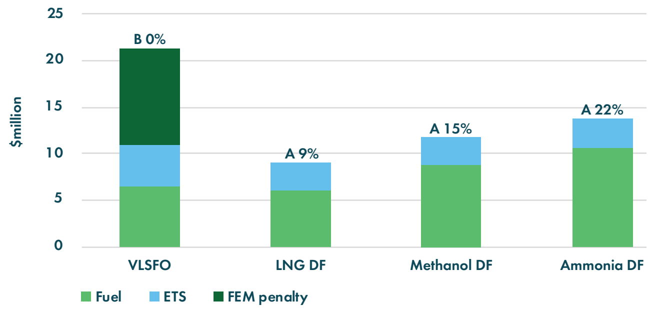
VESSEL FUEL PLUS COMPLIANCE COSTS 2035 (14KN)



VESSEL FUEL PLUS COMPLIANCE COSTS 2030 (15KN)



VESSEL FUEL PLUS COMPLIANCE COSTS 2040 (12KN)



LNG Bunker Vessel BRASSAVOLA deployed by Total Energies in Singapore in 2024.
Photo credit TotalEnergies.

KEY TAKEAWAYS FROM THE ANALYSIS SHOWED ARE:

- **Operational costs are likely to be significantly higher for fleet operators under IMO and EU decarbonisation regulations. In the case of the VLSFO vessel regulatory compliance will increase annual operating costs by almost 50% in 2025 and by more than 200% in 2040.**
- **The use of LNG, methanol and ammonia dual-fuel engine technologies can reduce compliance costs.**
- **LNG dual-fuel vessels provide the lowest cost option. This is driven by the fact that they have lower GHG emissions than VLSFO in its fossil form and vessels can avoid using relatively expensive MGO for ECA compliance.**
- **LNG is able to comply with FuelEU Maritime until 2039 in its fossil form. Green fuels i.e .liquefied biomethane are only needed for compliance from 2040 onwards.**
- **Ammonia and methanol dual-fuel vessels operate mainly on VLSFO and MGO to 2040. They will need to use blue, bio or electro fuels to ensure compliance with FuelEU Maritime from 2025 onwards.**
- **LNG fuelled vessels also have the best CII rating for same vessel speed.**

It should be noted that the LNG dual-fuel results for 2025, 2030 and 2035 do not include the additional value that can be derived from FuelEU Maritime credits generated by fossil LNG's over-performance in relation to FuelEU Maritime GHG intensity limits.

SEA-LNG extended this analysis to an 8-vessel container fleet operating the Rotterdam-Singapore trade route consisting of two alternatively fuelled "balancing vessels" and six conventionally fuelled vessels. The analysis showed that the overall cost of compliance with the LNG pathway will be between US$5-17 million per annum lower than in the case of methanol and ammonia.

This analysis also illustrated how FuelEU Maritime will have a major impact on how fleet operators run their alternatively fuelled vessels. Operators will offset non-compliance by traditionally fuelled (VLSFO) vessels by ramping up the quantity of green fuels they burn in alternatively fuelled vessels in order to generate credits.

Finally, the analysis suggests that the high FuelEU Maritime penalty price will not only incentivise the demand for blue, bio and e-fuel versions of LNG, methanol and ammonia but there will also be a major impetus for bunker fuel suppliers to develop liquid biofuels at scale.

CONCLUSION: WAITING IS NOT AN OPTION. WE MUST ACT NOW.

It is SEA-LNG's view that the surge of investments in LNG-fuelled vessels and associated bunkering infrastructure seen in 2024 will continue. Yet, we do anticipate that the shipping industry is heading towards a multi-fuel future. In order to deliver net-zero by 2050 across the global shipping fleet, a basket of fuels is required, and a 'my fuel' versus 'your fuel' mindset will not help anyone. The reality is that all 'our fuels' are needed. We are conscious that lessons learned from the experience of first-mover companies developing the LNG pathway can provide a template for the industry as we all work to a net zero future.

The growth in the LNG pathway's uptake will continue to be driven by its immediate emissions benefits, its availability as a marine fuel, its practicality, availability, and importantly its safety record. There is also the growing recognition that the LNG pathway currently offers the lowest cost of compliance with IMO and EU regulations which are incrementally leading us to net-zero.

The LNG pathway is not a vague concept but has been a realistic solution for years. Liquefied biomethane is already commercially available and regulation is catalysing investment in e-methane to meet demand from the shipping industry and gas and power utilities. The industry recognises the challenges associated with implementing the pathway, in particular the issue of methane emissions, and is effectively addressing them.

SEA-LNG will continue to advocate for the LNG pathway in shipping but is conscious of the need for broader collaboration as illustrated by its involvement in the Rotterdam-Singapore Green Corridor. The introduction of LNG as a marine fuel has driven the first transition in the way that ships are propelled since the introduction of liquid fuels over a century ago.

> **At BSM, we are committed to LNG as a marine fuel. It is a proven, technically mature solution already being used on many ships, offering comprehensively developed supply and bunkering infrastructure.**
>
> Nick Topham, Managing Director of Bernhard Schulte Shipmanagement

LIQUEFIED BIOMETHANE FACT SHEET

What is liquefied biomethane?	Liquefied biomethane (LBM), also known as bio-LNG, is chemically identical to LNG (liquefied natural gas). In North America biomethane is sometimes also known as renewable natural gas (RNG).
How is liquefied biomethane produced?	Biomethane is mainly produced from anaerobic digestion of agricultural and human waste streams eg animal manure, silage, wastewater and landfill. It can also be produced through gasification of cellulosic waste, such as sawmill and forest harvest residues. This is a less mature technology.
Does liquefied biomethane compete with food production?	Biomethane is produced from sustainable biomass feedstocks, which are nationally, or regionally defined, for example by the EU (RED III)[6] in Europe and the EPA[7] (Renewable Fuel Standards) in the USA. This means that it does not compete with the production of food, fibre or fodder.
What emissions reductions does liquefied biomethane deliver?	Emissions reduction will depend on how the liquefied biomethane is produced and the engines in which it is used. In general, the use of liquefied biomethane as a marine fuel can reduce GHG emissions by up to 80% compared to marine diesel on a full well-to-wake basis. When produced from the anaerobic digestion of waste materials, such as manure, methane that would otherwise be released into the atmosphere is captured, resulting in negative emissions of up to -190% compared with diesel.
How much liquefied biomethane is available now?	Production of biomethane, is currently running at approximately 30Mt pa, or 10% of shipping's total energy demand.
What is the potential for liquefied biomethane the future?	Biomethane produced from sustainable biomass has massive global potential – up to 20 times current production levels by 2050. Once demand from other sectors is taken into account liquefied biomethane has the potential to play a significant role in decarbonizing shipping. If used in the form of a 20% blend with LNG, it could cover up to 16% of global shipping demand by 2030.
Is liquefied biomethane available to shipping?	Liquefied biomethane is an established bunker fuel and is commercially available in Europe, North America and Asia.

How expensive is liquefied biomethane?	All biofuels and biogases such as liquefied biomethane are significantly more expensive than traditional marine fuels. However, negotiations are on-going in the International Maritime Organization (IMO) to introduce a global pricing carbon mechanism or economic measure that will effectively narrow the price gap.
How is liquefied biomethane typically sold?	Liquefied biomethane is typically sold as a blend with fossil LNG.
Are there any blending issues with liquefied biomethane?	Liquefied biomethane is pure, liquefied methane and effectively identical to the highest quality LNG, so there are no blending issues.
How is liquefied biomethane delivered to ship owners?	Liquefied biomethane can be delivered in the form of physical molecules from liquefied biomethane plants to a ship, or through a system of mass balancing and certified guarantees of origin, whereby biomethane is injected into the gas network and delivered from LNG terminals or liquefaction plants using existing infrastructure.
Does using liquefied biomethane impact methane slip?	Methane slip is a function of engine technology and is not impacted by the use of liquefied biomethane.

For more information on the role of liquefied biomethane in shipping industry decarbonization, please see the report published by the Maritime Energy and Sustainable Development Centre of Excellence in October 2022.

LIQUEFIED E-METHANE FACT SHEET

What is liquefied e-methane?	Liquefied e-methane, also known as e-LNG, is chemically identical to LNG (liquefied natural gas). It is an electro-fuel, or e-fuel, so called because it is produced from renewable electricity. It is also known as liquefied synthetic methane, or natural gas.
How is liquefied e-methane produced?	Liquefied e-methane is produced by combining hydrogen and carbon dioxide. For liquefied e-methane to be considered a zero-emission fuel, the hydrogen has to stem from electrolysis, using water and renewable electricity as inputs; the carbon dioxide has to be obtained from biogenic sources, or captured from the atmosphere.
How does liquefied e-methane relate to other green fuels?	Liquefied e-methane is one of a family of electro-fuels including e-methanol and e-ammonia which are being discussed for use in maritime. These fuels are all derived from the same renewable hydrogen feedstock. Liquefied e-methane and e-methanol are produced by combining hydrogen with carbon dioxide; ammonia is produced by combining hydrogen with nitrogen.
What emissions reductions does liquefied e-methane deliver?	Emissions reductions will depend on how the liquefied e-methane is produced and the engines in which it is used. In practice zero greenhouse gas emissions are achievable if liquefied e-methane is produced using renewable electricity and carbon dioxide obtained from biogenic sources, or captured from the atmosphere, and used in engines with no methane slip.
How much liquefied e-methane is available now?	Production of liquefied e-methane is currently limited to a number of pilot plants in Europe, but sizable production facilities are being developed in Europe, North America and Australia.
What is the potential for bio-LNG in the future?	Supplies of liquefied e-methane are potentially unlimited, dependent on the build out of renewable electricity and hydrogen electrolysis capacity. Liquefied e-methane has the advantage over other green marine fuels in that it can be delivered using existing natural gas and bunkering infrastructure.
Is liquefied e-methane available to shipping?	Liquefied e-methane has been successfully piloted in shipping. As with other e-fuels, it is currently only available in small volumes, but bunker fuel suppliers have supply agreements with e-LNG producers for commercial delivery from 2026 onwards.

How expensive is liquefied e-methane?	All electro-fuels including liquefied e-methane are many times more expensive than traditional marine fuels and biofuels and biogases such as liquefied biomethane. However, negotiations are on-going in the International Maritime Organization (IMO) to introduce a global pricing carbon mechanism or economic measure that will effectively narrow the price gap.
How is liquefied e-methane typically sold?	Liquefied e-methane is in the early stages of commercialization. It is likely that it will initially be sold as a blend with fossil LNG.
Are there any blending issues with liquefied e-methane?	Liquefied e-methane is chemically identical to the highest quality fossil LNG, so there are no blending issues.
How is liquefied e-methane delivered to ship owners?	Liquefied e-methane can be delivered in the form of physical molecules from e-LNG plants to a ship, or through a system of mass balancing and certified guarantees of origin, whereby e-methane is injected into the gas network and delivered from LNG terminals or liquefaction plants using existing infrastructure.
Does using liquefied e-methane impact methane slip?	Methane slip is a function of engine technology and is not impacted by the use of liquefied e-methane.

For more information on the role of e-LNG in shipping industry decarbonization, please see the report published by the CE Delft on Availability and Costs of Liquefied Bio- and Synthetic Methane – the Maritime Shipping Perspective.

METHANE SLIP FACT SHEET

What is methane slip?	In LNG-fuelled marine engines, methane slip refers to the small amounts of the fuel that does not burn in the engine but escapes with the exhaust gases into the atmosphere.
Why is methane slip important?	Methane slip is important because methane is a powerful greenhouse gas, with a global warming potential of 28-36 times that of carbon dioxide on a 100-year timescale, according to the IPCC (Intergovernmental Panel on Climate Change). Methane slip reduces the benefit of lower carbon dioxide emissions offered by LNG-fuelled engines.
What determines levels of methane slip?	Levels of methane slip are dependent on engine technology and the way in which the engines are operated. High-pressure, diesel cycle dual fuel engines offer negligible levels of methane slip, while higher methane slip values are reported for low-pressure, Otto cycle dual fuel engines. Operations at lower engine loads tend to increase methane slip compared to higher engine loads where vessels operate for the majority (90%) of their voyage time.
Are all LNG-fuelled engines affected by methane slip?	No, high-pressure 2-stroke, diesel cycle engines have effectively eliminated methane slip. These engines account for approximately 75% of the LNG-fuelled vessel order book.
Does methane slip eliminate LNG's GHG emissions benefits?	No, independent analysis[9] based on data from all major engine manufacturers shows that once methane slip is taken into account, the use of LNG as a marine fuel offers significant GHG emissions reductions on a full lifecycle (Well-to-Wake) basis, compared with the use of traditional marine fuels. These reductions range from 6% to 14% for low pressure, 4-stroke engines and up to 23% for high pressure, 2-stroke engines which represent three quarters of the vessel order book.
Can methane slip be fixed?	Yes, for those low-pressure engine technologies for which methane slip is an issue, manufacturers have already cut the levels of slip from low pressure, 4-stroke engines by more than 85% over the past 25 years. It is worth noting that methane slip has been eliminated for the similar LNG dual fuel engine technologies used in the heavy-duty vehicle sector.
What is being done to address methane slip?	Addressing methane slip is the focus of a number of industry initiatives including the Methane Abatement in Maritime Innovation Initiative (MAMII)[10] and the EU-funded GREEN RAY[11] project. These initiatives are accelerating the development of new engine technologies and exhaust stack abatement solutions which can be retrofitted to older engine technologies. Equipment manufacturers are confident methane slip will have been eliminated for all engine technologies within the decade.

What about the high levels of slip claimed by recent NGO studies?

Recent NGO studies reporting apparently high levels methane slip from LNG-fuelled vessels[12] use an experimental near-shore airborne measurement methodology which is not verified against industry standards. Putting the experimental nature of the measurement approach to one side, these studies were based on vessels using older engine technologies in atypical operating conditions ie vessels operating at low engine loads, manoeuvring in or near ports. These conditions are not representative of the vast majority of vessel activities.

What is the effect methane of emissions in the LNG supply chain?

Methane emissions in the LNG supply chain are responsible for a small fraction, approximately 5%, of the overall (Well-to-Wake) GHG emissions associated with the use of LNG as a marine fuel.

What is being done to address LNG supply chain emissions?

Eliminating LNG supply chain emissions is a major focus of the oil and gas sector. As a response to the Global Methane Pledge announced at COP26, the Oil and Gas Climate Initiative, whose members are responsible for one third of global oil and gas production, launched the Aiming for Zero Emissions Initiative[13] in March 2022. Existing emissions are below 0.2% and the goal is to reach near zero methane emissions from its members' operated oil and gas assets by 2030.

CHAIN OF CUSTODY MODELS FACT SHEET

Tracking low-carbon marine fuels through the bunkering supply chain

What does Chain of Custody mean?

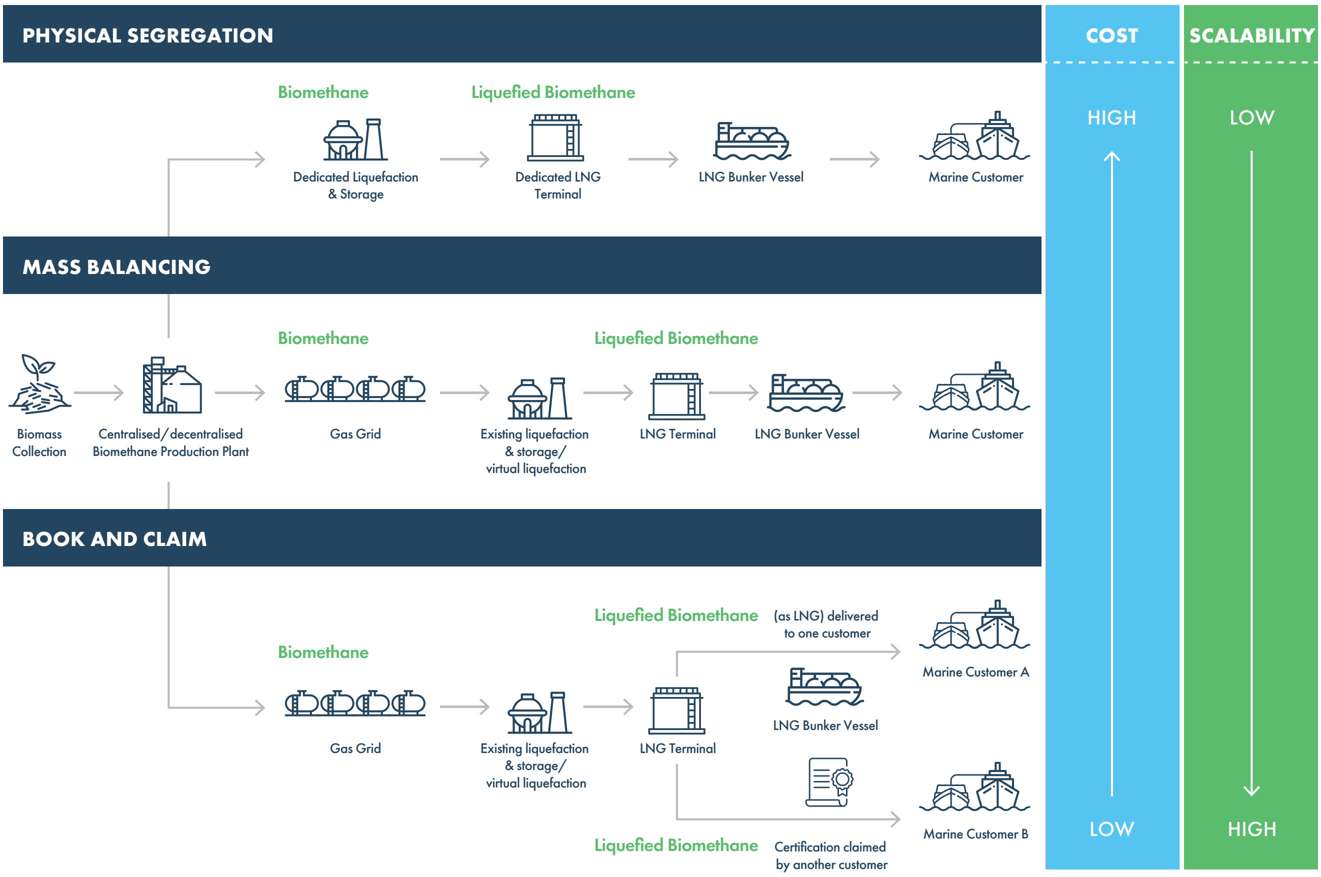
Chain of Custody refers to a transparent and verifiable way to track the greenhouse gas emission attributes of marine fuels throughout their lifecycle, from production to the end-use customer.

Why are chain of custody models important in decarbonisation?

Chain of custody models are important in maritime decarbonisation as they provide mechanisms to verify that the fuels used are low carbon. Such verification creates investor confidence in new fuel supply chains and accelerates the transition to low-carbon fuels, enabling early adoption in conditions of limited supply. They can create a market for green fuels by connecting buyers to fuel producers away from bunker ports enabling faster scaling and providing flexibility to shipping companies at lower cost.

What are the main chain of custody models being discussed in the maritime industry?

There are three relevant Chain of Custody models currently being discussed for low-carbon marine fuels such as liquefied biomethane (bio-LNG). These are Physical Segregation, Mass Balancing and Book & Claim.



What is Physical Segregation?	In the case of liquefied biomethane, Physical Segregation means that the biomethane molecule is produced, transported, stored, liquefied and delivered to the marine customer through a separate, dedicated infrastructure. The need for the supply chain to invest in this new infrastructure means that this is the most expensive way to supply liquefied biomethane and is also the most difficult to scale.
Why is Physical Segregation used?	Physical Segregation is sometimes preferred because some stakeholders see it as a more tangible and easily verifiable approach. Some cargo owners with voluntary decarbonization targets require it depending on the voluntary frameworks that they have signed up to. For example, the Science Based Targets initiative (SBTi) guidelines currently do not recognise Mass Balance and Book & Claim chains of custody.
What is Mass Balancing?	Mass Balancing allows biomethane producers to sell their fuel into existing natural gas grids and allows fuel customers to purchase this biomethane from the grid via a certificate.
Why is Mass Balancing used?	Mass Balancing uses existing infrastructure to connect buyers and sellers. It is favoured by regulators as it is lower cost and enables the market for green fuels such as liquefied biomethane market for maritime to scale more quickly. Mass Balancing has also been successfully used in other sectors such the chemicals and plastics industry. A growing number of key jurisdictions accept Mass Balancing for biomethane, including the EU, USA and Canada and regulators are exploring it in countries such as Japan, China and Australia.
What is Book & Claim?	In Book & Claim the greenhouse gas emissions of a low carbon fuel such as biomethane produced by a supplier are 'booked' in a central registry, and customers can 'claim' them without any connection to the physical biomethane molecule. Book & Claim is analogous to the system of renewable energy certificates used in the electricity sector whereby the electrons produced by a wind farm, aren't necessarily the same ones powering a green consumer's light bulb.
Why is Book & Claim used?	Book & Claim is the lowest cost Chain of Custody model as it decouples greenhouse gas emissions from the physical supply chain. As it can connect buyers to sellers anywhere on the globe it is also the most scalable and flexible Chain of Custody system. Book & Claim is being used in the voluntary carbon markets. The International Civil Aviation Organization (ICAO) is considering the implementation of a Book & Claim system for Sustainable Aviation Fuels (SAFs) and the International Maritime Organization (IMO) is actively exploring the potential of Book & Claim systems for maritime.

What is needed for a credible chain of custody system for marine fuels?

A credible chain of custody system requires the following:

- clear and verifiable standards for greenhouse gas emissions attributes of the marine fuel;
- certification of fuel supply chains by certification bodies such as ISCC (International Sustainability & Carbon Certification);
- robust tracking and traceability of fuels using digital certificates as they pass through the supply chain;
- independent verification of compliance by third party auditors;
- and full transparency and disclosure.

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