

Fuel for thought



LNG

**Expert insights into the
future of alternative fuels**

Your trusted adviser in alternative
and low carbon maritime fuel





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Introduction

The maritime industry is facing an era of unprecedented change. The challenge is not that change is happening, but that it is happening so quickly.

The evolution of sail to its heyday of the great tea clippers took centuries, and the transition to coal-powered steam ships was driven by greater supply chain mobility and speed. The efficiencies and competitiveness of oil led to a new type of vessel propulsion, but again these are transitions that took nearly a hundred years. And it was the pressures of global trade, rather than environmental factors, that determined the direction.

The energy transition the maritime industry faces today is therefore unprecedented in that it is not driven by simple market economics

but by a social need to become more sustainable and to cut back on emissions. Amid this change shipowners, charterers, insurers, financial markets and technology suppliers are all seeking clarity and a better understanding of the trends and direction the industry is facing together.

Fuel for Thought cuts through the latest technology advances, policy developments and market trends. Each edition focuses on fuels and technologies to create a concise platform for industry to continue updating itself, to find answers to its challenging questions and to help determine a direction and time at which to move.



This sixth report in the series focuses on liquefied natural gas, the most widely deployed alternative fuel in the shipping industry, making it an attractive proposition for reducing carbon emissions – albeit one that will require significant efforts from producers and technology providers if it is to become a long-term decarbonisation option.

Other editions of Fuel for Thought, dedicated to methanol, ammonia and other alternative fuels, can be found on the Fuel for Thought hub: www.lr.org/fuelforthought

Executive summary

LNG as a marine fuel is in the midst of an orderbook resurgence that highlights its credentials as the most mature of all alternative shipping energy sources. Technologies, supply infrastructure and regulatory frameworks have developed across two decades of widespread usage, offering a viable option for operators looking to reduce the GHG intensity of their fuel. The challenge for those investing in LNG today is to safeguard that status as other fuel options emerge.

Some key ingredients will be needed to secure LNG's long-term viability as a shipping fuel. First, emissions of unburned methane, known as methane slip, will need to be significantly reduced from shipboard technologies. With a Global Warming Potential (GWP) of 28 times that of carbon dioxide over a 100-year timeframe¹, even low methane emissions from shipboard consumption penalise LNG's overall GHG emissions. As methane is the prime component of LNG, this applies however the fuel is produced.

There is room for further greenhouse gas emissions reductions across the LNG supply chain. This means improving current production and distribution, with less carbon-intensive processes and lower fugitive methane emissions. Already today, green liquefaction can reduce GHG emissions involved in LNG production by 10%. But in the longer term, cleaner LNG means developing the production and supply of methane from renewable sources, giving shipping access to far deeper GHG emissions reduction potential from LNG as a fuel.

Crucially, regulators will need to acknowledge these supply chain improvements if they are to stimulate uptake of cleaner LNG. In current regulations at IMO and EU level, default well-to-tank emissions factors for LNG do not recognise upstream GHG improvements. Allowing for certification of LNG's upstream emissions (through schemes that already exist) will have multiple benefits: encouraging cleaner production practices; potentially facilitating cross-border trade in light of regional emissions requirements; and enabling shipowners to buy from and reap the full rewards of the cleanest sources.

In the future, LNG fuel users may be able to reap significant further benefits in GHG intensity from onboard carbon capture and storage. In many ways LNG is the ideal fuel with which to apply carbon capture. It emits less carbon than conventional liquid fuels, burns more cleanly and can harness precombustion technologies that produce hydrogen from methane, reducing the overall carbon content of the fuel mix further. All this leads to a reduction in the cost of applying carbon capture.

This report examines progress, potential, and the current state of play across these four pillars: methane abatement, carbon capture and storage, cleaner production and environmental certification. The resulting picture is of a fuel that is already a viable option for reducing GHG emissions from vessels today, and one with significant long-term decarbonisation potential if the challenges noted here can be further addressed.



1.1

Chapter 1: Foreword

Foreword from Peter Keller, Chairman, SEA-LNG

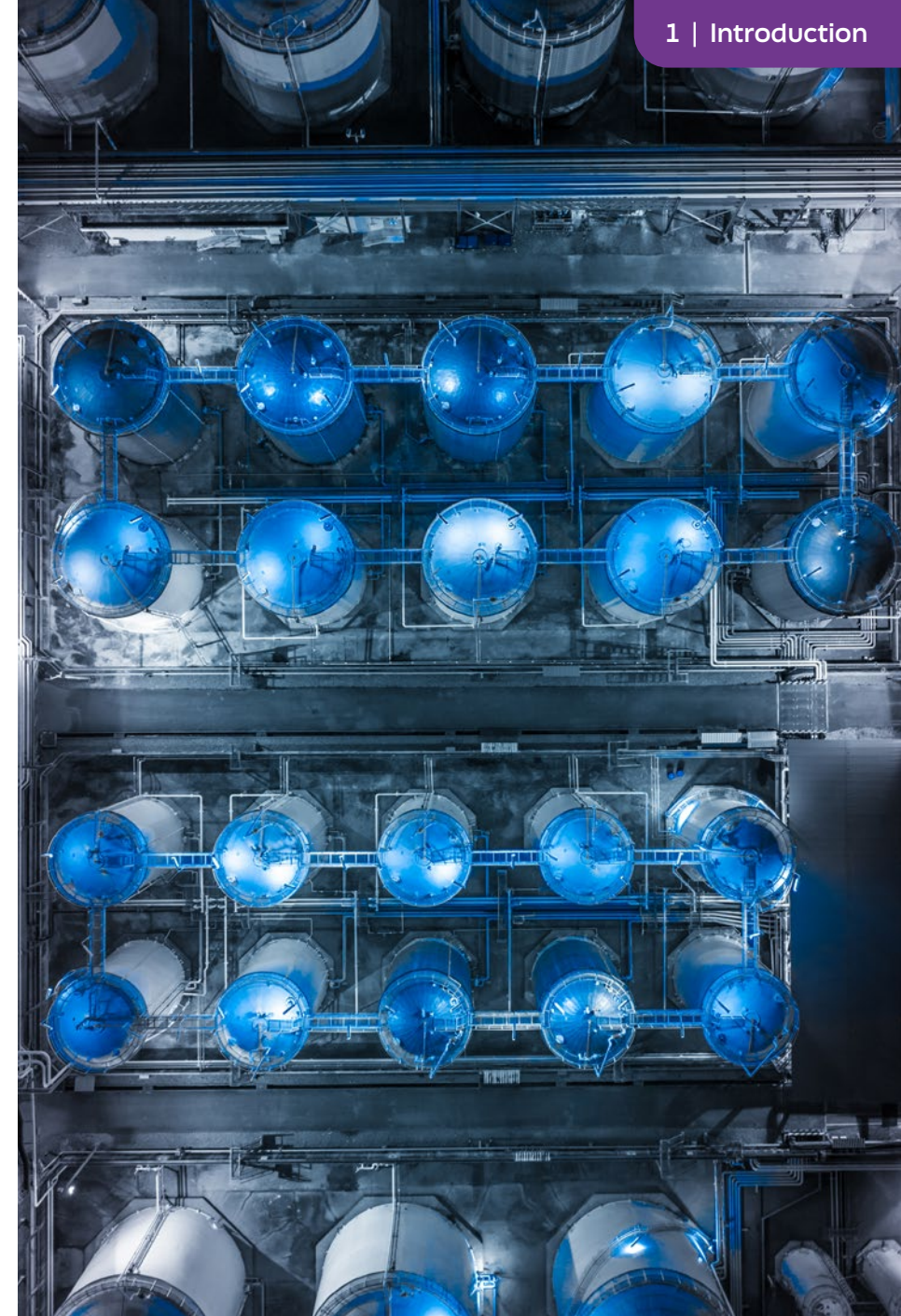
As the maritime industry navigates through an era of unprecedented change, the role of alternative fuels in achieving sustainability goals has never been more critical. Liquefied Natural Gas (LNG) and the methane pathway to net zero stands at the forefront of this transition, offering a viable option to reduce greenhouse gas emissions and enhance environmental performance.

SEA-LNG is proud to support this comprehensive report, *Fuel for Thought: LNG*, which delves into the multifaceted benefits and challenges of LNG as a marine fuel. This report provides valuable insights into the technological advancements, regulatory frameworks, and market trends that shape the future of LNG in the shipping industry.

The maritime sector's journey towards decarbonisation is complex and requires collaboration across various stakeholders, including shipowners, charterers, technology providers, and regulators. LNG has emerged as a mature and widely deployed alternative fuel, capable of significantly reducing carbon emissions and contributing to a cleaner, more sustainable future.

We commend the efforts of Lloyd's Register in producing this detailed analysis, which serves as a crucial resource for industry professionals seeking to navigate the evolving landscape of marine fuels. By cutting through the latest technology advances, policy developments, and market trends, this report equips the industry with the knowledge needed to make informed decisions and drive meaningful progress.

SEA-LNG remains committed to promoting the adoption of LNG and supporting the maritime industry's transition to a low-carbon future following the methane pathway. We believe that with continued innovation and collaboration, LNG can play a pivotal role in achieving the ambitious environmental targets set by the global community.



1.2

LNG fact file



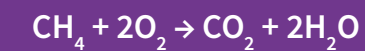
What is it? CH₄

LNG refers to liquefied natural gas, a fossil fuel energy source composed primarily of methane, with small quantities of higher carbon components such as ethane, propane and butane, transformed into a liquid state. Originally viewed as a useful byproduct of oil extraction, today natural gas is extracted mainly from dedicated gas fields for use as a primary energy source.

The potential to use biomass to create biomethane or renewable energy and captured carbon to create synthetic methane offer the long-term prospect of LNG as a zero or near-zero emissions fuel. There are also several measures that can be taken to reduce the greenhouse gas (GHG) impact of LNG both during production and distribution (upstream) and in use (downstream).

LNG is the favoured transportation medium for the seaborne trade in natural gas, as opposed to pipelines which carry the gas in its native gaseous state. As a cryogenic fuel, LNG is maintained at temperatures between -161°C and -163°C to remain in liquid state. This is one of the biggest challenges for its use as a maritime fuel, requiring handling of boil-off gas for onboard storage and fuel gas supply system (FGSS) technology designed for handling cryogenic, low flashpoint fuels. Once liquefied, it can be stored onboard in sufficient volumes to power even very large vessels.

LNG combustion formula:



Properties table



Energy density
48,000 kJ/kg



Volumetric density
24.750 MJ/m³



Storage volume
1.6-1.9 greater storage volume than MDO for equivalent energy
(at -162°C)



Onboard storage temperature
~ -162°C in atmospheric tanks



Flashpoint
-188°C



Boiling point
-162°C



Autoignition point
537°C

1.3

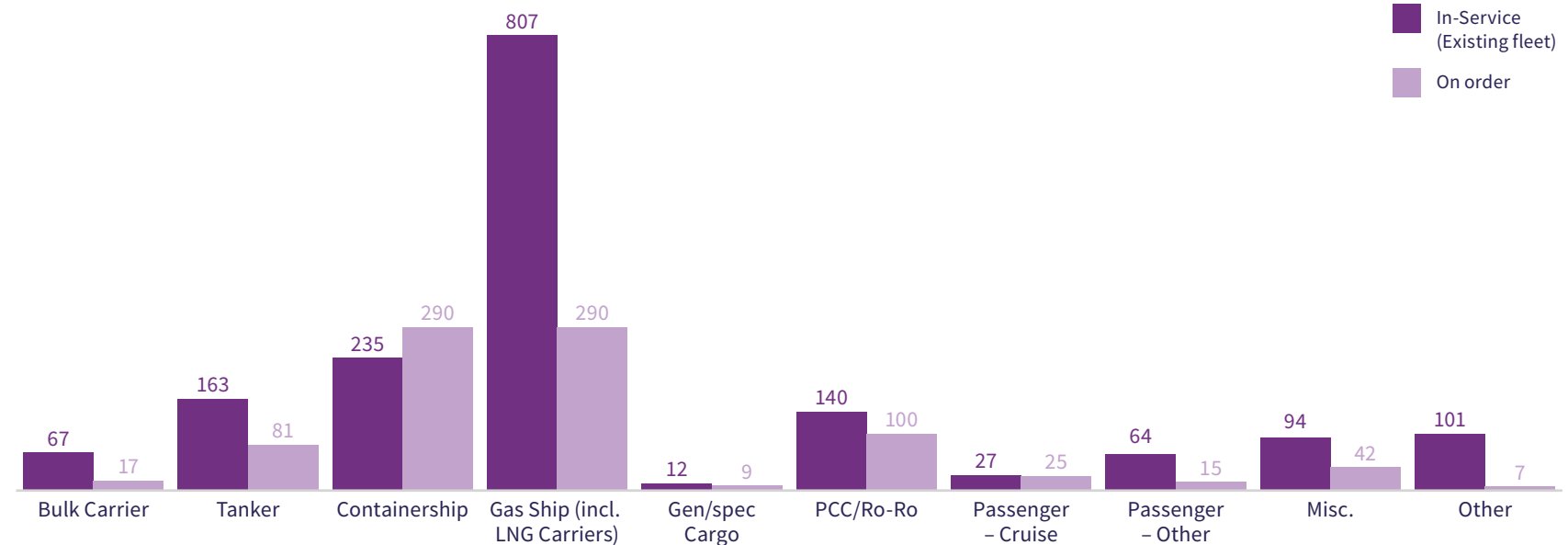
State of the fleet

The current fleet of LNG dual-fuel vessels (as of January 2026) stands at 1,710 vessels, with the LNG carrier segment and other merchant segments accounting for around three-quarters of vessels. The orderbook meanwhile stands at 876 vessels, adding another 51% to the existing gas-fuelled fleet. Despite the steady emergence of methanol-fuelled orders over the past year alongside an early trickle of ammonia-capable vessels, LNG remains by far the most popular alternative to conventional fuels, with 12% of vessels on order destined to install LNG dual-fuel engines.

Naturally, LNG carriers remain the largest vessel segment for LNG dual-fuel engines, and vessels on order will grow the LNG-capable LNG carrier fleet by a further 50%. Other segments are increasing their uptake even more dramatically. Notably, the containership segment has almost 1.2 times as many LNG-capable vessels on order as exist today. The cruise segment has similar numbers on order as are already in service.

The annual trend also seems to be steady. As of January 2026, there continues to be more LNG-fuelled vessels ordered than any other alternative fuel type. The container segment trend is illustrative. From the fourth biggest vessel segment for LNG-capable ships a few years ago, based on the current orderbook, it will shortly become the second largest vessel segment.

Figure 1: LNG dual-fuel fleet, in-service and orderbook, by number of vessels



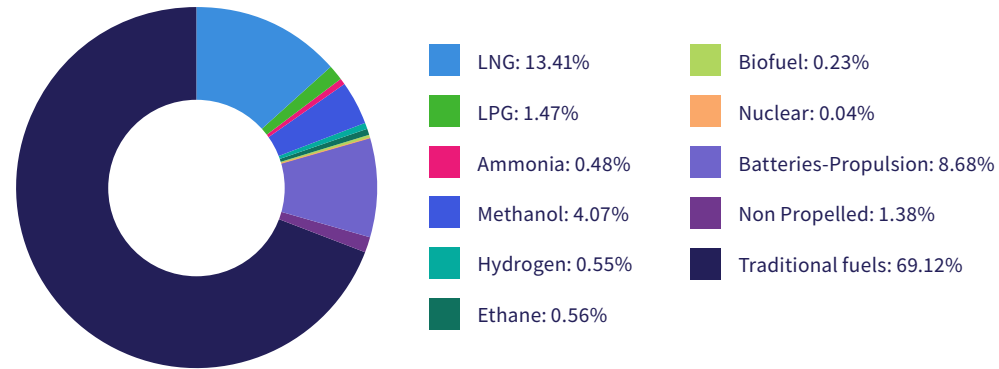
Source: IHS Database, December 2025

Figure 2: LNG dual-fuel fleet and orderbook by share of global installed power

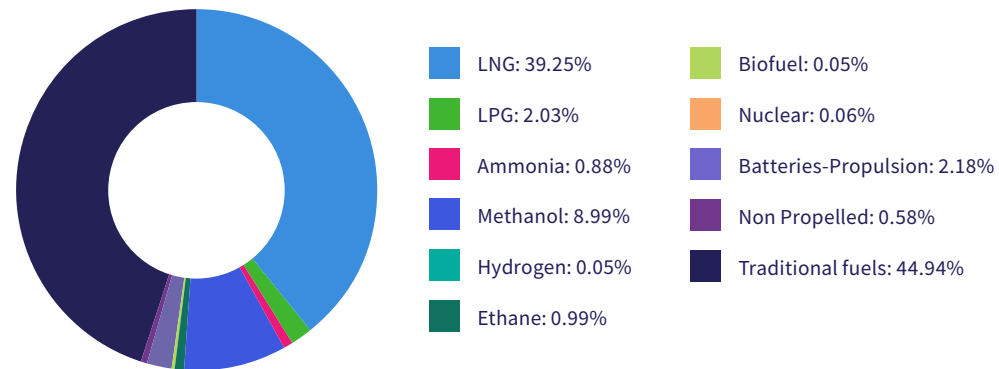
Ship Type	Share by Power service					
	DF Existing [kW]	Existing [kW]	Existing [%]	DF Orderbook [kW]	Orderbook [kW]	Orderbook [%]
Bulk Carrier	917,283	126,480,135	0.7%	261,580	10,170,828	2.6%
Tanker	1,762,413	102,470,075	1.7%	1,070,390	13,169,151	8.1%
Containership	9,091,132	183,149,469	5.0%	11,629,576	26,574,924	43.8%
LNG Carriers	16,971,019	22,329,590	76.0%	8,312,102	8,312,102	100.0%
Passenger Ships (incl. cruise)	2,785,622	47,115,348	5.9%	2,005,490	3,890,238	51.6%
Other	3,874,615	206,582,939	1.9%	2,149,989	12,187,284	17.6%

Source: IHS Database, December 2025

Figure 3:
Orderbook fleet by fuel type – number of vessels, January 2026



Orderbook fleet by fuel type – % million Gross Tonnes (mGT)



Source: Clarksons, IHS, Lloyd's Register

The new enthusiasm for LNG amongst liner operators is noteworthy as it is not, as may be the case in other segments, a first step towards lower carbon fuels. At least two large containership operators have announced pursuing ambitions of establishing methanol as part of their fuel mix. But current ordering trends – both directly and orders placed on operators' behalf by tonnage providers – confirm that these operators increasingly view LNG-fuelled vessels as an attractive option.

Perhaps a more significant metric for LNG's maturity as a fuel choice is its share of installed power across the entire orderbook. According to IHS data, by share of installed power, dual-fuel LNG vessels represent nearly a quarter of the orderbook. Across all vessel segments, a far higher percentage of installed power on order is for LNG-capable ships. For example, LNG-capable container ships currently represent 3.8% of the installed power in the segment. When current vessel orders are fulfilled, that figure will stand at 46.3%.

The clear message in the data is that demand for LNG-capable vessels is increasing dramatically, both in the number of vessels ordered and in terms of the size of dual-fuel LNG applications—indicating growing maturity in both the technology to use LNG and the global availability of the fuel.



VLCCs seize advantage of emerging LNG tank technology

The very large crude carrier (VLCC) segment is a small but growing niche for LNG as a marine fuel, with 22 vessels in service and 13 on order (as of December 2025). In 2023, four VLCCs were built by Hanwha Ocean, formerly Daewoo Shipbuilding & Machinery Engineering, for tanker operator Advantage Tankers.

The vessels were built as part of the Neptune project, under which the ten first dual-fuel VLCCs were delivered – all built under LR class – with Advantage Tankers' Advantage Verdict being the very first. Alongside the four Advantage vessels, three were built for AET and another three for International Seaways.

As well as being among the first LNG-fuelled VLCCs on the market, the vessels were the first tankers to feature LNG tanks built from high-manganese steel. Manufactured by steelmaker POSCO, the new material benefits from similar or better cryogenic handling properties as high nickel steel traditionally used to make LNG tanks but at a significantly lower cost.

The Advantage vessels were designed and built to LR class, with expertise derived from long involvement in the development of high-manganese steel. From 2010, LR participated in a three-year joint development project with Korean shipbuilders and POSCO to examine the feasibility of the new material. That project laid the groundwork for the approval in 2018 of IMO interim guidelines on manufacturing high-manganese steel and applying it to cryogenic LNG cargo and fuel tanks.

Since their delivery, the vessels have been running successfully on mainly LNG, stored in two on-deck Type C tanks. Operated under a long-term charter by energy major Shell, they are an example of the increasing uptake of LNG across diverse vessel segments, the continuing advances that make using the fuel ever more cost effective, and the collaboration and expertise driving those technology improvements.

Advantage Victory was among the first series of VLCCs to deploy high-manganese Type C tanks for LNG fuel.

Image courtesy of Advantage Tankers

2.1

Chapter 2:

Demand drivers

Regulatory drivers

The regulatory environment comprises global and regional goal-based decarbonisation initiatives which encourage owners and operators to switch their ships to less carbon-intensive operations. The key regulations at IMO and European Union level are described in this section, along with a discussion of the extent to which the various forms of LNG can be deployed for compliance and cost reduction.

EU Regulations

Some of the most advanced regulations are from the European Union (EU). Shipping companies need to be aware of five elements of the EU Fit for 55 package that impact shipping. The Fit for 55 package is the bloc's overarching decarbonisation strategy across society and business. It includes:

- A revised Monitoring, reporting, and verification of greenhouse gas emissions from maritime transport regulation (EU MRV)
- A revised Directive on the EU Emissions Trading System (EU ETS)
- A new FuelEU Maritime Regulation
- Revised Alternative Fuels Infrastructure Regulation (AFIR)
- A revised Renewable Energy Directive (RED III)

These interlocking requirements will drive ship owners to adopt more stringent ship efficiency strategies, as well as low-carbon fuels such as biofuels.



EU Emissions Trading System

As of 1 January 2024, passenger and cargo ships of 5,000 GT and over calling at European Economic Area (EEA) ports became subject to the region's emission trading scheme (ETS). Additional ship types and sizes will fall into scope of the scheme in future years.

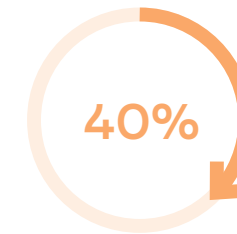
Shipping companies with responsibility for affected ships will need to buy allowances to cover tank-to-wake (TtW) greenhouse gas (GHG) emissions (CO₂, CH₄ and N₂O) reported under EU MRV for intra-EEA (EU plus Norway and Iceland) voyages, in EEA ports, and for half of the GHG emissions created during voyages to and from the EEA. From 1 January 2024, EU allowances for CO₂ emissions had to be surrendered under EU ETS, with CH₄ and N₂O emissions falling into the scope of ETS from 2026.

There are no free allowances for shipping as there were for other sectors in the early stages of EU ETS, but there has been a phase-in period (see figure to the right). This has means that shipping will only be required to surrender 100% of verified emissions for data collected in 2026 and onwards, despite being in scope of the EU ETS since 2024

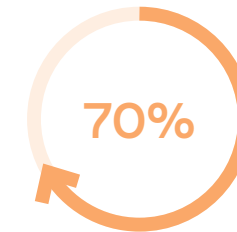
Surrender of allowances for each reported year will be required by 30 September of the following year. Failure to surrender sufficient allowances will result in the accrual of penalties.

The review of EU ETS due in 2026 requires the European Commission to:

- Assess the pending IMO GHG pricing and market-based measures with a view to adjusting the EU ETS if necessary.
- Examine the possibility of extending the EU ETS to include emissions from smaller vessels between 400 and 5 000 gross tonnage.
- Monitor the implementation of the ETS for maritime transport, particularly on routes providing essential territorial-continuity services (e.g., islands, remote or outermost regions), and consider legislative changes to strengthen effectiveness and limit evasion or circumvention.
- Simplify and enhance the ETS framework, including ensuring consistency with other EU laws (e.g., biomass rules), supporting uptake of renewable and low-carbon maritime fuels, and streamlining monitoring, reporting and verification requirements.



**of verified emissions
reported for 2024**



**of verified emissions
reported for 2025**



**of verified emissions
reported for 2026 (and
each year thereafter)**

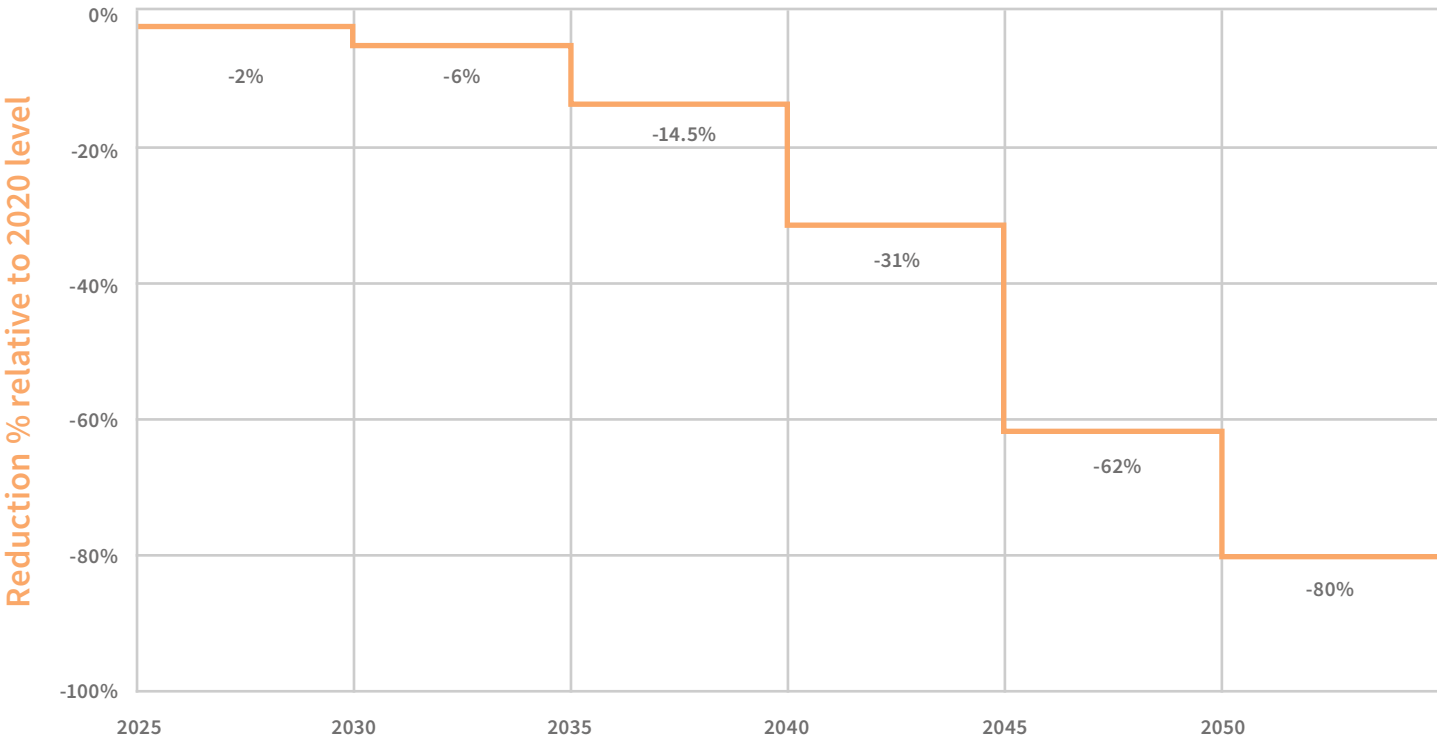
FuelEU Maritime

This regulation operates alongside EU ETS and promotes the use of alternative low or zero-carbon fuels. FuelEU creates demand for these fuels, noting that the carbon pricing policies in EU ETS (that in part support improvements in energy efficiency) alone will not be sufficient to meet the EU’s target to be carbon neutral by 2050.

Since 1 January 2025, shipping companies operating ships of over 5,000 GT calling at EEA ports (but currently excluding Norway and Iceland) have been required to meet stepped reductions in the GHG intensity of energy used onboard as shown in the table opposite, with an additional requirement to have zero at-berth emissions (for container and passenger ships) coming into effect from 2030.

The FuelEU Maritime Regulation requires submission of a monitoring plan, separate to the MRV monitoring plan. Assessment for each ship should indicate the chosen method used to monitor and report the amount, type and emission factor of energy used on board. Data should be collected for any voyages and port calls in scope each year (January to December). By 30 March 2026, and by that date in each subsequent year , data collected during the previous year must be verified and reported.

Figure 4: FuelEU Maritime reduction factors



Above: Reduction in GHG intensity of energy used on board from 2020 levels (%).

FuelEU Maritime pooling

Included in the provision of each ship's FuelEU data is the optional notification of the decision to pool ships. Pooling allows the responsible owners and managers to bring together ships that have been operated within a fleet, within a company or among companies. The objective is to encourage the deployment of new ships using low- or zero-GHG-emission solutions, instead of focusing only on improving the performance of existing ships.

Pooling allows the benefits of one ship to be shared among a fleet to reduce the GHG intensity of the individual ships. The purpose of pooling is to incentivise the use of and investment in other alternative fuels, including LNG. See the section, 'Economic Drivers', for an example of how a single LNG-fuelled vessel can offset the penalties for multiple conventionally fuelled vessels.

GHG emission factors for fuels under Fuel EU Maritime

FuelEU Maritime provides a methodology for establishing the GHG intensity of the energy used on board, with Well-to-Tank (WtT) and Tank-to-Wake (TtW) calculations. For fossil LNG, default emission factors are provided in Annex II of FuelEU.

For biomethane, emissions factors can be determined using the methodologies set out in Renewable Energy Directive (RED). GHG emissions savings from the use of biomethane must be at least 65% for fuels used in the transport sector (i.e. a baseline of 94 g CO₂eq/MJ). RED contains default CO₂eq emissions values (without combustion) which can be used for all fuels whose pathways are included in RED. Alternatively a RED-approved certification scheme can be used.

Figure 5: FuelEU Maritime default emission factors, fossil and bio-LNG

Pathway name	LCV [$\frac{\text{MJ}}{\text{g}}$]	WtT	TtW				
		CO _{2eq WtT} [$\frac{\text{gCO}_2\text{eq}}{\text{MJ}}$]	Fuel Consumer Unit Class	C _{f CO₂} [$\frac{\text{gCO}_2}{\text{gFuel}}$]	C _{f CH₄} [$\frac{\text{gCH}_4}{\text{gFuel}}$]	C _{f N₂O} [$\frac{\text{gN}_2\text{O}}{\text{gFuel}}$]	C _{slip} As % of the mass of the fuel used by the engine
LNG	0,0491	18.5	LNG Otto (dual fuel medium speed)	2,750	0	0,00011	3,1
			LNG Otto (dual fuel slow speed)				1,7
			LNG Diesel (dual fuel slow speed)				0,2
			LBSI				2,6
Liquefied Bio-methane as transport fuel (Bio-LNG) Production of Pathways of Directive (EU) 2018/2001			LNG Otto (dual fuel medium speed)	2,750	0	0,00011	3,1
			LNG Otto (dual fuel slow speed)				1,7
			LNG Diesel (dual fuels)				0,2
			LBSI				2,6

Source: FuelEU Maritime, Annex II²

It is important to note the wide range in the GHG intensity of biomethane, depending on the feedstock used, production process and other factors. RED contains typical and default values for the GHG emissions savings from a range of biofuels by feedstock against a fossil comparator of 94 g CO₂eq/MJ, assuming no net carbon emissions from land-use change.

Further information on this topic can be found in LR's research report [Fit for 55: Managing compliance and optimising operations under the EU's new regime](#).

Figure 6: Biomethane for transport default greenhouse gas saving values

Biomethane production system	Technological options	Greenhouse gas emissions savings – default value
Wet manure	Open digestate, no off-gas combustion	72 %
	Open digestate, off-gas combustion	94 %
	Close digestate, no off-gas combustion	179 %
	Close digestate, off-gas combustion	202 %
Maize whole plant	Open digestate, no off-gas combustion	17 %
	Open digestate, off-gas combustion	39 %
	Close digestate, no off-gas combustion	41 %
	Close digestate, off-gas combustion	63 %
Biowaste	Open digestate, no off-gas combustion	20 %
	Open digestate, off-gas combustion	42 %
	Close digestate, no off-gas combustion	58 %
	Close digestate, off-gas combustion	80 %

Source: EU Renewable Energy Directive ³





International Maritime Organization regulations

In 2018, following the 2015 Paris Climate Agreement, the IMO agreed an initial GHG strategy to outline a pathway to reduce shipping's CO₂ emissions as part of keeping average global temperatures to within 1.5 degrees Celsius of their pre-industrial levels. The initial strategy led to the development of short-term measures including the Energy Efficiency Existing Ship Index (EEXI) and the Operational Carbon Intensity Indicator (CII).

At the 80th meeting of its Marine Environment Protection Committee (MEPC 80), IMO adopted a revised GHG reduction strategy. This aims to achieve net-zero CO₂ equivalent (CO₂ as well as nitrous oxide and methane) emissions by or around 2050. There are indicative checkpoints along the way for shipping to aim for, including:

- Total GHG emissions to reduce by 20–30% by 2030 compared to 2008 levels
- Total GHG emissions to reduce by 70–80% by 2040

There is also a target for low or zero-GHG fuel uptake of at least 5%, striving for 10%, as well as a reduction in the carbon intensity of international shipping by at least 40%, also compared to 2008 levels, by 2030.

The revised GHG reduction strategy also set a timeline for the adoption of mid- and long-term measures to reduce GHG emissions from shipping.

Mid-term measures in the form of a technical GHG energy intensity standard and an associated economic element were agreed at MEPC 83 in spring 2025. However, the proposed draft regulations have not been adopted by IMO as was expected in October 2025. Accordingly, any entry into force and application dates remain unknown.

IMO Net Zero Framework

At MEPC 83 in April 2025, a basket of mid-term measures—reframed as the ‘IMO Net Zero Framework’—was agreed. At an extraordinary meeting scheduled to vote on its adoption in October 2025, MEPC decided to postpone the decision on whether to adopt the IMO Net Zero Framework for a year. Full details of the new framework, which was originally due to come into effect on 1 March 2027, can be found in LR’s MEPC 83 Summary Report, noting that as a result of the decision to adjourn the meeting which has delayed adoption, the dates within the Framework will require review.

The most significant element of the IMO Net Zero Framework is the GHG Fuel Intensity (GFI) standard and pricing mechanism. Ships of more than 5,000GT (with some exceptions) will be required to calculate an annual GFI based on the weighted average of GHG energy intensity of energy sources it uses, including fuel, but also energy from other sources, and savings in emissions from technology such as carbon capture. The GFI will be calculated from emission values in IMO’s Lifecycle Analysis (LCA) Guidelines (see next section) and using methodologies to be published in future guidelines.

To ascertain penalties and rewards under the GFI pricing mechanism, a vessel’s annual attained GFI is compared to two annual GFI reduction trajectories, with target values based on reductions from the global fleet average energy intensity in 2008 (93.3 gCO₂eq/MJ). The ‘direct compliance target’ trajectory represents the GFI at or below which no penalties—in the form of Remedial Units—will need to be paid. The higher ‘base target’ trajectory represents the GFI level above which vessels will need to buy Tier 2 Remedial Units at

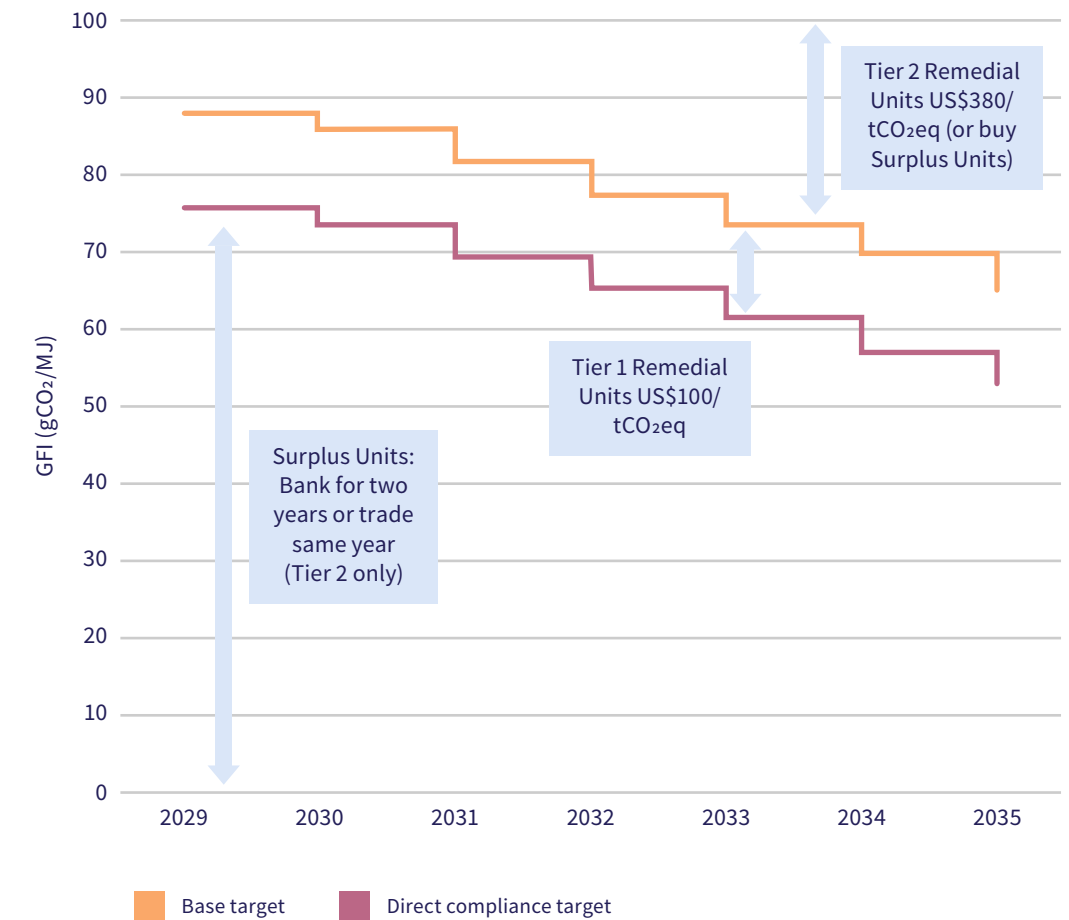
US\$380 per tonne of CO₂eq emissions, or privately agree to obtain compliance surplus in the form of Surplus Units from other ships which out performed the direct compliance target. Between the direct compliance and base targets, vessels will need to pay Tier 1 Remedial Units at US\$100 per tonne of CO₂eq emissions.

GFI reduction targets have been included for the first eight years of the regime. The draft regulations then set out that by 1 January 2032, the IMO must determine the reduction targets for the years to 2040 and that the 2040 base target shall be set at 65% below the reference 2008 GFI of the global fleet.

As with FuelEU Maritime, vessels with a compliance surplus—those achieving an annual attained GFI below the direct compliance target—will be able to either bank or trade Surplus Units. Surplus Units banked from the previous two years can be used to balance a Tier 2 compliance deficit, or Surplus Units from a specific year can be sold privately to help balance another ship’s Tier 2 compliance deficit that same year.

Separately from the reduction trajectories, a reward is available for the use of zero or near-zero emissions (ZNZ) fuels with an energy intensity of 19gCO₂eq/MJ until the end of 2034, and 14gCO₂eq/MJ from 2035. This would likely include e-LNG made using renewable electricity and carbon capture. The amount of the reward is to be determined by no later than 1 March 2027 and will be reconsidered every five years thereafter. There is also scope for MEPC to agree other Zero and Near Zero emissions (ZNZ’s).

Figure 7: Greenhouse Gas Fuel Intensity (GFI) target trajectories and Remedial/Surplus Units



Net Zero Framework impact on fuel costs

The IMO’s framework means that ship operators using fuels with an energy intensity that takes their vessel’s annual attained GFI above the direct compliance target would need to buy Remedial Units and/or Surplus Units. These costs would therefore become another factor to be considered when selecting fuels.

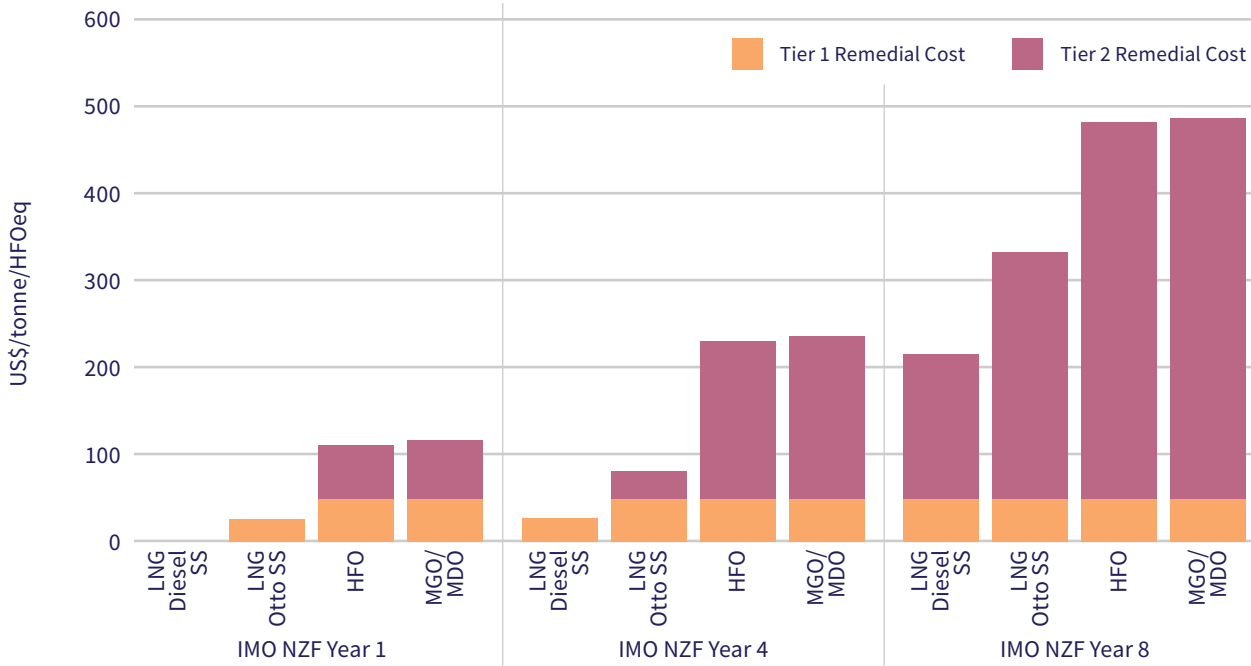
In the case of LNG, this means that the fuel would be subject to Remedial Units earlier than it will be subject to FuelEU Maritime penalties. For vessels with Diesel-cycle slow-speed LNG dual-fuel engines for example, FuelEU Maritime penalties only begin after 2039. However, under the IMO Net Zero Framework, they will require Tier 1 Remedial Units from the second year, and Tier 2 Remedial Units in addition to Tier 1 remedial units as well from year six.

While this means significant additional compliance costs for LNG users, this must be considered comparatively. Penalties under the IMO Net Zero Framework would begin at an earlier stage for vessels using VLSFO than for those using LNG, with Tier 1 and Tier 2 Remedial Units required from the outset of the regime at 2028. The level of cost is also far higher, as indicated in Figure 8, which shows GFI costs for an amount of fuel with the energy equivalent to a tonne of HFO, or ‘tonne of HFO equivalent’.

The overall impact of the Net Zero Framework would be to penalise energy sources with higher GHG energy intensity, and this means VLSFO and HFO would be penalised more than LNG – thus actually increasing the competitive advantage of LNG over these fuels. When bio-LNG can be sourced and added to the blend, or used as a substitute, this has an even greater impact, with substantial surpluses possible in the early years of the new regime.

The full impact of the Net Zero Framework cannot be truly determined without knowing the reward value for using ZNZ fuels. This will determine the extent to which the framework succeeds in reducing the cost gap between zero GHG or near zero GHG emitting fuels and conventional fuels, and thus incentivising their uptake. In the meantime, it is clear that while the mechanism does place additional costs on LNG in absolute terms, it does not jeopardise LNG’s competitiveness relative to other conventional fuels.

Figure 8: Levelised GFI cost per tonne of HFO equivalent by fuel type



MEPC developments affecting LNG engines

Also at MEPC 83, draft revisions to the NOx Technical Code and related parts of MARPOL Annex VI were approved that aim to codify existing best practice around NOx certification. In particular, the amendments place new certification requirements on engines with multiple engine operating profiles (MEOPs) and those using auxiliary control devices. Furthermore, these revisions include a screening mechanism for emissions between and beyond the test cycle mode points (“off-cycle emissions”) to verify that the emission control strategy is “rational”, as required by MARPOL Annex VI.

Lifecycle Assessment

The GHG lifecycle analysis of LNG is critical to proving its GHG emissions reduction. Of particular importance is the issue of methane slip, the emissions of unburned methane from engines using LNG. As indicated in Figure 9, methane emissions from specific engine types each have different emission slip values.

The IMO adopted guidelines on the lifecycle analysis of marine fuels (LCA Guidelines) at MEPC 81 and continues to develop them. The well-to-tank (WtT) and tank-to-wake (TtW) emissions factors attributed to each fuel pathway and energy converter in the guidelines are expected to be used in future IMO regulations for the reduction of GHG emissions in shipping. It is worth noting that the emission factors vary slightly from those under FuelEU Maritime.

In a WtT calculation, the GHG intensity of the feedstock, fuel production process and associated transport and distribution – the so-called “fuel pathway” – are all accounted for. TtW emissions evaluate the intensity of CO₂, CH₄, and N₂O emitted onboard a ship related to use of the fuel and all relevant fugitive emissions.

The default factors included in IMO’s LCA Guidelines for both WtT and TtW emissions do not yet take into account recent improvements in emissions from fuel pathways and emission slip from engines. For example, several certification schemes already exist for methane production and distribution (see Chapter 3 on fuel production and supply) while engine designers are working to reduce methane slip in new engines (see Chapter 4 on fuel technologies).

The IMO has established a mechanism for scientific review of default values and all existing default emissions factors are likely to be reviewed by a GESAMP group established for this purpose before the NZF moves to operationalisation. These updates to emissions factors will be needed to further incentivise sustainability improvements in LNG supply chain and technology – and to ensure that those already investing in them are not penalised.

Figure 9: IMO Lifecycle Analysis Guidelines, default emission factors, fossil LNG

Fuel type	Fuel Pathway Code	LCV (MJ/g)	Energy Converter	C _f CO ₂ (gCO ₂ /g fuel)	C _f CH ₄ (gCH ₄ /g fuel)	C _f N ₂ O (gN ₂ O/g fuel)	C _{slip} /C _{fuel} (mass %)	Note
Liquefied Natural Gas (Methane)	LNG_f_SLP_gm	0.0480	LNG Otto (dual fuel medium speed)	2.750	0	0.00011	3.5/-	Resolution MEPC.364(79) Fourth IMO GHG study
			LNG Otto (dual fuel slow speed)				1.7/-	
			LNG Diesel (dual fuel slow speed)				0.15/-	
			LBSI (Lean-Burn Spark-Ignited)				2.6/-	
			Steam Turbines and boilers				0.01/-	

Source: IMO Lifecycle Analysis Guidelines ⁴

Methane slip in the maritime fleet

All engine technology providers have made progress in improving methane slip performance over the last few years. High-pressure two-stroke engines (HP2S) already deliver minimal slip in the range of 0.2g/kWh, while both low-pressure two-stroke (LP2S) and four-stroke (LP4S) engines have managed to reduce methane slip below 1g/kWh with the use of Exhaust Gas Recirculation (EGR) and Spark Ignition (SI) respectively.

As shown in the table on page 18 (Figure 9), latest developments on such engine configurations are not yet included in either the FuelEU Maritime or IMO lifecycle analysis frameworks. This is despite their deployment in the current fleet – for example, LP2S+EGR is used on several LNG carriers already. The shipping industry has made significant progress in incorporating methodologies and systems that help reduce GHG emissions and this needs to be acknowledged and incentivised by regulators. From 2026 LR shall offer a new descriptive note with associated ShipRight procedure for recognising methane reduction measures.

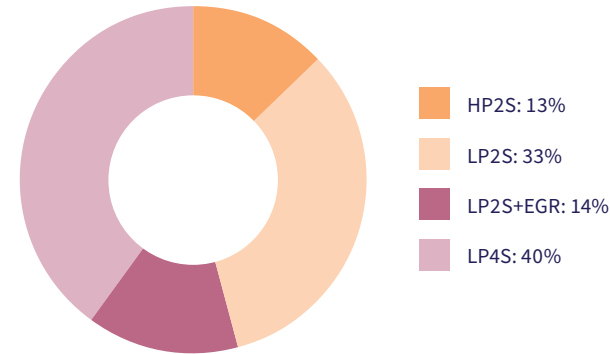
This is a flexible route to identify potential sources of methane emissions onboard, develop an action plan to reduce and control those emissions and for LR to verify. This approach is designed to provide flexibility in methane emission mitigation, enabling tailored solutions based on the ship's design, operating profile and the technologies available.

As well as improving engine technologies, it is also evident that shipowners are paying greater attention than ever to methane slip performance. This is reflected in fleet metrics and dynamics. The LNG-fuelled fleet (excluding LNG carriers) has made a giant leap in adopting the best performing technology for methane slip, HP2S. This technology represents 48% of installed main engine power in the existing fleet and increases to 78% in the orderbook.

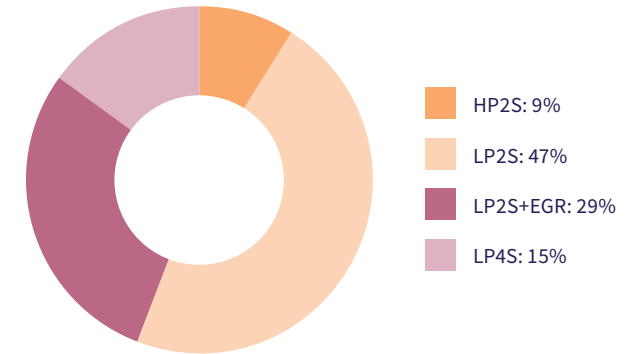
The LNG carrier fleet, which has not shown the same preference for HP2S*, has shifted from dual-fuel diesel-electric four-stroke technology to primarily LP2S, with most recent new-build vessels also deploying Exhaust Gas Recirculation (EGR) or equivalent. This signifies a methane slip reduction in excess of 70%. Today, HP2S and LP2S+EGR are the only technologies applied in the LNG carrier segment, both achieving methane slip below 1g/kWh.

Figure 10: LNG-fuelled ships and LNG carriers, main propulsion technology, existing fleet vs orderbook

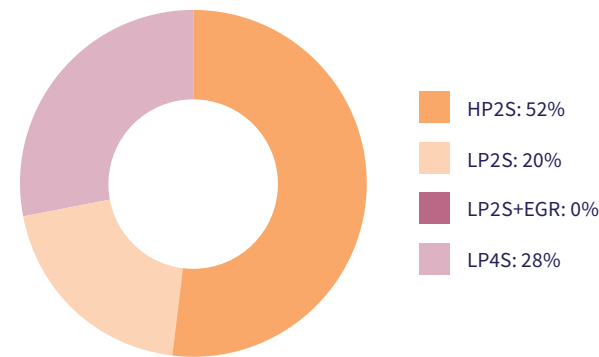
LNG Fleet – Existing



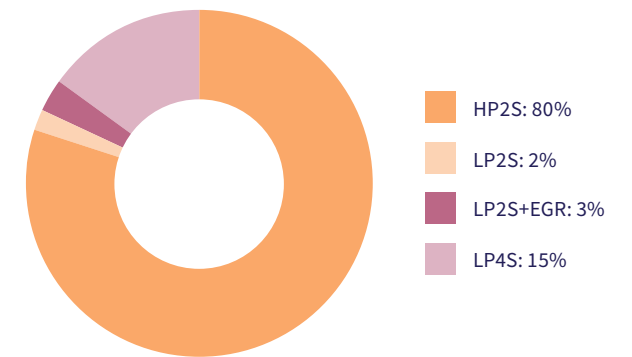
LNG Fleet – Orderbook



LNG DF Fleet (excl. LNGCs) – Existing



LNG DF Fleet (excl. LNGCs) – Orderbook

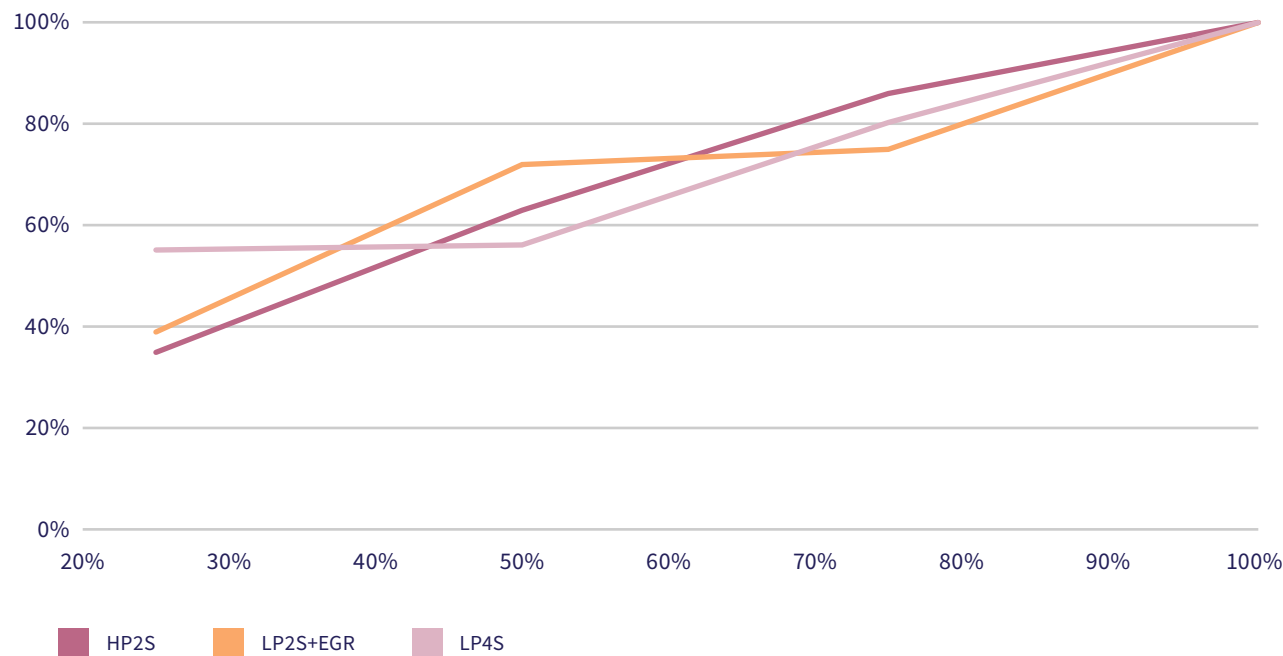


Source: IHS Database, December 2025

* Both categories of LNG-consuming ships need to manage their boil off. In the case of LNG carriers however, the volumes of boil-off to manage constitute the primary component of fuel used. LNG carriers are practically fuelled by compressed vapor rather than pumped liquid. This requires a large compressor that, in the case of HP2S engines, must deliver fuel vapour at 300 bar pressure. The challenges posed by a such a component have in many cases inclined owners' preference towards LP2S engines. With methane emissions regulations coming into force in the forthcoming years, methane slip is expected to become even more important in engine technology selection.

The issue of methane slip performance at low engine loads has received much attention, especially as more vessels adopt slow steaming in response to energy efficiency requirements. However, while slip factors increase at lower load points, the overall absolute mass of methane decreases. In the case of an ultra-large containership with HP2S sailing at 40% load, for example, there is an approximately 50% decrease in the mass of methane mass slip.

Figure 11: Methane emissions mass by engine load (as a percentage of methane emissions mass at maximum continuous rating)

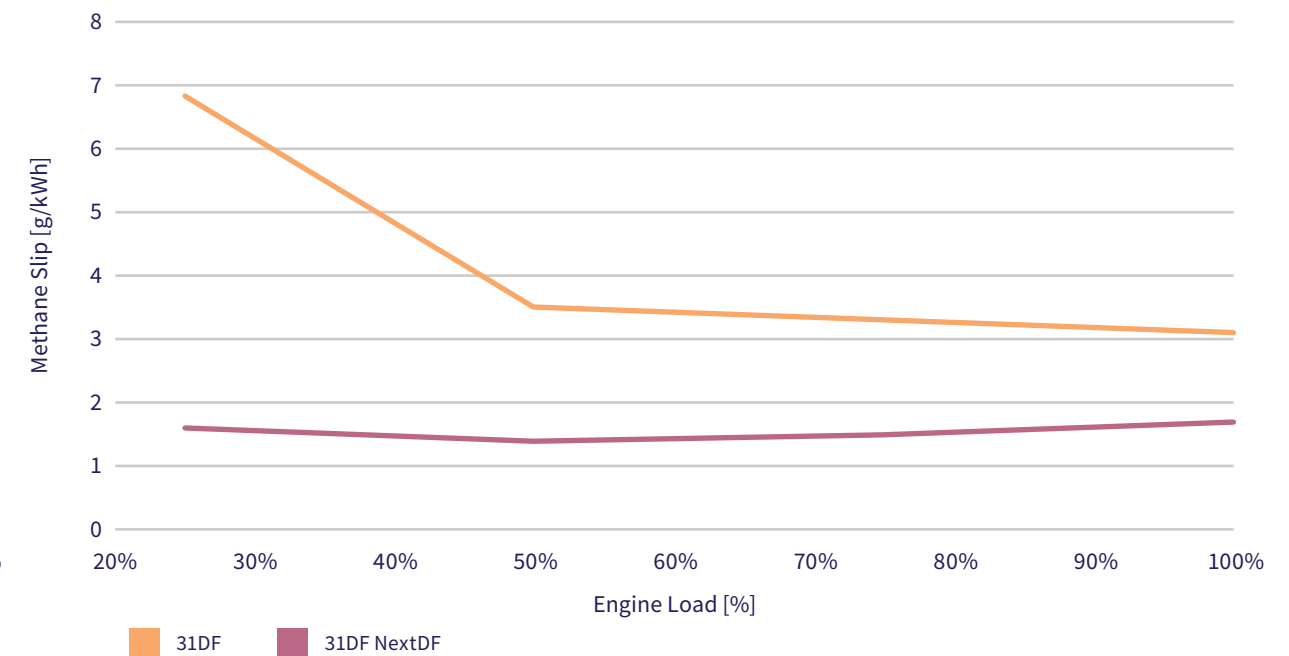


Source: IHS, Lloyd's Register, MAN Energy Solutions, Wartsila, WinGD

Meanwhile, in the case of four-stroke engines which were previously more vulnerable to higher methane slip at low loads, today technologies are emerging to address that point. One example is Wärtsilä's 31DF 'NextDF' technology, as shown in the chart below (see Chapter 4.1 for more details).

Tackling methane slip is a key priority for LNG users. Fleet and technology metrics show great progress is already taking place, but the industry needs take more steps, towards slip rates below 0.5g/kWh. It is essential to enrich the mix of technologies with abatement that can reduce methane slip from existing engines, as well as seizing the potential of supportive technologies including shaft generators, batteries and other.

Figure 12: Wärtsilä 31DF NextDF, methane slip vs previous technology



Source: Lehtoranta, K. et al., 2023

2.2

Economic drivers

Shipowners considering LNG as a fuel face several alternative options for which they will need to consider economic impacts, many of which are not yet entirely predictable. As well as the price and availability of competing fuel candidates, owners and operators will also need to understand compliance costs for each fuel choice under FuelEU Maritime, the EU ETS, the IMO Net Zero Framework and any subsequent regional or national policy.

To illustrate the economic drivers influencing shipowners, two ship types are used to model a variety of scenarios: an **Aframax tanker** with annual consumption of 6,000 tonnes of VLSFO and with 50% of its emissions exposed to EU regulations; and an **ultra large container ship (ULCS)** with annual VLSFO consumption of 22,000 tonnes and 40% of its fuel consumption exposed to European regulations.

These example profiles are based on analysis of annual trading patterns using LR's ship performance model and

publicly available consumption data (submitted under the EU Monitoring, Reporting and Verification regulation).

The fuel scenarios are modelled for the period 2025-2050. They are:

1. Comparing VLSFO and conventional LNG
2. Comparing transitional LNG, methanol and ammonia pathways

The modelling below was performed before the MEPC voted to postpone the vote on adoption of the IMO Net Zero Framework until October 2025. This means that, while the models show the impact of remedies, surpluses and rewards for GHG fuel intensity under that framework from 2028, in fact they will not come into effect until at least 2029. The modelling remains useful as an indication of the impact of fuel choices as regulatory costs evolve.

Disclaimer on economic modelling

As the discussion involves future fuels, it is important to note that these estimates are subject to significant uncertainty. Factors such as technology maturity, changes in demand, policy shifts, and market dynamics can rapidly influence production costs and market prices. These projections should therefore be interpreted with caution and viewed as indicative rather than definitive.

Owners and operators considering alternative fuels can benefit from analysis of their specific business and vessel case by contacting the [LR Advisory team](#).

Assumptions on fuel prices, carbon tax levels, fuel production pathways and emissions factors can be found in Annex I, along with details of the data illustrated in the charts below

Comparing LNG and VLSFO

To compare the impact of maintaining a ‘business as usual’ approach – continuing to operate with VLSFO – with the potential advantages of switching to LNG today, the charts opposite show the FuelEU Maritime, EU ETS and IMO Net Zero Framework (NZF) exposure of both options. The opportunity for pooling vessels under FuelEU Maritime is also considered.

Taking the Aframax tanker case, an LNG-fuelled vessel saves around US\$9 million in EU ETS costs across the period, in the form of EU Allowances surrendered. For FuelEU Maritime, the VLSFO-fuelled vessel is exposed to a total of US\$18 million more in costs, in the form of penalties accrued for energy used beyond the reduction target.

The comparison of NZF costs reinforces how IMO’s measure would extend the advantage of LNG compared to conventional fuel, with an LNG-fuelled Aframax paying nearly US\$30 million less than a VLSFO-fuelled vessel over the period 2028-2050.

Figure 13: Aframax, EU ETS costs, LNG vs VLSFO, 2025-2050

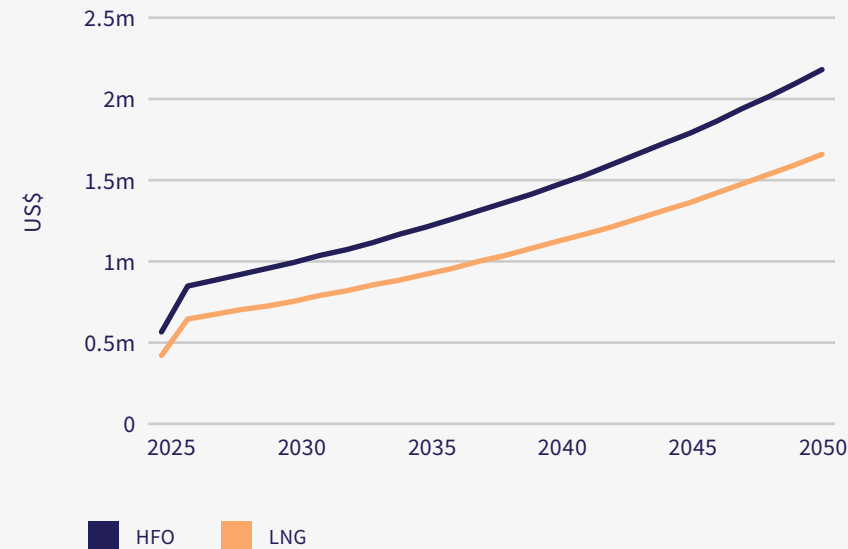


Figure 14: Aframax, FuelEU Maritime costs, LNG vs VLSFO, 2025-2050

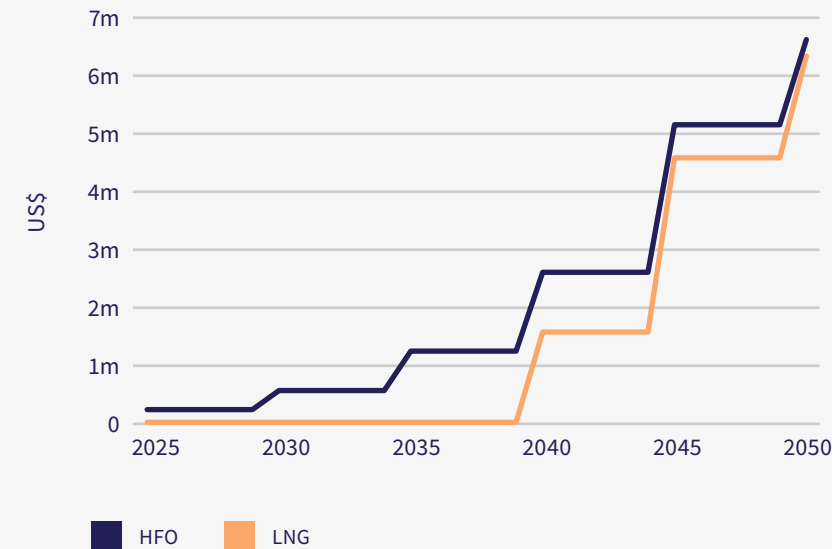
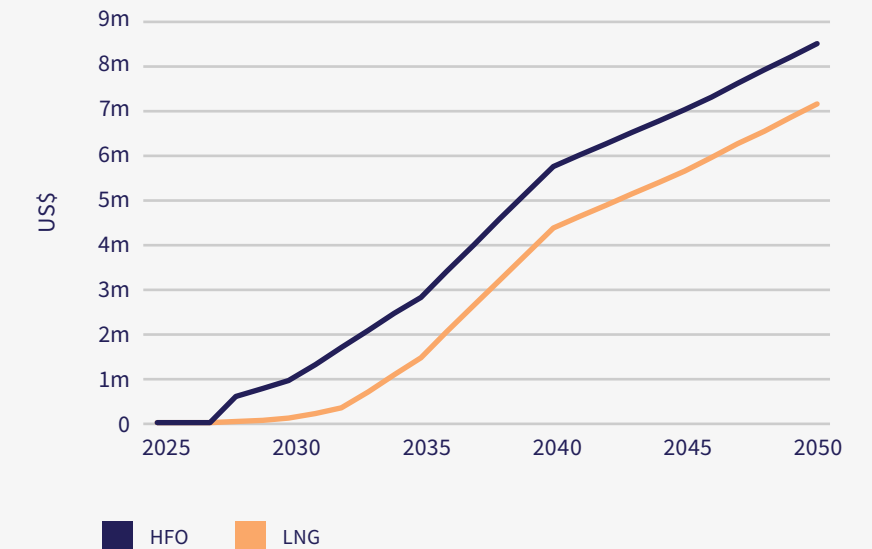


Figure 15: Aframax, IMO GFI costs, LNG vs VLSFO, 2025-2050

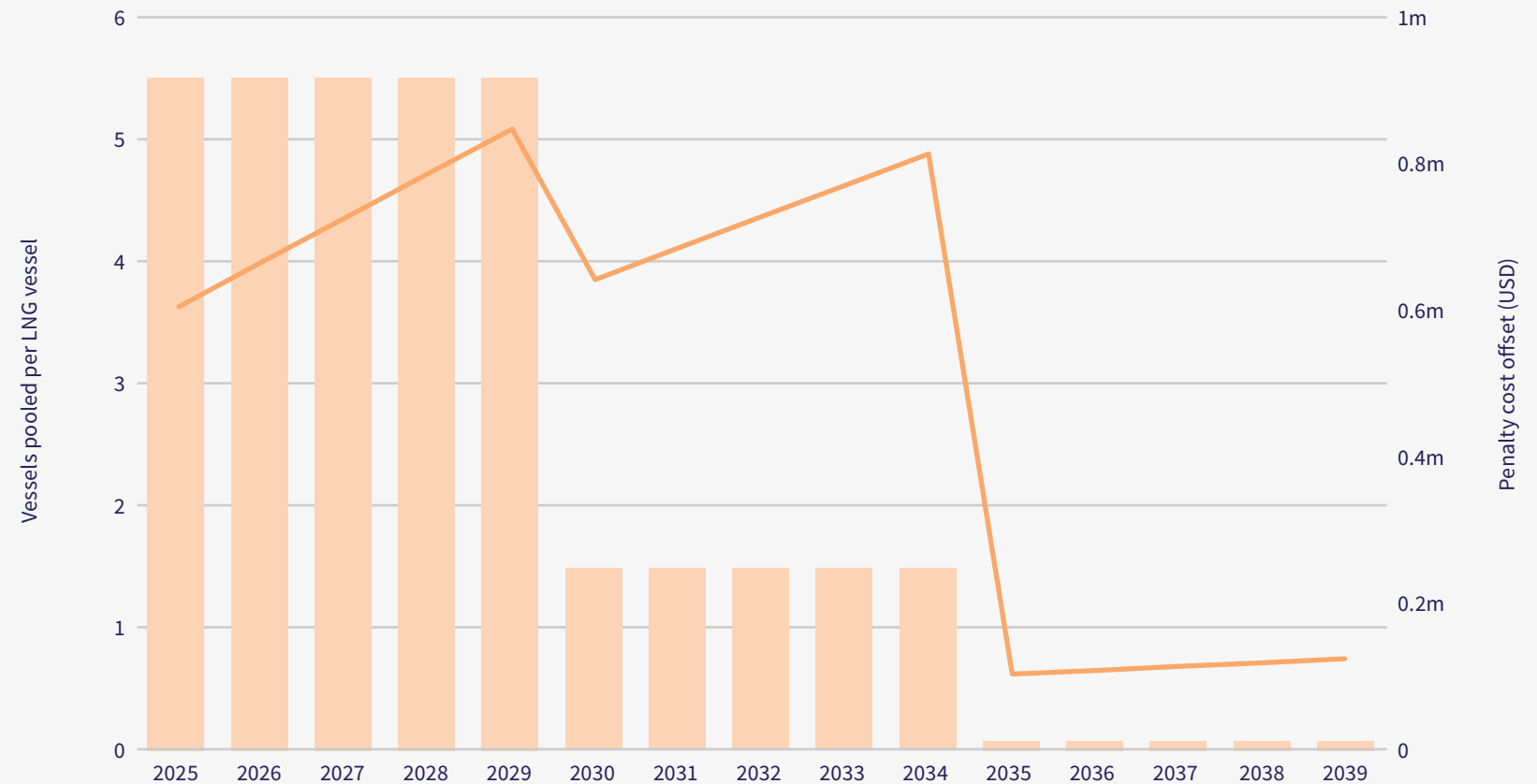


FuelEU Maritime pooling benefit

Figure 16 shows how the LNG-fuelled vessel can be used to offset the surplus energy use from initially 5.5 VLSFO-fuelled vessels in the same pool before the first ratchet in the reduction target in 2030. Even between 2030 and 2034, until the next increase in the reduction target, an LNG-fuelled vessel can offset penalties for more than one other conventionally fuelled vessel in its pool. The pooling effect finally tails off in 2039, when the reduction requirement surpasses reductions achievable with fossil LNG. By this time the LNG-fuelled vessel will have accrued around US\$12.5 million in revenue from offsetting energy surpluses from other vessels.

These are relative gains compared to a vessel fully exposed to European regulation; the absolute cost base will certainly rise for LNG-fuelled vessels under EU ETS and FuelEU Maritime. Over the 26 years to 2050, the vessel will be exposed to nearly US\$73 million in additional costs from the European regulations alone, with the prospect of further costly IMO measures looming. While this compares favourably to the US\$187 million extra paid by a VLSFO-fuelled vessel, it highlights the urgency with which solutions to further reduce the GHG impact of LNG are needed – by further reducing methane emissions across the fuel lifecycle and by using non-fossil methane.

Figure 16: FuelEU Maritime vessel pooling revenues and penalties offset, LNG-fuelled Aframax tanker



Benefits of scale

Figures 17 to 19 show a similar comparison with a vessel type with higher fuel consumption, an ultra large container vessel. This shows the difference between LNG and conventionally fuelled vessels scales with the amount of fuel used.

While the LNG-fuelled container ship is exposed to nearly US\$206 million in European regulatory costs between 2025 and 2050, the cost advantage against the VLSFO vessel rises to US\$343 million when pooling revenue opportunity is considered. Virtually the same number of conventionally fuelled vessels can be pooled to offset surplus energy use as for the Aframax case, but the larger fuel consumption and excess energy use means the value of pooling is greater, with revenue of US\$37.7 million accrued by 2039.

Figure 17: ULCS, EU ETS costs, LNG vs VLSFO, 2025-2050

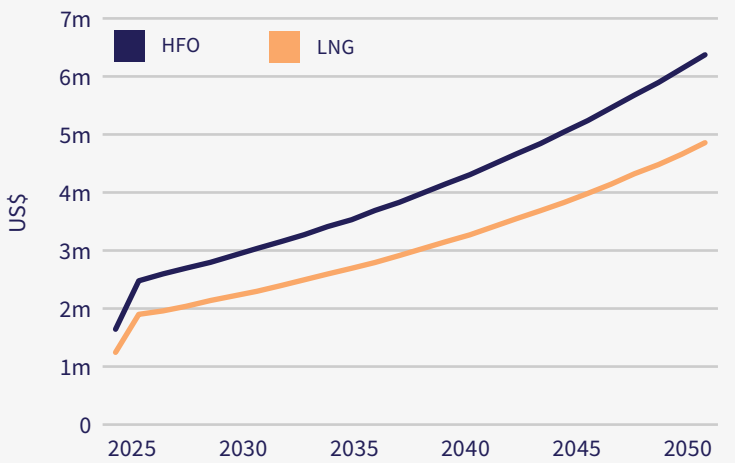


Figure 18: ULCS, FuelEU Maritime costs, LNG vs VLSFO, 2025-2050

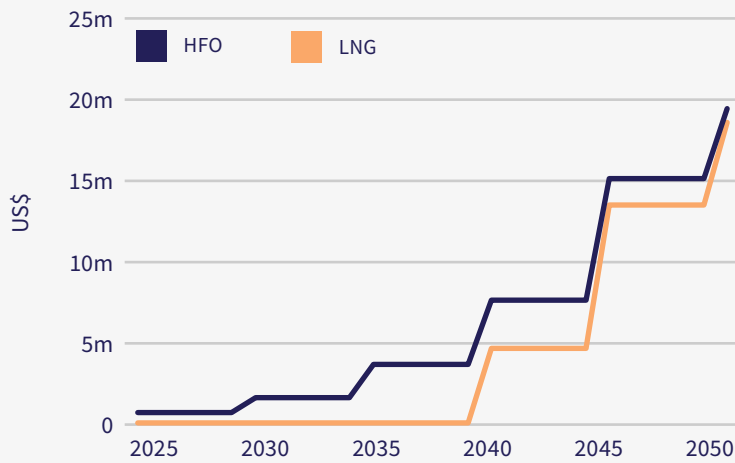


Figure 19: ULCS, IMO GFI costs, LNG vs VLSFO, 2025-2050

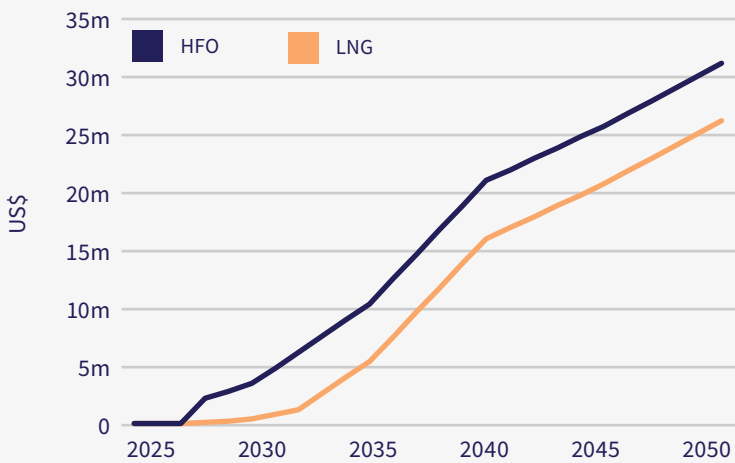
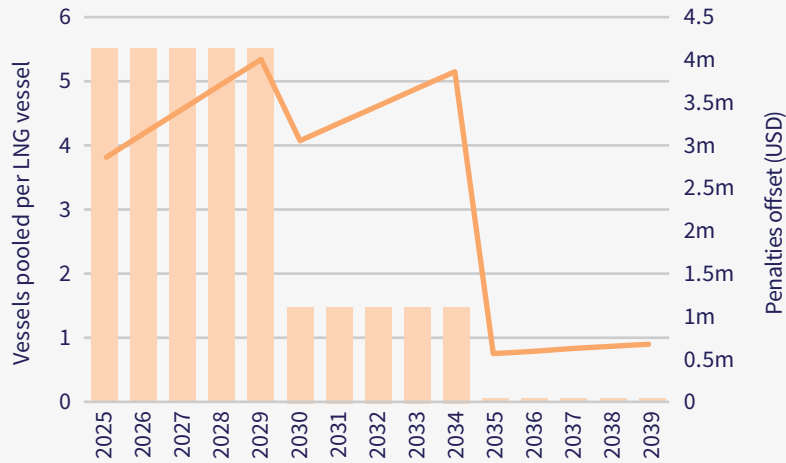


Figure 20: FuelEU Maritime pooling revenue and penalties offset, LNG-fuelled ULCS



Factoring in methane slip

The LNG-fuelled vessels in the illustrations use the engine technology with by far the lowest methane slip factor – Diesel-cycle two-stroke engines, with a methane slip factor of 0.2% of fuel gas consumption under FuelEU Maritime accounting, and 0.15% under IMO’s GHG Fuel Intensity mechanism. If the default methane slip factor for Otto-cycle two-stroke engines is used instead, the picture changes dramatically.

The similar 2025 costs for the EU ETS highlight that methane slip, along with N₂O emissions, are not in scope until 2026. Thereafter, the difference in costs between vessels powered by high-pressure (HP) or low-pressure (LP) two-stroke dual-fuel engines is evident. At just over US\$30.5 million in surrendered EU Allowances between 2025 and 2050, low-pressure dual-fuel engines sit between their high-pressure counterparts, at around US\$27 million, and VLSFO-fuelled vessels at US\$36 million.

For FuelEU Maritime, the value of a surplus is determined by energy intensity rather than GHG intensity, so high-pressure and low-pressure LNG engines reap similar surpluses in the early years of the regulation. But those surpluses end at different times when each fails to meet the required reduction in GHG intensity: in 2034 for low-pressure engines, ahead of the 2035 increase in the reduction target from 6% to 14.5%; and in 2039 for high-pressure engines. This five years of extra surpluses means that over the 26-year period to 2050, an Aframax powered by high-pressure dual-fuel engines will pay around US\$39.5 million less than those with low-pressure engines, representing almost half the cost.

Figure 21: EU ETS costs, Aframax tanker, High Pressure vs Low Pressure engine LNG

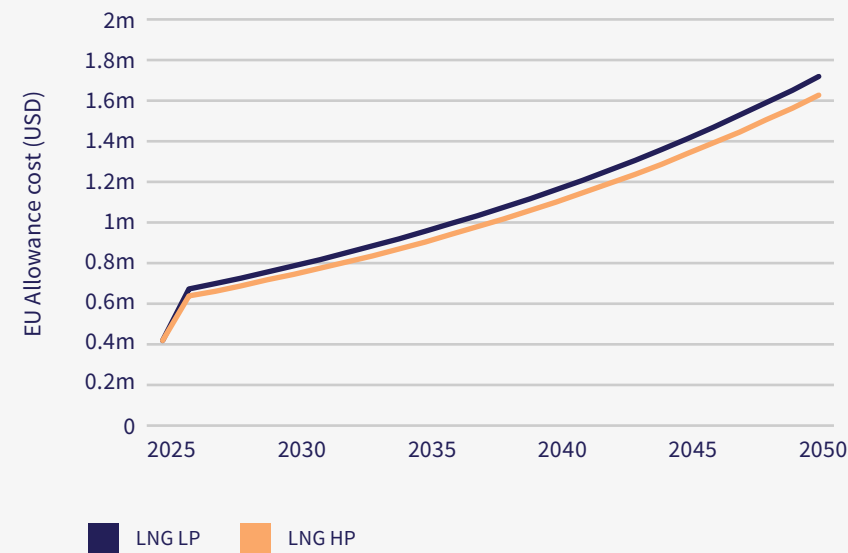


Figure 22: FuelEU Maritime penalties, Aframax tanker, High Pressure vs Low Pressure engine LNG

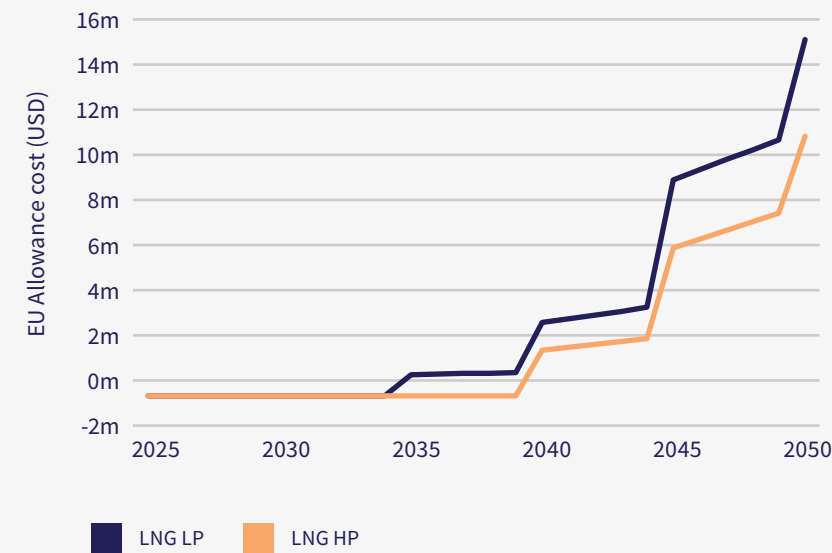
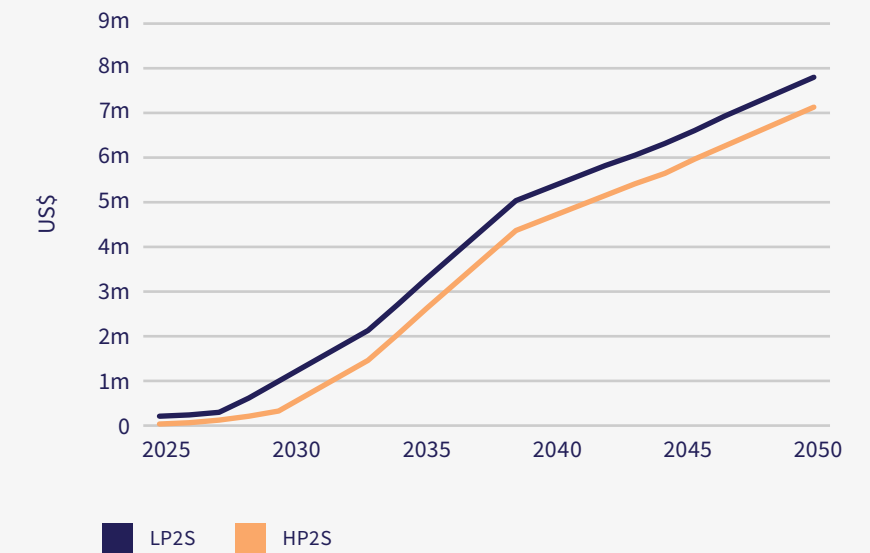


Figure 23: Aframax, IMO penalties, LNG HP2S vs LP2S, 2028-2050



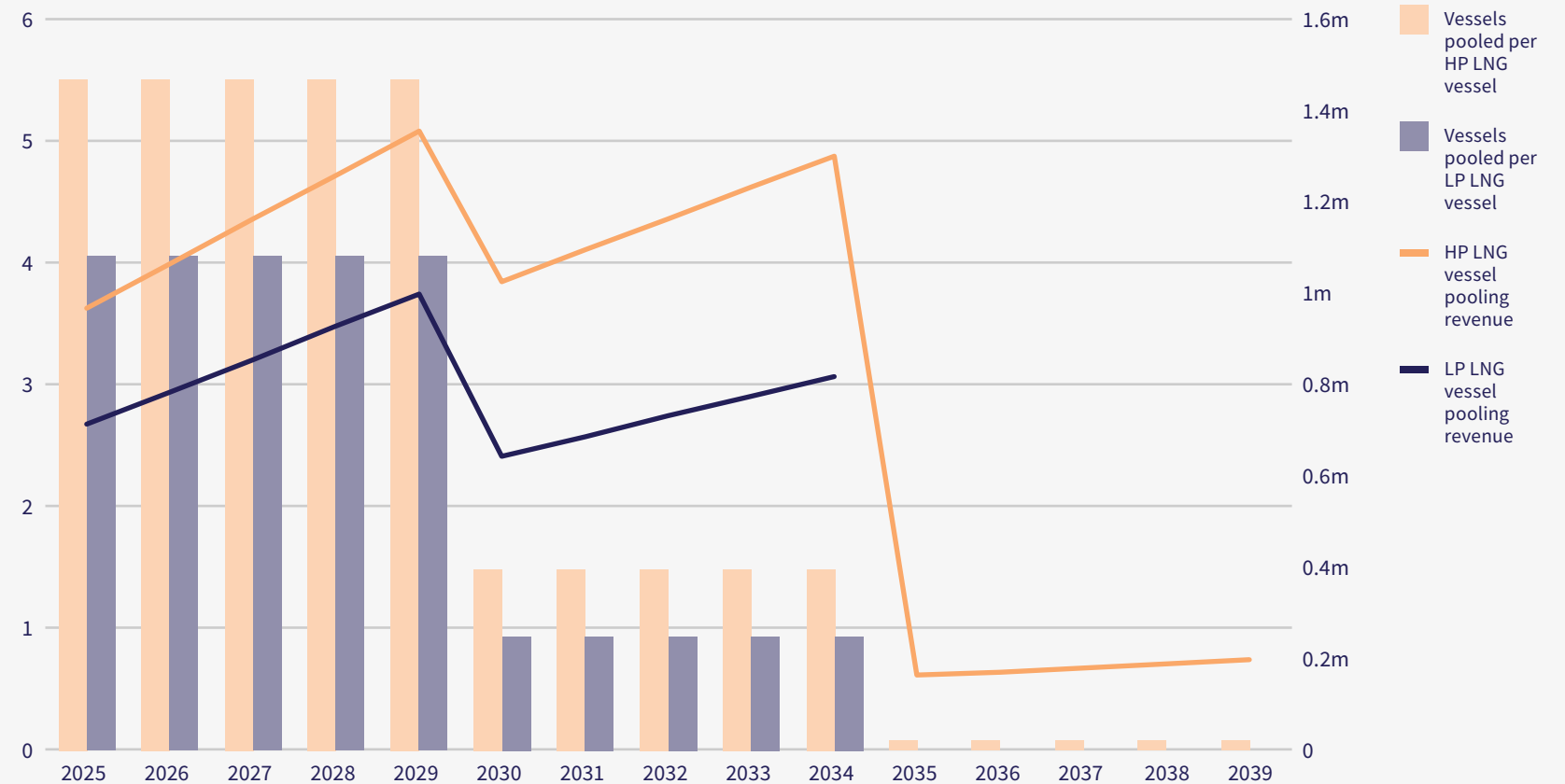
Those surpluses can also be used more effectively when they are achieved. The figures in this report show that the extra methane slip from low-pressure engines means that one vessel with a surplus can only cover the deficits of nearly two conventionally fuelled vessels, compared to nearly six for Aframaxes with high-pressure engines. By 2030, they cover only a fraction of another vessel's emissions. Subsequently, the revenue potential of selling surpluses falls substantially from US\$12.5 million to US\$2.4 million.

Under IMO's Net Zero Framework, higher methane slip would mean that low-pressure (or Otto-cycle) two-stroke engines cross the GHG Fuel Intensity thresholds for Tier 1 and Tier 2 remedial units earlier than low-methane high-pressure engines, and receive higher penalties in each tier due to the greater excess GHG intensity. Over the years 2028 to 2050, this translates to around a further US\$13.5 million penalty for low-pressure engines.

When it comes to total European and IMO penalties, the difference between an engine with methane slip of 1.7% and one with 0.2% or 0.15% (depending on the regulatory accounting regime), could stand in excess of US\$55 million. This fact highlights once more the need for continued focus in reducing methane slip, particularly for low-pressure engines.

It should be noted here that neither the 1.7% default methane slip factor used in EU regulations for low-pressure/Otto-cycle two-stroke dual-fuel engines, nor the 3.2% default for four-stroke low-pressure engines, are representative of state-of-the-art engines. OEMs report significant advances, with reductions of well over 50% compared to current default factors, and mechanisms have been developed for the use of actual methane slip values as opposed to default factors. This is detailed further in Section 3 on technology and in the first part of this section, on regulatory drivers.

Figure 24: FuelEU Maritime pooling and offsetting revenue, Aframax, HP vs LP LNG



Transitional alternative fuel pathways

The modelling above shows the significant compliance cost impact of using VLSFO or conventional LNG. However there are many more options to consider.

Methanol and ammonia are both candidate fuels for deep sea shipping and, as with LNG, investments are being made in the production of lower-emission fuel variants.

For all three fuels, there are potentially viable pathways emerging to achieve near-zero emissions. To illustrate the potential cost impact of these alternatives, the two vessel cases above have been modelled for all three fuels.

For each ship type, fuel pathways from 2025 to 2050 have been considered, with the aim of minimising FuelEU Maritime exposure. The timing of the introduction of fuels is based on expected availability and the stepped reductions in GHG intensity required by FuelEU Maritime.

LNG pathway

The LNG-fuelled vessels use conventional LNG only (with MDO as pilot fuel) until 2030, when 5% of bio-LNG is added to the energy mix. A further 5% is added each year. From 2039, e-LNG enters the mix with a 5% blend, increasing each year. By 2043, the vessel runs on a blend of 65% bio-LNG and 35% e-LNG, with the blend reaching 30% and 60% respectively by 2050.

Figure 25: Fuel evolution and total costs, LNG pathway, Ultra Large Container Ship (ULCS)

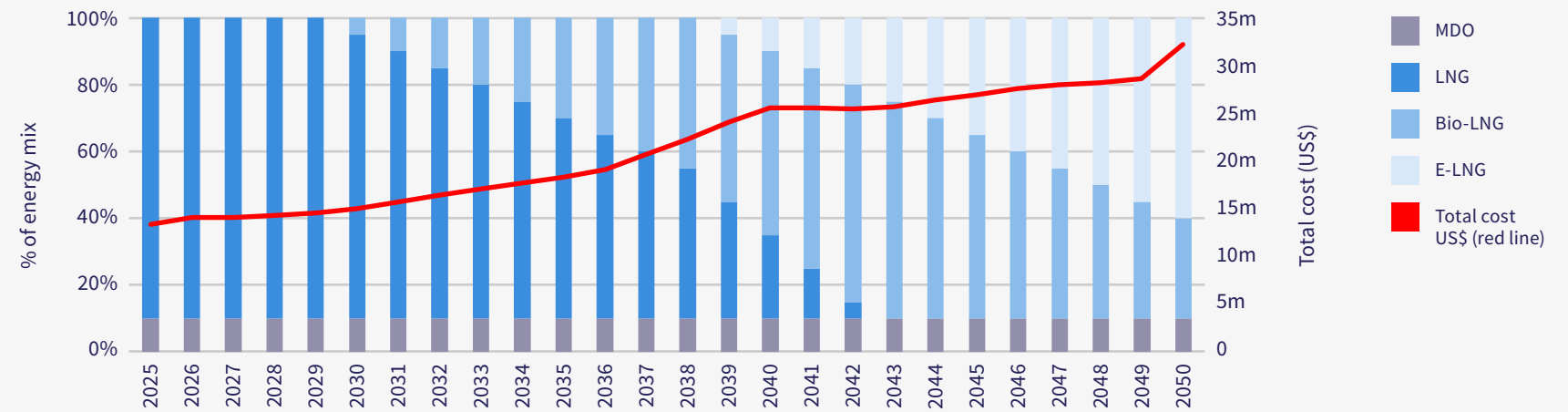
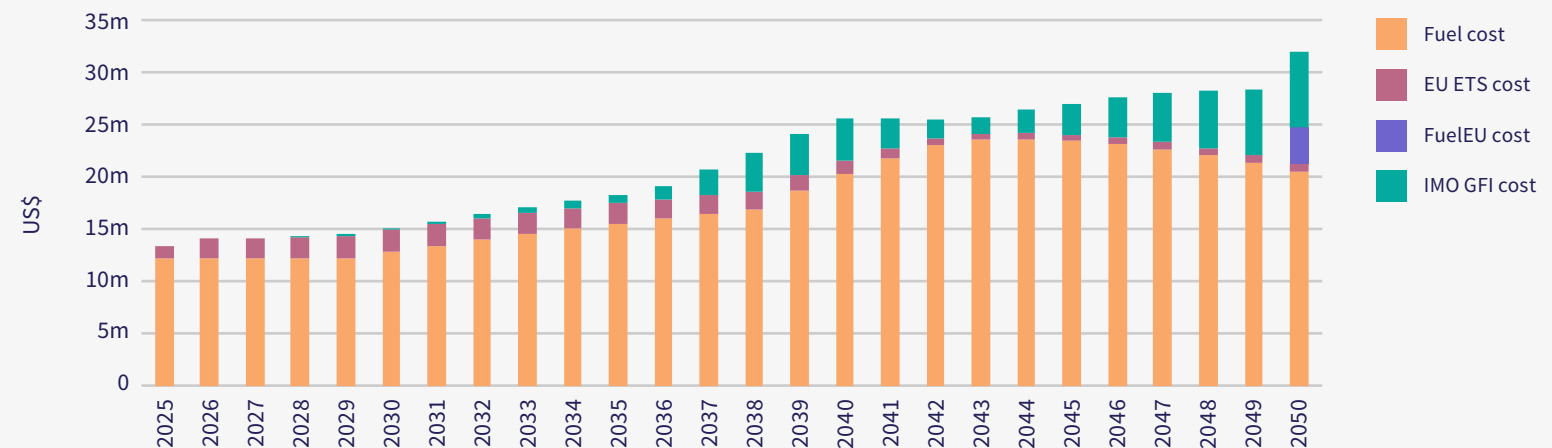


Figure 26: ULCS, LNG transition, annual costs, 2025-2050



Methanol pathway

The methanol-fuelled vessels begin sailing in 2025 on mainly VLSFO (80%), with a 10% blend of bio-methanol. The proportion of bio-methanol is increased gradually, to 80% by 2032. VLSFO is removed and e-methanol added from 2033. Bio-methanol use is then phased out, with the vessel running entirely on e-methanol (excluding MDO pilot fuel) from 2048.

Figure 27: Fuel evolution and total costs, methanol pathway, Aframax

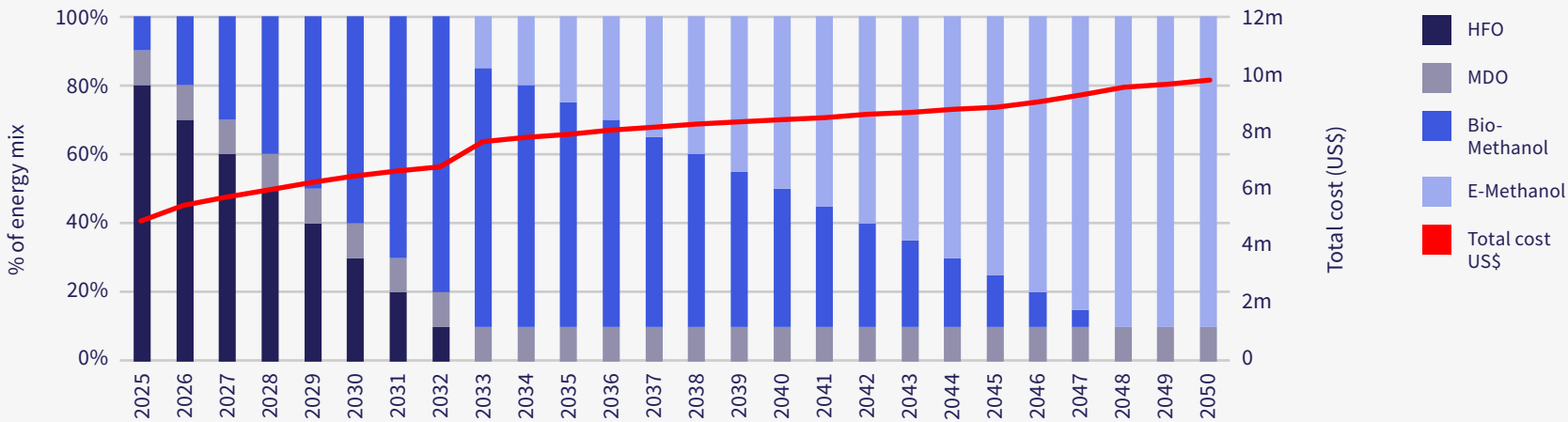
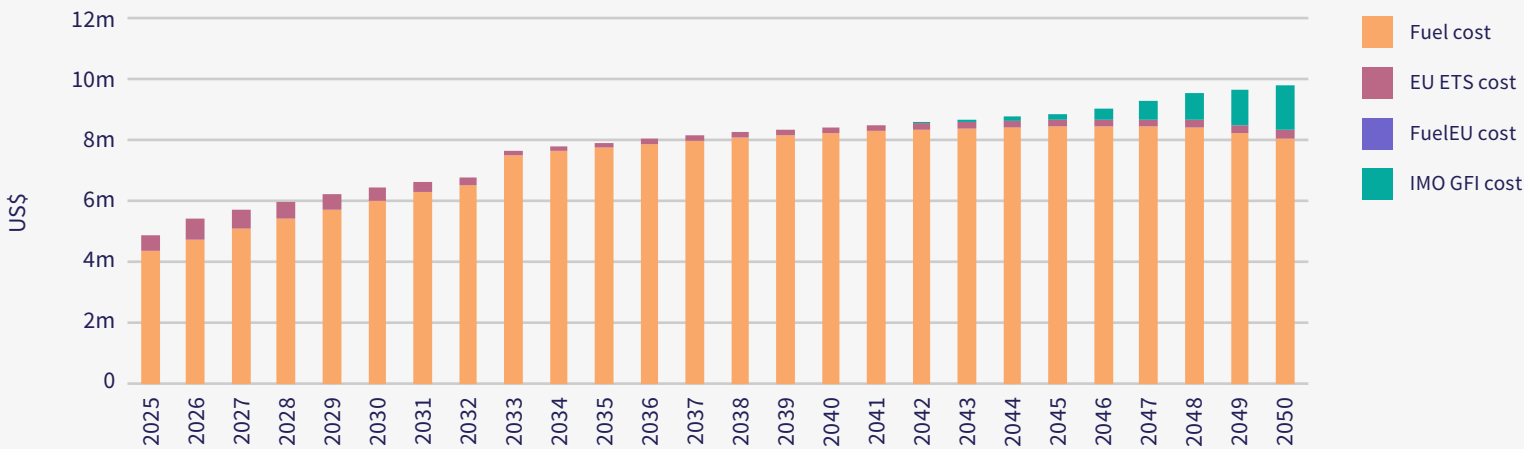


Figure 28: Aframax, methanol transition, annual costs, 2025-2050



Ammonia pathway

The ammonia-fuelled vessels begin sailing with VLSFO and 10% blue ammonia, made using non-renewable resources with carbon dioxide captured during the production process. As with the methanol pathway the transition to e-fuels begins in 2033, by which time VLSFO use has been phased out. By 2048 the vessels run entirely on e-ammonia (excluding MDO pilot fuel).

Figure 29: Fuel evolution and total costs, ammonia pathway, ULCS

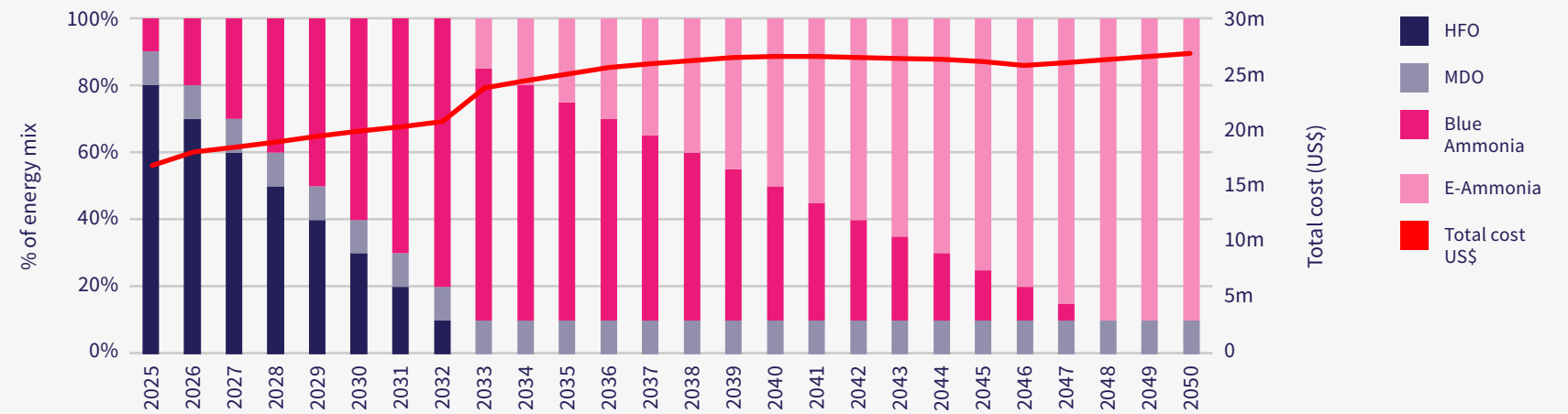
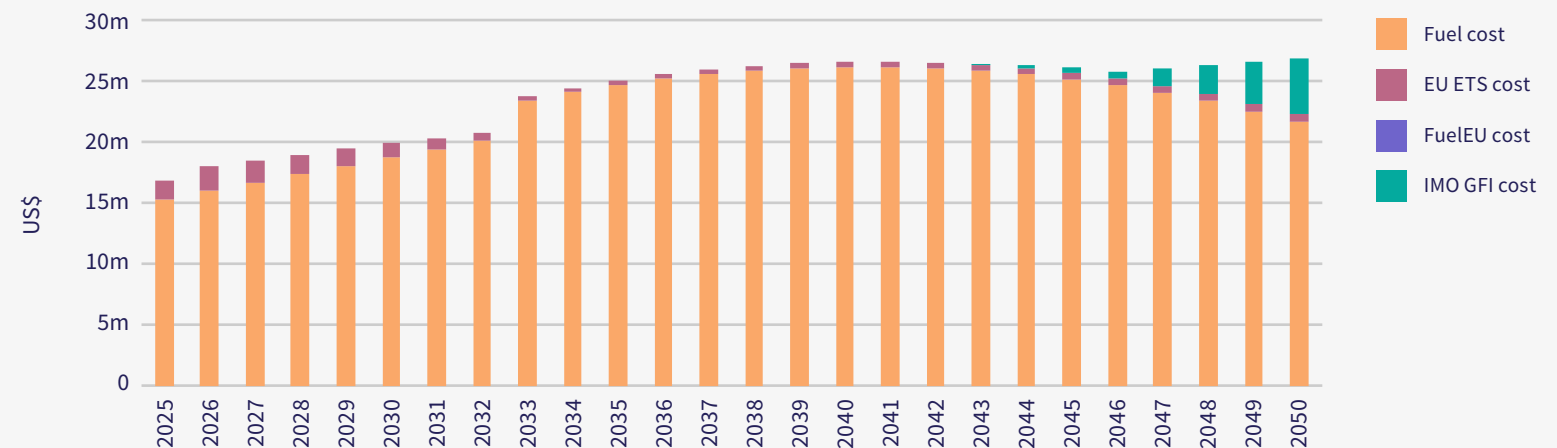


Figure 30: ULCS, ammonia transition, annual costs, 2025-2050



Comparison

Comparing total costs for all three pathways reveals that, under the assumptions above and in Annex I, LNG is the most cost-effective option for running a FuelEU Maritime-compliant vessel. Ammonia costs reach parity with those of LNG by around 2044, while the methanol option remains more expensive.

In 2050 there is an uptick in LNG costs – making it more expensive than the ammonia option but still below the costs for methanol – as vessels using LNG of any form will exceed the FuelEU Maritime GHG intensity target for that year. However, considered across the whole period 2025-2050, LNG remains the least expensive option; around 10% cheaper than ammonia and around 30% cheaper than methanol.

From the modelling above, it is evident that the methane transitional pathway is the most exposed to penalties under the IMO Net Zero Framework, with related costs starting in the second year of the regime. For both ammonia and methanol pathways, IMO penalties only begin at least ten years later.

It can thus be inferred that any postponement in the IMO Net Zero Framework will extend the business case in favour of the methane pathway--a fact that can already be seen in newbuild ordering trends since the vote on the Net Zero Framework's adoption was postponed.

Figure 31: Aframax, fuel transition pathways, total annual cost, 2025-2050

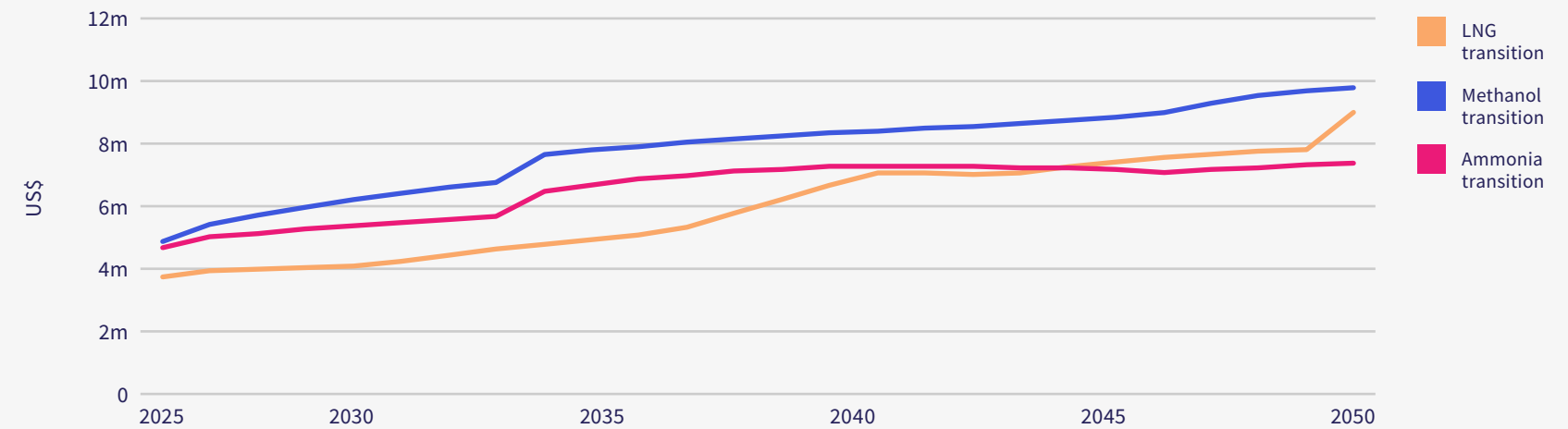
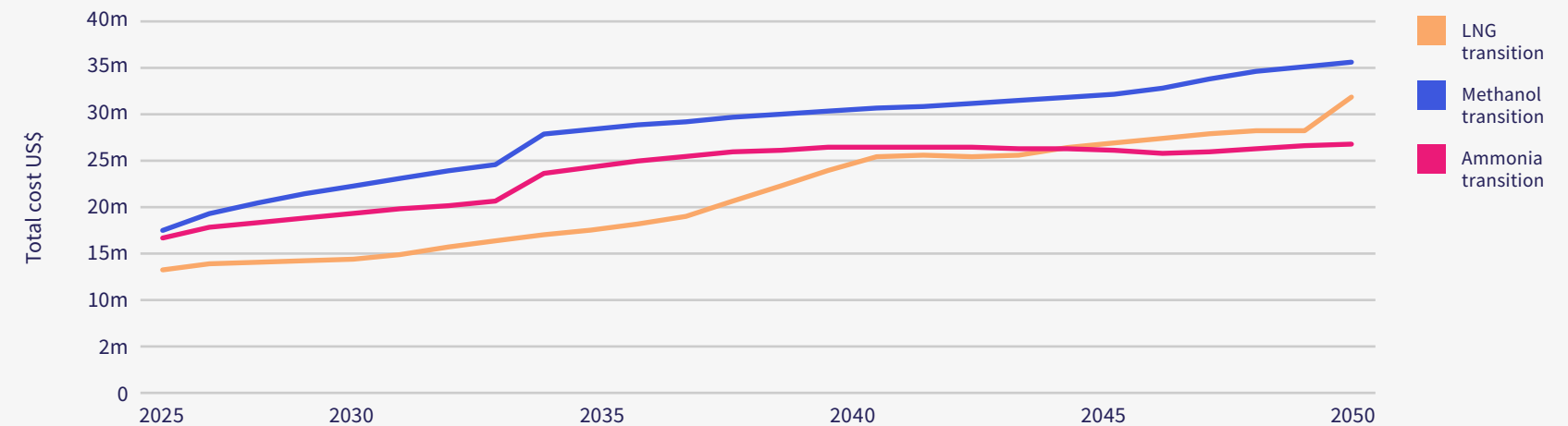


Figure 32: ULCS, fuel transition pathways, total annual cost, 2025-2050



Observations

Based on the scenarios modelled above, the immediate economic advantages of LNG are clear. A vessel fuelled with today's conventional LNG would have significantly lower cost exposure to European and IMO emissions legislation compared to a conventionally fuelled vessel, along with the opportunity to benefit from FuelEU Maritime pooling revenues, offsetting the penalties associated with several VLSFO-fuelled vessels.

However, using LNG that is not produced sustainably will still result in significant emissions that are not in line with IMO's 2050 targets or, from the late 2030s, FuelEU Maritime's GHG intensity reduction requirements. A transition to bio- and e-LNG must be considered to meet these targets, and this transition needs to be compared against other low-carbon fuel alternatives.

The analysis above shows that, for foreseeable fuel transition pathways, LNG remains the most cost-effective choice up to 2049. However, while the LNG pathway enables owners to minimise cost, even synthetic methane still delivers higher emissions than either green methanol or ammonia. For owners targeting deeper decarbonisation irrespective of the regulatory regime, these options – based on current emissions factors – would be more appropriate.

The issue of methane emissions – a factor not just for conventional LNG but also for bio- and e fuel variants – will continue to have a bearing on compliance costs and on overall emissions reduction. Regardless of the economic benefits of adopting LNG, there is an urgent ongoing need to address both upstream and downstream methane emissions, whichever colour of LNG operators choose.



Image courtesy of AET

Chapter 3:

Production and supply

LNG is in plentiful and growing supply, as is the global bunkering capacity to enable its use as a maritime fuel. But the non-fossil variants that will enable far greater emissions reductions will need to be scaled up – and certification challenges addressed – if they are to supplement and ultimately replace their fossil counterpart.

LNG production

Worldwide production of natural gas reached 4,059 billion cubic meters (bcm) in 2023, with consumption at 4,010 bcm⁵. Of this, 936.9 billion bcm was exported, with 58.6% of that (549.2 bcm) transported as LNG. While the international gas trade fell 2.7% to 936 bcm in 2023, LNG exports rose 1.8%.

In 2023, the US overtook both Australia and Qatar to become the world’s largest exporter of LNG. Collectively they represented 64% of total LNG exports. China overtook Japan to become the largest importer of LNG, with one-third of its imports coming from Australia. Collectively, the Asia Pacific region accounted for 64% of all LNG imports. Europe increased its imports from the US by 6% whilst its LNG imports from Russia remained relatively stable at around 19 bcm.

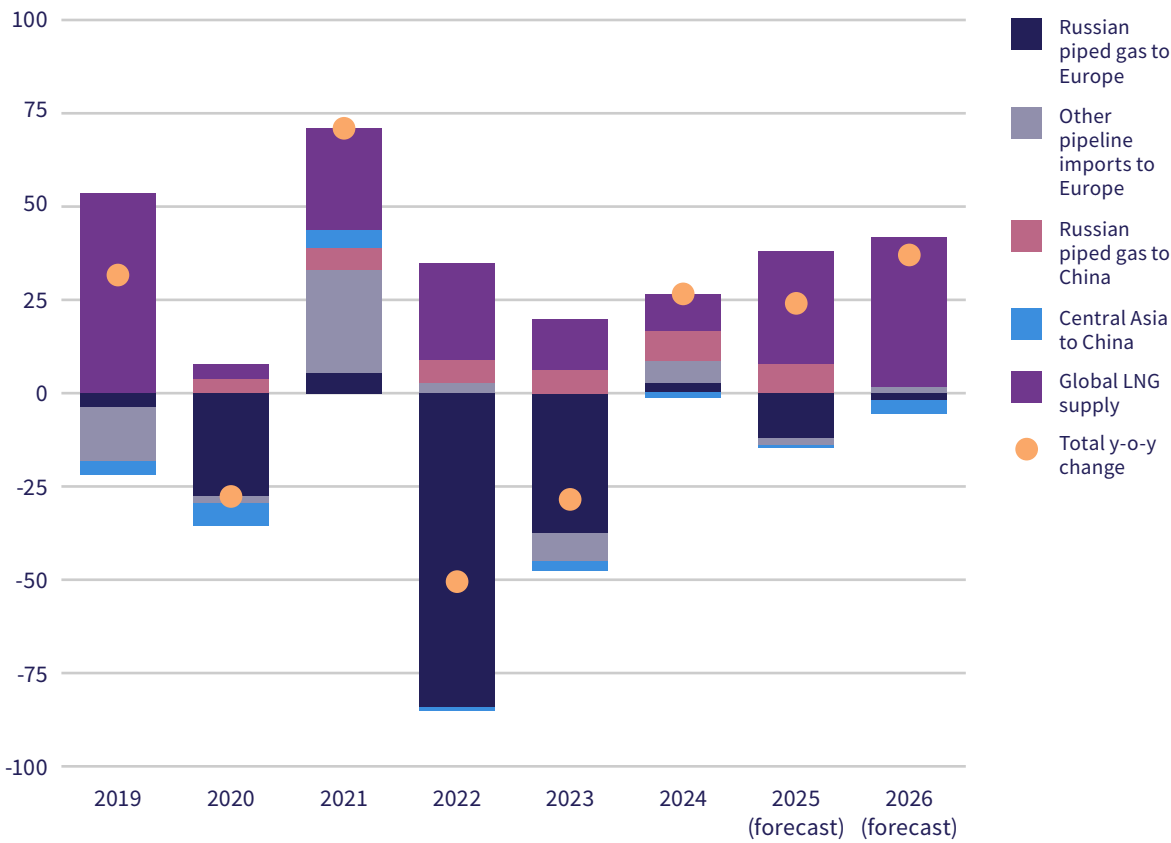
According to the International Energy Agency’s quarterly Gas Market Report for Q3 2024, global LNG supply grew by 2%, or around 6 bcm, in the first half of the year. However, in Q2 LNG output suffered its first year-on-year decline since 2020, when Covid-induced lockdowns drastically reduced LNG demand and led to widespread cargo cancellations. In the second quarter of 2024, the decline in LNG production was largely driven by a combination of feed gas supply issues and unexpected outages.

Year-on-year growth in LNG supply was expected to accelerate during the second half of 2024, with new liquefaction capacity coming online. The US provided the lion’s share of new export capacity in 2024 as existing plants expanded and new plants began operating. This includes the expansion of Freeport LNG, the ramp-up of Plaquemines LNG Phase 1, and the expected start-up of Corpus Christi Stage 3. The Tortue FLNG plant off the coast of West Africa was also due to come online in the fourth quarter.

However, despite the blip in Q2 2024, long-term supply growth of fossil LNG seems assured as the result of new natural gas projects coming online. Starting in late 2024, the global LNG market will witness its fastest ever capacity growth, representing a 40% increase in the coming five years⁶. The industry is on track to add almost five times as much new liquefaction capacity from 2025 through 2028 compared to the previous four-year period.

The bulk of new LNG capacity to be completed by 2028 will be concentrated in the US and Qatar. Substantial additional capacity is also under construction in Russia, Canada, and African nations.

Figure 33: Year-on-year changes in key piped natural gas trade and global LNG supply, 2019-2025⁷



Source: International Energy Agency



Reducing methane leakage from LNG production

The natural gas sector is responsible for around 11% of global methane emissions, with LNG itself representing around 4%. As methane is a potent greenhouse gas, any emissions prevented during the lifecycle of LNG will have significant impact on Well-to-Tank (WtT) emissions. As methane has a bigger climate impact over the short term rather than long term – with a global warming potential 84 times that of carbon dioxide over a 20-year period – there is reason for urgency in reducing unnecessary methane emissions.

In the default factors to be used in FuelEU Maritime calculations, for example, fossil LNG is listed as having WtT emissions of 18.5 g CO₂eq/MJ. This is more than a third higher than the conventional oil fuels used by shipping.

Energy production is the primary focus of methane emissions reductions targeted by global initiatives including the [Global Methane Pledge](#). There are several reasons cited for this:

- Methane is the primary constituent of natural gas and LNG;
- Under certain assumptions, some methane mitigation measures pay for themselves;

- Oil and gas supply chains are mostly managed by large industrial organisations that are technically sophisticated and well capitalised. Thus, they are well equipped to deal with their methane emissions;
- Emissions from the oil and gas industry are easier to control than those from natural sources, agriculture and biomass burning⁸.
- Under certain assumptions, some methane mitigation measures pay for themselves;

Partly for these reasons, many natural gas producers have committed to reduce upstream methane intensity. According to the [Oil and Gas Climate Initiative \(OGCI\)](#) industry group, its members have reduced upstream methane intensity from their -operated oil and gas assets by an average of 17% in 2022, a decrease of 50% compared with a 2017 baseline.

While less than 1% of LNG methane emissions are currently attributable to shipping, well-to-tank methane emissions fall within the industry's sphere of influence. Shipping companies should understand the total GHG emissions impact of the LNG they consume and procure fuel with minimal, transparent, and verifiable emissions.

The Methane Abatement in Maritime Innovation Initiative (MAMII)

The [Methane Abatement in Maritime Innovation Initiative \(MAMII\)](#) is a coalition of shipping and fuel stakeholders – led by the Safetytech Accelerator. It is united in identifying, accelerating, and advocating technology solutions to measure and abate methane emissions including LNG carriers and LNG-fuelled vessels. In its debut report issued in 2024, MAMII examined the conventional LNG value chain of wells, pipelines, processing, liquefaction, transport, and storage⁹.

The report noted that 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. Technologies such as satellite surveillance and advanced sensors are available to practically trace methane escaping from installations, while the implementation of effective piping and compression arrangements can significantly minimise methane leaks.

Given societal pressure, producers' own climate ambitions and the basic common sense of reducing losses of a valuable commodity, methane emission-proof upstream facilities will become increasingly common. Shipowners should consider LNG producers that successfully apply these measures and technologies. Several certification schemes are currently working with natural gas producers to obtain greater visibility of methane emissions performance. These 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 7 Oil and Gas Climate Initiative, 2023: Methane emissions
- The International Group of Liquefied Natural Gas Importers (GIIGNL) framework: Delivering verified statements of greenhouse gas intensity and emissions within the LNG value chain



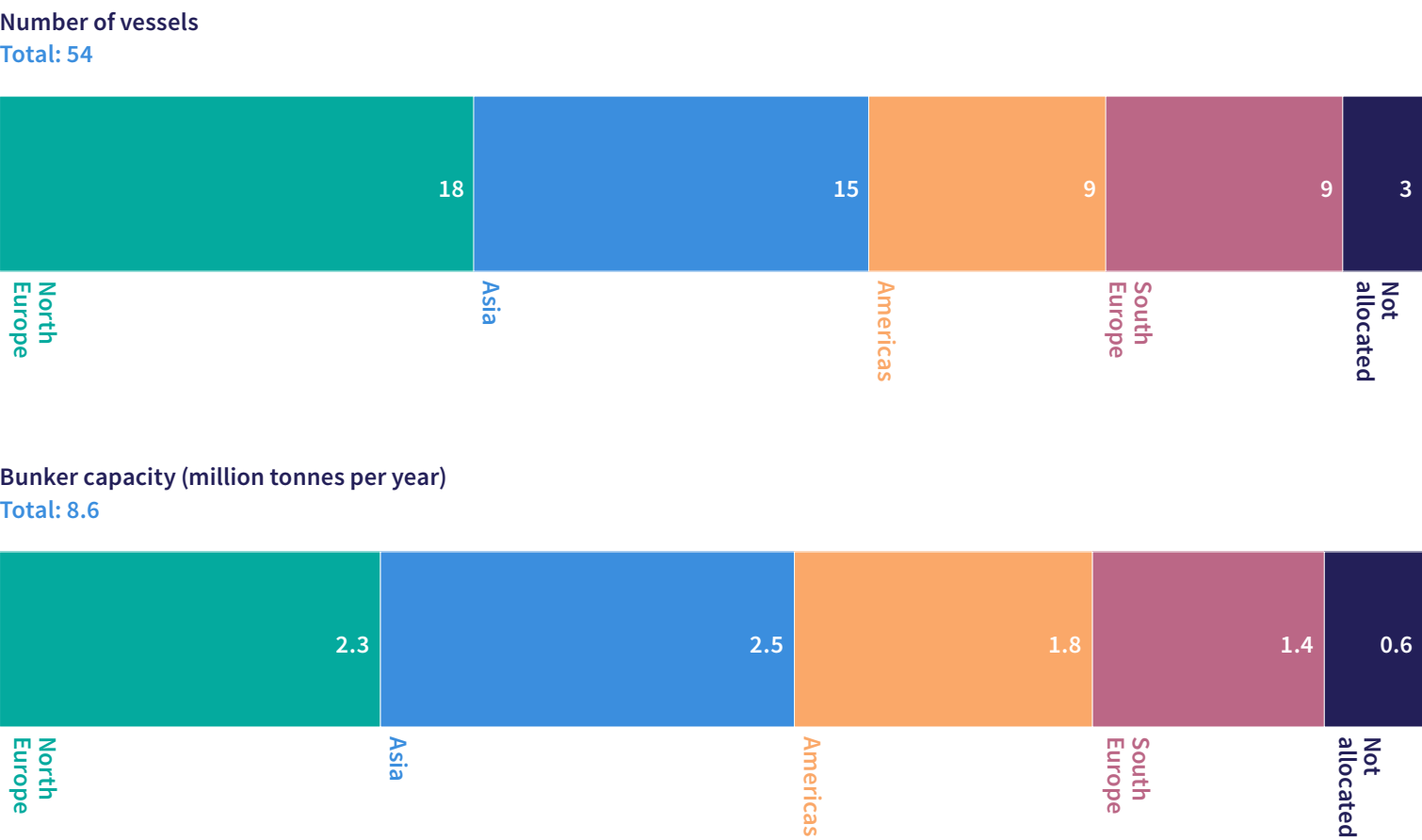
LNG marine fuel distribution network

In 2023, LNG bunkering hit a record high with 4.7 million cubic metres delivered globally, 62% more than in 2022¹⁰. Ship-to-ship deliveries doubled to 2.9 million cubic meters. According to SEA-LNG, the global bunkering network currently comprises around 190 port facilities (including those from which bunkering can be performed by truck), with a further 80 implementing plans or actively considering LNG bunkering.

The expansion of LNG bunkering availability at ports is being driven both by demand and by climate regulation. In the European Union, for example, Directive 2014/94/EC on the deployment of alternative fuels infrastructure requires the availability of LNG at EU core maritime ports – more than 100 locations – by 31 December 2025 and at core inland ports by 31 December 2030.

In addition, demand is served by a fleet of nearly 60 LNG bunkering vessels. As the number of LNG-fuelled vessels in service grows, the bunkering network will also need to grow. Forecasts indicate that there is room for further growth in the LNG bunker vessel market, with oil and gas major TotalEnergies projecting the need for additional bunker vessel capacity from 2025, with a further 35 vessels – of which more than 20 are already on order – needed to meet demand anticipated for 2030.

Figure 34: Global LNG bunker vessel fleet as of 2024



Source: TotalEnergies

3.2

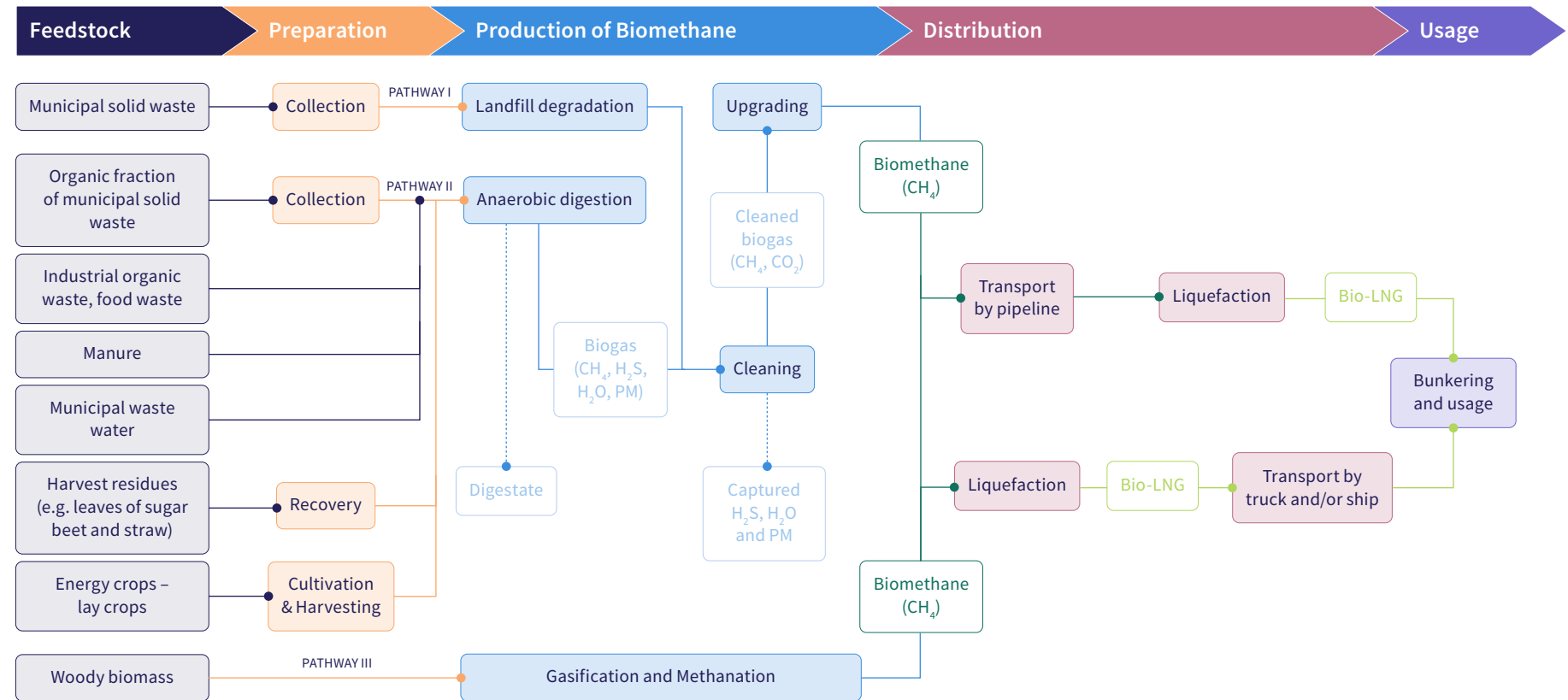
Biomethane production

Biomethane is a near-pure source of methane produced either by removing CO₂ and other contaminants from biogas (a mixture of methane, CO₂ and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment) or through the gasification of solid biomass followed by methanation.

By using non-fossil carbon as a source, biomethane can deliver significant reductions in greenhouse gas emissions, even potentially generating negative emissions if it can eliminate emissions from other associated processes. Overall emission reductions can differ significantly depending on the feedstock and production process.

Methane leakage from production and supply remains a consideration for biomethane, while tank-to-wake emissions – including methane – are the same as for fossil LNG. This means that progress in reducing methane emissions across the fuel lifecycle being made with fossil LNG today will remain essential even when biomethane is used.

Figure 35: Biomethane production pathways



Source: Nanyang Technological University¹¹



Certifying emission reductions from biomethane

Because emissions reductions can vary so widely for biomethane, understanding the source of supply is essential when accounting for greenhouse gas impact. Hence the European Renewable Energy Directive II, enacted in 2018, promoted the extension of ‘guarantees of origin’ from renewable electricity to renewable gas. The aims were to provide a consistent means of proving to final customers the origin of renewable gas including biomethane, and to facilitate greater cross-border trade¹².

As a part of these efforts, the EU Database of Biofuels was launched in January 2024. Its extension to biogas and biomethane is imminent. As this report is published, an extremely timely development for ship operators considering biomethane ahead of FuelEU Maritime requirements taking effect from 2025. The database aims to ensure proper accounting of renewable energy as well as avoiding double incentives resulting from support schemes in different Member States.

However, certifying biomethane holds some challenges, as evidenced by the response to European efforts from the US Department of Commerce’s International Trade Administration. In market analysis dated 17 October 2024¹³, the administration noted:

“As currently constructed, the [database] will only provide sustainable certifications for biogases produced within the EU natural gas grid. The European Commission has noted the intention to exclude the certification of biogases produced in third countries as they claim non-EU gas grid systems are not mass balanced and therefore do not provide sufficient chain of custody guarantees. The EU is taking this approach due to concerns about traceability and double counting from third-country markets.”

Once the database is extended to biogas, “all non-EU biogas suppliers will no longer receive sustainable certifications within the EU. Prior to the UDB (Union Database for Biofuels) implementation, biogas supplies from third countries were able to be certified as sustainable/renewable in the EU. US biogas producers are concerned [that the database] will remove incentives for EU customers to buy higher-priced renewable biogas from the US as it will not count towards RED II renewable targets.”

The concern, which was flagged earlier in 2024 by SEA-LNG¹⁴, is that the EU’s certification rules will obstruct a global approach to ensuring fuel supply chain sustainability. Conversely a harmonised approach that allows mass balancing from all grids and enables book-and-claim buying of sustainable fuels will be essential to securing an adequate biomethane supply for shipping.

Biomethane availability and supply

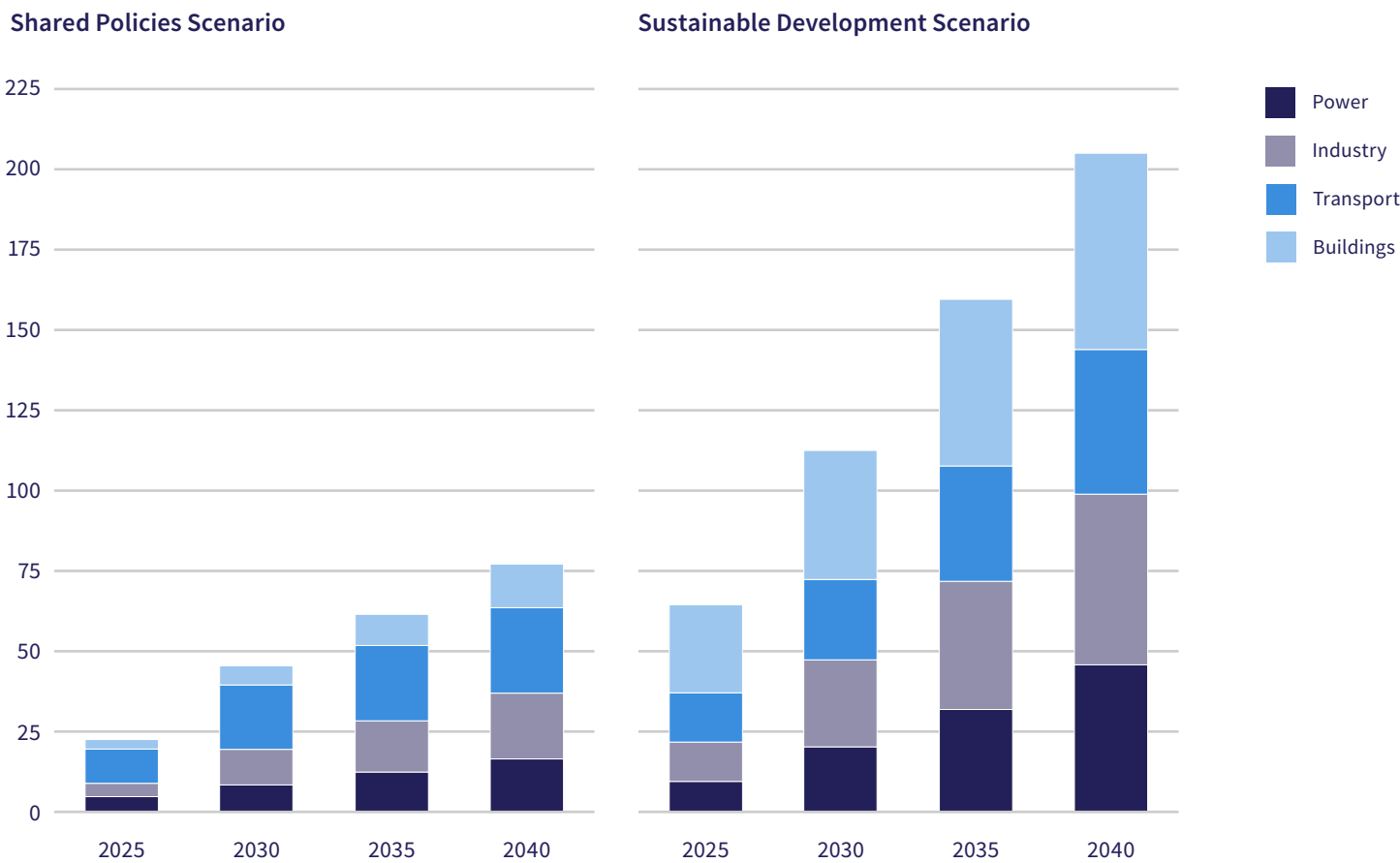
According to gas industry analyst CEDIGAZ¹⁵, global biomethane production reached 7.7 bcm (or 445 TWh) in 2022, representing annual growth of 20%. Production is estimated at 9.5 bcm in 2023, up a further 23%. Demand from the transport sector, which accounts for 45% of biomethane use worldwide, represented 57% of total growth in 2022, with CEDIGAZ noting emerging demand in marine transportation.

Under IEA’s Net Zero Scenario – in which the infrastructure to produce and supply enough renewable electricity and fuel to achieve net-zero emissions globally by 2050 – a growth rate of 32% is needed between 2023 and 2028 to meet demand to 2050. Based on targets announced by regional and national governments around the world, CEDIGAZ expects production to reach 117 bcm a year by 2030. That would mean compound annual growth of 40% for the decade, more than matching IEA’s Net Zero Scenario.

The EU’s REPowerEU Plan is an example of the ambitious targets being set by governments, with the region targeting annual production of 35 bcm by 2030. The US Inflation Reduction Act and other national legislation around the world, including incentives to contribute biomethane to national gas grids, are further driving investment in biomethane production.

In a 2022 study commissioned by SEA-LNG¹⁶, researchers at Nanyang Technological University found that, if 80% of the biomethane available for transport is used for shipping, biomethane could cover up to 3.1% of shipping’s total energy demand by 2030 and up to 12.6% by 2050. If used as a drop-in fuel at a 20% blending ratio, it could cover up to 15.7% and 62.9% of shipping’s energy demand in 2030 and 2050 respectively.

Figure 36: Biomethane consumption by sector and scenario, 2025-2040¹⁷



Source: International Energy Agency

Biomethane pricing

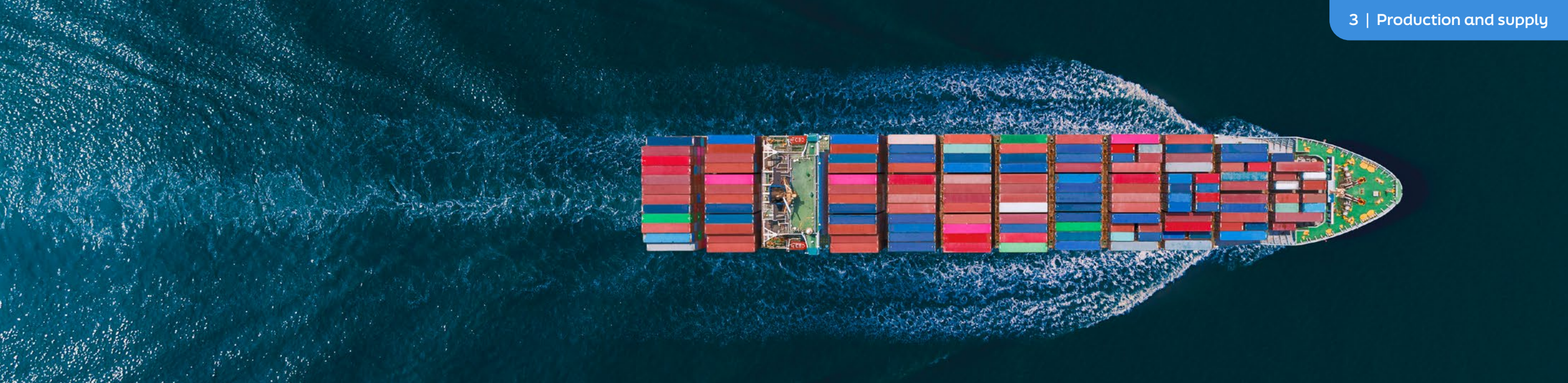
While biomethane production costs are usually higher than for natural gas, it is not subject to the price volatility that natural gas and fossil LNG suffers from. The cost varies depending on the feedstock, production scale and operating costs. The International Energy Agency estimates European production costs at €55-90/MWh, equating to around €834-€1,364/tonne¹⁸.

Nanyang Technological University (NTU) puts the 2020 bunker cost of biomethane at between US\$18-38/GJ, or US\$982-2,073/tonne¹⁹. However, biomethane production and liquefaction costs – which make up the bulk of the product cost, with the rest attributed to transport and bunkering and port fees – are likely to decrease as technology matures and scales.

The authors note that for biomethane from manure and agricultural residues produced in Asian regions and delivered to major eastern ports, cost could reach US\$20/GJ (US\$1,091/tonne) by 2030 and US\$15/GJ (US\$818) by 2050. That represents more than a 60% price reduction compared to today's costs, but also means it will likely be more expensive than fossil LNG in 2050.

The required carbon tax to make biomethane competitive with fossil gas today ranges from US\$260-440 per tonne of CO₂, according to the NTU paper. By 2050 the tax needed would reach US\$160-280, “substantially above the highest carbon tax currently active in the world”. Negative emissions biomethane, for example that produced from waste such as manure which emits methane, would require a tax of US\$120-220 in 2030 and US\$100-160 in 2050. This could make biomethane competitive with fossil LNG.





Bio-methane readiness

According to SEA-LNG's latest annual report, liquefied biomethane is already commercially available as a bunker fuel in 70 ports worldwide. And in key ports, multiple suppliers are already operating; by July 2024, for example, the GATE terminal in Rotterdam already boasted four suppliers, with German energy company Uniper the latest to start liquefied biomethane at the bunkering hub.

The industry is also building experience of the commercial and certification frameworks needed for using bio-LNG. Mass balance methodology is one such framework, allowing stakeholders to trace the sustainability of fuel moving along the value chain.

In October 2024, the Rotterdam-Singapore Green and Digital Shipping Corridor project conducted a successful pilot for the bunkering of mass-balanced liquefied bio-methane, with total of 100 tonnes of the fuel supplied by Shell to CMA CGM's liquefied natural gas-powered containership CMA CGM Tivoli. The test was also intended to provide experience of using mass balanced bio-methane so it is properly recognised under the EU Emissions Trading System and FuelEU Maritime.

According to IEA's Global Outlook for Biogas and Biomethane report published in May 2025, only 4% of potential feedstocks are currently used to make these fuels - suggesting considerable potential for future growth in available volumes. As the production of bio-methane increases, as certification schemes mature and as more ports offer bunkering, the industry's readiness for using bio-methane will grow further.

Chapter 4: Technologies

The engine, fuel supply and storage technologies associated with LNG as a marine fuel are mature and well understood. However, engines are being developed further to minimise methane slip and a range of new technologies are emerging to further abate and monitor methane slip from LNG engines.



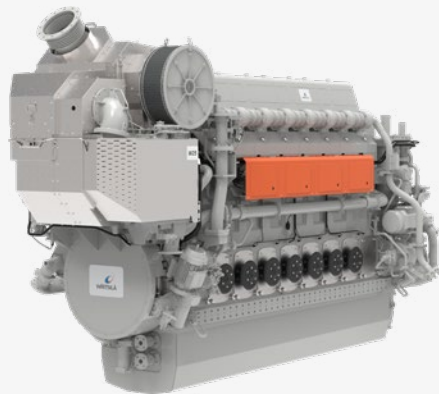
4.1

Engine technologies

Four types of engine technologies are used on ships with LNG as fuel:

Otto dual-fuel medium-speed, or low-pressure

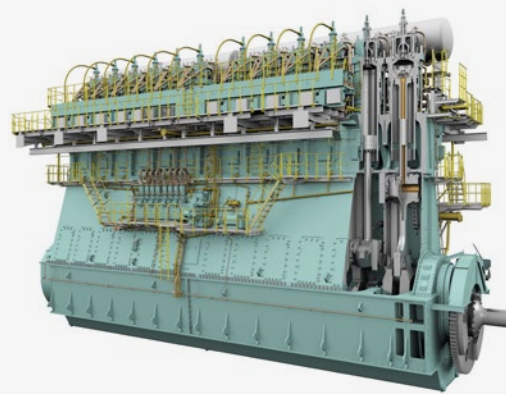
4-stroke (LP4S): The most widely used engine type amongst LNG-fuelled vessels, deployed as the prime mover on passenger vessels, offshore vessels, DFDE LNGC and smaller coastal or short-sea vessels, or as auxiliary engines on larger deep-sea vessels where main propulsion power is provided by two-stroke engines. Wärtsilä is the biggest supplier of these engines in the marine market, with a range of engines extending from 20- to 50-bore diameter.



Wartsila 25DF

Otto dual-fuel slow-speed, or low-pressure

2-stroke (LP2S): Two-stroke engines employing the Otto combustion cycle, where LNG under low pressure is pre-mixed with air during compression and ignited with pilot fuel. Commonly deployed on LNG carriers in particular, with wide references across other merchant sectors. WinGD is the biggest supplier in the marine market, with X-DF engines ranging from 52 to 92-bore.



WinGD 12X92DF

Diesel dual-fuel slow-speed, or high-pressure

2-stroke (HP2S): Two-stroke engines deploying the Diesel combustion cycle, where both LNG and pilot fuel is injected into the combustion chamber under high pressure. Commonly deployed across merchant deep-sea vessel segments, with some references on LNG carriers. Everllence is the biggest supplier in the marine market, with ME-GI engines ranging from 35- to 95-bore.



Everllence 8G95ME-GI

Lean-burn spark ignition (LBSI): Four-stroke engines using Otto cycle combustion where LNG admitted as gas under low pressure is ignited by spark plugs, without pilot fuel, when under pressure. Very limited references in the small passenger and offshore vessel segments. Bergen and MTU are among the suppliers to this niche in the maritime sector, with Wärtsilä also introducing a spark ignited variant of its 31 bore engine.



Wärtsilä 31SG

Drydocking with LNG fuel

Among the several operational considerations for using LNG as marine fuel, the impact on drydocking procedure is critical. Unlike conventional ships, LNG-fuelled vessels present unique challenges during drydocking due to the presence of cryogenic fuel and pressurized gas systems.

LNG is stored at extremely low temperatures (around -162°C), and even when the ship is not operating, residual LNG (known as a “gas heel”) may remain in the tanks. This creates risks such as flammability, cryogenic burns and pressure hazards.

The Society for Gas as a Marine Fuel (SGMF) has published detailed guidance for dry docking LNG-fuelled ships. They include the need for risk assessments before docking; fuel management protocols such as inerting tanks; the need for specialist personnel with LNG expertise; and requirements for shipyards to have the infrastructure and training to handle LNG safely.

Drydocking of LNG-fuelled vessels is governed by IMO’s SOLAS Convention, including the IGC and IGF Codes for gas transport and fuel use. Local harbour and environmental regulations may also restrict docking of vessels with LNG onboard.

Lloyd’s Register (LR) offers several resources and training opportunities related to LNG vessels and drydocking. As well as specific considerations in Technical Guidance and Rules covering LNG ships and barges, LR offers training courses covering drydocking planning, execution and safety—as well as featuring drydocking elements in its LNG ship operations, design and safety course.

Courses are available in person or virtually and are ideal for superintendents, fleet managers, and technical staff involved in the planning and execution of drydocking LNG-fuelled vessels.

Further information on LR rules governing LNG drydocking can be found at [Regs4ships](https://www.lloydregister.com/regs4ships). Information on LR’s training courses can be accessed via LR’s training portal on [LR.org](https://www.lloydregister.com/training).





Methane slip from LNG fuelled engines

LNG is uniquely treated under emissions accounting for regulations in that the type of engine used – rather than just the inherent fuel characteristics – determines tank-to-wake emissions. This is because, while CO₂ and N₂O factors are similar across engine types, methane emissions during combustion vary significantly.

The default values provided under the FuelEU Maritime regulation illustrate the significant differences in methane slip performance. See the comparison of LP2S and HP2S engines in the ‘Regulatory Drivers’ section for an example of how the difference in methane emissions factor affects costs associated with FuelEU Maritime and the EU ETS.

To support the developments in engine technologies, in April 2025 IMO adopted MEPC.402(83) which details the approval process for testbed or onboard measurements of CH₄ and/or N₂O. Following these guidelines enables the issuance of a Statement of Emission Values and which can be used to report the verified CH₄ emissions applicable to a particular engine that differs from the default values

The difference in methane slip across engine types is related to the injection and combustion concepts deployed. Methane slip occurs from engines as a result of two main factors²⁰:

Quenching: Methane cools down rapidly in the coldest parts of the combustion chamber and, as it requires a high temperature of >600°C to auto-ignite, remains unburned and escapes during exhaust scavenging²¹.

Hiding: When gas is added into the combustion chamber, parts of the fuel can be forced into crevices, such as the gasket area between the cylinder head and the cylinder liner. If the ignition flame cannot reach these areas and if heat is not high enough for auto-ignition, hidden methane remains unburned and escapes during exhaust scavenging

The likelihood of either of these factors is significantly lower for HP2S engines than for other engine types. This is because the gas is injected immediately after the pilot fuel and thus burned instantly, which reduces the opportunity for methane to cool or settle into crevices.

Across all engine types, there are further opportunities for methane slip under the right (or rather wrong) circumstances:

- If the exhaust valve is partly open during gas admission, a fraction of methane may flow directly to exhaust stack
- Natural gas composition, which affects energy content and methane number, together with ambient conditions can affect the optimal air-to-fuel ratio performance and emissions.
- During fluctuating load conditions (such as heavy weather) the turbocharger may fail to follow changing air demand which may alter the methane slip.
- Early or incomplete combustion may occur due to pre-ignition of lubrication oil or dripping fuel atomizers.

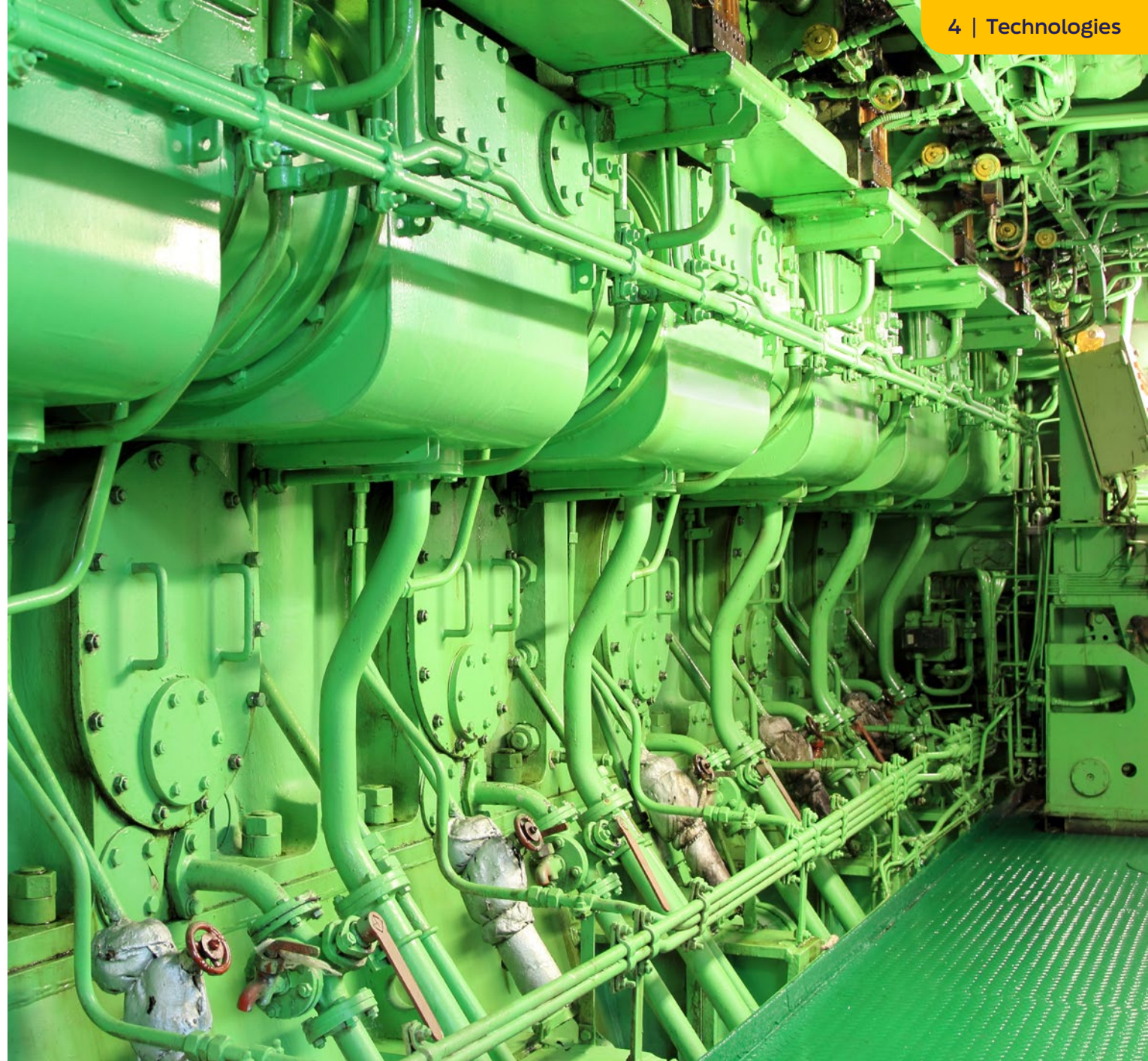
Reducing methane slip by engine measures

Engine manufacturers have made significant strides to reduce methane slip through core engine design over the years. Methane emissions from low-pressure four-stroke engines were cut by 75% over the 25 years to 2020²², with the latest engines promoting further reductions of up to 41% on those levels. Meanwhile, WinGD has recently communicated that its newest low-pressure two-stroke X-DF engines achieve methane levels ‘well below’ the FuelEU Maritime default value, at 0.8-1.0% of fuel mass compared to the default 1.7%²³.

Recognised engine technologies for reducing methane slip include engine component design to minimise crevices, as well as using engine tuning and control software to optimise the timing of valve opening, pilot fuel injection and combustion. Exhaust gas recirculation has also been shown to reduce methane slip by offering another chance to burn methane that would otherwise have been released to the atmosphere.

Further engine innovations are also emerging. One example is WinGD’s Variable Compression Ratio (VCR) technology²⁴, which dynamically optimises compression ratio depending on fuel type, engine load and ambient conditions. Because dual-fuel engines are designed for a relatively wide window of air-fuel mixes to reduce the risk of incomplete combustion or early ignition, dynamic optimisation of compression ratios means that this margin can be exploited at low loads to deliver more complete combustion.

Four-stroke engine manufacturers are also taking steps to improve the design of their LNG-fuelled engines to reduce methane slip. The HiMSEN DF engine produced by HD Hyundai Heavy Industries Engine & Machinery Division has been redesigned with internal abatement measures that include minimising crevices in the combustion chamber design and the use of control logic that includes multi pilot fuel injection and cylinder cut-off strategies. These measures target low-load performance in particular and aim to cut methane slip by around 80% at 25% load.



4.2

Onboard methane abatement technologies

For further methane slip reductions, a range of new onboard abatement technologies are also being investigated and developed. The Methane Abatement in Maritime Industry Initiative (MAMII) has explored several of these technologies. MAMII identified more than 90 companies with methane abatement technologies, of which 17 had the potential for maritime deployment. An indicative list of solutions proposed include Daphne Technology, Plenesys, Johnson Matthey, CDTi, SailPlan, and Rotoboost being shortlisted for imminent trials.

Methane reduction catalysts

Catalysts can be installed in the exhaust stream, before or after the turbocharger, to convert methane into less harmful molecules. Once installed, they are usually low maintenance and have a lifespan of several thousand hours.

There are various catalysts under development using different chemistries, resulting in a range of performance improvements both before and after the turbocharger. 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.

As an example, CDTi Advanced Materials offers a 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 is conducting a feasibility study for MSC Shipping and Capital Gas.

Plasma torches

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.

As an example, French technology provider Plenesys uses plasma torch systems with industrial-grade alternating current to split exhaust methane into constituent hydrogen and carbon elements, thus producing clean hydrogen reliably. Hydrogen can then be added to the vessel fuel mix to improve combustion where engines allow, improving fuel efficiency and further reducing methane slip.

Plenesys has been invited to perform a feasibility study with LNG carrier operator Seapeak, using methane slip from the exhaust stream more efficiently via conversion to hydrogen and integrating the resultant hydrogen it into a blended engine fuel.

Rule requirements for the design, construction and installation survey of methane emissions abatement plant are included in the LR class notation EACH4. Requirements associated with the new class notation address the safety risks that may present to the vessel, covering aspects such as materials, structure, containment, piping, refrigeration plant, electrical, control, safety systems, vessel integration and manufacturing. Requirements associated with READY descriptive note cover the preparation of a vessel for the future installation and integration of methane emissions abatement plant, such as structures, layout, interfacing, materials, electrical and safety systems. Further details are available on www.lr.org/rules

Combustion enhancement

Several innovative technologies, including that from Plenesys described above, aim to optimise combustion through the addition of hydrogen into the fuel mix. Producing hydrogen from the fuel and cargo resources onboard offers clear efficiencies, and has been applied using thermo-catalytic decomposition (TCD) of LNG.

Rotoboost's TCD technology enables onboard production of hydrogen fuel by leveraging the ship's existing LNG supply and minimal electrical input. 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.

Low-load methane slip improvements

As engines running at low load lead to a higher proportion of methane slip, operators can consider taking steps to reduce the use of LNG engines at low load.

Hybrid propulsion is one such solution, with shaft generators allowing energy storage such as batteries and fuel cells to be charged while engines run at a higher load than needed for propulsion. This stored energy can then be used for low-load operations instead of engines. Depending on the vessel configuration, for example, it may be possible to use hybrid power for port entry, docking and manoeuvring.

There are also operational measures that can be taken to reduce methane slip at low load. In some cases, for example, it may generate lower overall emissions to switch to VLSFO or MDO at low engine loads. The use of engine optimisation tools can also support operators in ensuring they minimise low-load engine running.



4.3

Methane detection technologies

The maritime industry generally has relatively few methane slip measurement installations. MAMII's investigation found several techniques to measure methane proven in the 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.



Satellites: The technology can detect and estimate the levels of methane emitted from certain sites, but greater resolution is needed for maritime use.

For measurement to be useful in proving emissions and targeting abatement, measurement must be continuous, not just the result of inspection. A variety of alternative approaches will be required until technologies are mature enough to provide reliable continuous measurement.

For certification measurements the default analyser technology for measuring methane (and total hydrocarbons) is the Flame Ionisation Device (FID) but that is not well suited for onboard installation. Accordingly, other analyser technologies are being investigated for suitability. The following technologies have already been deployed in maritime, for example to 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.

As an example of the evolution from land-based to onboard monitoring capability, Everimpact started as a real-time greenhouse gas monitoring platform for cities using satellites, sensors and AI. It has since partnered with Mitsubishi and Wilhelmsen to launch a sensor-based continuous emissions measurement system (CEMS) for ships, now implemented on a Mitsubishi vessel.



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.

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. In 2023, the company produced a feasibility study with MAMII anchor partners MOL and Shell. Following a successful collaboration, it is now engaged in several pilots with other anchor partners.

4.4

Onboard carbon capture



Onboard carbon capture and storage (OCCS) holds significant potential as one more alternative option for compliance. With a new framework being developed at the IMO and numerous breakthrough technology solutions under development, OCCS remains a key compliance prospect.

LNG appears to be a good fit for OCCS applications with more than 30% less CO₂ to handle than conventional fuel, as well as better compatibility and cryogenic synergies. This adds to the diverse LNG pathways and indemnifies LNG from the commercial risk OCCS poses to non-carbon and e-fuels.

However, while solutions are evolving at pace, establishing a value chain for carbon dioxide with collection and sequestration points around the globe will be key to the uptake of this technology.

LNG is not simply compatible with onboard CCS; LR estimates that it will deliver a 30-35% discount capture cost, as LNG emits less carbon than conventional fuel to that extent. It also burns cleaner, making it easier to handle in the capturing process, and is compatible with precombustion technologies cracking methane to hydrogen. These attributes make LNG the most optimal fuel for which onboard carbon capture can be applied.

The three main types of CO₂ capture systems for the maritime sector are post-combustion, pre-combustion, and oxyfuel combustion. Oxy-fuel and pre-combustion remove carbon from the fuel before use. These systems typically require complete engine redesign because they need to be integrated into a fuel supply and power generation system of a vessel. This can be costly and time-consuming, so may not be suitable for the shipping industry.

The post-combustion process, however, captures CO₂ from flue gas produced after combustion and can be added to traditional engine design without the need for large changes, making carbon capture

less costly and more attractive for ship owners. One example is Value Maritime's Filtree system, which has been fitted on Eastern Pacific Shipping's carriers *Pacific Cobalt* and *Pacific Gold*, making them the largest ocean-going vessels to be fitted with carbon capture technology.

In August 2024, LR assigned its first class notation for carbon capture onboard a ship to the *Pacific Cobalt*. The 50,000 dwt mid-range chemical carrier retrofit features a prefabricated carbon capture system supplied by Value Maritime to significantly reduce exhaust emissions.

The Emission Abatement Carbon Capture & Storage (EACCS) (Amine, HFO) class notation assigned by LR provides assurance that any safety risks associated with the OCCS installation have been mitigated and the solution is effective and reliable. Rule requirements for the design, construction and installation survey of OCCS are included in the LR class notation EACSS.

Requirements associated with the new class notation address the safety risks that may present to the vessel, covering aspects such as materials, structure, containment, piping, refrigeration plant, electrical, control, safety systems, vessel integration and manufacturing. Requirements associated with an associated READY descriptive note cover the preparation of a vessel for the future installation and integration of carbon capture, such as structures, layout, interfacing, materials, electrical and safety systems.

Today carbon capture technologies are developing at pace and it is highly likely that over the next decade there will be significant advances. Cost is likely to fall as more technology providers, infrastructure, storage solutions come online at major industrial hubs and ports around the world. Developing the market in captured carbon will also be essential and LR has undertaken foundational work on de-bunkering CO₂ from ships, cooperating with Global Centre for Maritime Decarbonisation.



Chapter 5 Conclusion

Progress and pragmatism

Newbuild orders and announcements across the global merchant fleet suggest that LNG as a marine fuel is increasingly attractive to ship owners. As is often the case in shipping, pragmatism is a key rationale.

As regulations emerge that place a real financial impact on greenhouse gas emissions, ship operators are realising that LNG is one of few low-carbon fuels to be available immediately, widely, with established safety protocols and at relatively predictable cost. The modelling in this report also illustrates how an LNG pathway that includes bio-LNG and e-LNG can be competitive against similar routes for ammonia and methanol. As a result, the LNG-fuelled fleet can expect growth: Clarkson Research predicts that the segment (excluding gas carriers) will grow to represent around 24% of the merchant fleet by 2050.

Meanwhile, the wider global demand for LNG continues to grow, while supply is increasing thanks to big new fields being activated in several regions, including Qatar and the US. The LNG carrier (LNGC) fleet is expanding to accommodate the growing trade and, for those vessels in particular, the ability to use their cargo as fuel, which is a fundamental for LNG cargo temperature and pressure control, also makes unquestionable economic sense.

There are several opportunities to improve the long-term sustainability of LNG. These are already being addressed and the measures that are being worked on – from cleaner production and supply processes through to onboard methane abatement technologies, as well as regulatory acceptance of these improvements – are likely to increase uptake of LNG even further.

In summary, LNG represents an immediately deployable, scalable, and well-established fuel alternative that aligns with both operational imperatives and emerging regulatory requirements. As global bunkering infrastructure continues to expand, renewable gas supply chains mature, and emissions control technologies become more widely adopted, LNG is expected to remain a central component of the maritime sector's transitional energy landscape. Rather than constituting a definitive endpoint in decarbonisation, LNG serves as a technically robust and adaptable platform that facilitates the progressive reduction of greenhouse gas emissions and supports the industry's evolution toward lower-carbon and ultimately carbon-neutral shipping over the coming decades.

Chapter 6

Other resources and annexes

Annex I: Techno-economic modelling assumptions

Fuel prices

The input fuel prices used in the model for the period 2025–2050 were derived from a combination of market data and in-depth research. For conventional fuels such as HFO, MDO, and grey LNG, six-month average prices were calculated based on actual bunker price data to provide a reliable baseline for these widely traded fuels.

For alternative low-carbon fuels, including Bio-LNG, E-LNG, Bio-methanol, E-methanol, green ammonia, and blue ammonia, the prices were determined through LR Advisory's extensive research and production cost assessments. These assessments incorporated data from multiple third-party reports and sources to ensure a robust and comprehensive evaluation. Key factors such as feedstock costs, production efficiencies, regional differences, and transportation dynamics were taken into account to provide credible price estimates for these emerging fuels.

Emissions factors

For HFO, MDO and Grey LNG the default emission factors as per ANNEX II of reg 2023/1805 (13 September 2023) were used. For Bio-LNG, the manure production pathway as per page 118 of reg 2023/1805 (13 September 2023) was used to derive the E factor for the WtT emission factor. For e-LNG the EU JEC (JRC-EUCAR-Concawe) tool, a collaboration

between the European Commission's Joint Research Centre, EUCAR and Concawe was used to derive the E factor. For Biomethanol the Waste wood production pathway was used as per page 90 of reg 2023/1805 (13 September 2023). For E-Methanol, green and blue ammonia, the US Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) tool was used to get the E factor.

IMO Net Zero Framework

The IMO's Net Zero Framework was postponed for a year at an extraordinary meeting of the Marine Environment Protection Committee in October 2025. The draft initially agreed at MEPC 83 in April 2025 provides base compliance and direct compliance targets from 2028 to 2035, as well as the pricing of remedial units.

For the years beyond 2035, the GHG fuel intensity reduction targets (base and direct) have yet to be decided, but are expected to follow a trajectory that meets IMO's ambition to reach net-zero emissions from international shipping by or around 2050. In the modelling in this document, LR has therefore used a reduction trajectory in line with that ambition.

The Net Zero Framework will also include a reward factor for the use of zero- or near-zero emissions fuels and energy sources. This mechanism

has yet to be detailed, but is likely to have a significant impact on the net cost of e-fuels. Readers should be aware that no reward for e-fuels has been factored into modelling provided in this report.

EU Allowance price

The EUA price was assumed to start at approximately 75 EUR/tCO₂eq and gradually increase to 200 EUR/tCO₂eq by 2050. This projected increase is driven by the planned reduction in the number of EUAs issued each year, aligning with the EU's decarbonization targets. As the supply of allowances becomes more constrained, their scarcity is expected to lead to higher prices, incentivizing emissions reductions and the adoption of low-carbon alternatives across industries.

FuelEU Maritime non-compliance multiplier

For the FuelEU Maritime regulation, the potential impact of the multiplier applied in cases of consecutive years of non-compliance has not been considered in the analysis. Additionally, the potential dollar value of FuelEU surpluses (arising from overperformance in meeting carbon intensity reduction targets) has also been excluded since multiple factors can change the financial benefit that owners or charterers can gain from these FuelEU surpluses.

Factors used for FuelEU

	HFO	MGO/MDO	LNG	Bio-LNG	E-LNG	Biomethanol	E-Methanol	E-Ammonia	Blue Ammonia
LCV (MJ/g)	0.041	0.043	0.049	0.049	0.049	0.020	0.020	0.019	0.019
Cf CO ₂ (CO ₂ /gFuel)	3.114	3.206	2.750	2.750	2.750	1.375	1.375	-	-
Cf CH ₄ (gCH ₄ /gFuel)	0.000	0.000	0.002	0.002	0.002	0.000	0.000	-	-
Cf N ₂ O (gN ₂ O/gFuel)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-
WtT (gCO ₂ /gFuel)	0.547	0.615	0.908	(1.670)	(2.406)	(1.108)	(1.276)	0.093	0.242
TtW (gCO ₂ /gFuel)	3.163	3.255	2.830	2.830	2.830	1.424	1.424	-	-
WtW (gCO ₂ /gFuel)	3.710	3.870	3.738	1.160	0.423	0.318	0.149	0.093	0.242
	3.710	3.671	3.083	0.957	0.349	0.647	0.302	0.203	0.527
CO ₂ eq WtT (gCO ₂ /MJ)	13.500	14.400	18.500	(34.008)	(49.008)	(55.595)	(64.095)	5.000	13.000
GHG emissions default value E				22.000	7.000	13.500	5.000	5.000	13.000
CO ₂ eq WtW (gCO ₂ /MJ)	91.601	90.632	76.129	23.621	8.621	15.967	7.467	5.000	13.000

Factors for IMO

Factors are based on the current IMO Lifecycle Analysis Guidance for marine fuels. For fuels that are absent from the current draft—including biomass- and synthetically derived variants of methanol and ammonia—factors used are the same as for FuelEU Maritime on the previous page.

	HFO - VLSFO	MGO/MDO	LNG (HP2S)	LNG (LP2S)	Bio-LNG (HP2S)	e-LNG (HP2S)
LCV (MJ/g)	0.040	0.043	0.048	0.048	0.048	0.048
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206	2.750	2.750	2.750	2.750
Cf CH ₄ (gCH ₄ /gFuel)	0.000	0.000	0.0015	0.017	0.0015	0.00015
Cf N ₂ O (gN ₂ O/gFuel)	0.000	0.000	0.000	0.000	0.000	0.000
WtT (gCO ₂ /gFuel)	0.567	0.756	0.888	0.888	-1.694	-2.414
TtW (gCO ₂ /gFuel)	3.163	3.255	3.208	3.208	2.817	2.817
WtW (gCO ₂ /gFuel)	3.730	4.011	4.096	4.096	1.123	0.403
CO ₂ eq WtT (gCO ₂ /MJ)	14.10	17.70	18.50	18.50	-35.29	-50.29
CO ₂ eq WtW (gCO ₂ /MJ)	92.78	93.93	85.33	85.33	23.40	8.40

Factors used for EU ETS

	HFO	MGO/MDO	LNG	Bio-LNG	E-LNG	Biomethanol	E-Methanol	E-Ammonia	Blue Ammonia
LCV (MJ/g)	0.041	0.043	0.049	0.049	0.049	0.020	0.020	0.019	0.019
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206	2.750	-	-	-	-	-	-
Cf CH ₄ (gCH ₄ /gFuel)	0.000	0.000	0.002	0.002	0.002	0.000	0.000	-	-
Cf N ₂ O (gN ₂ O/gFuel)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-
TtW (gCO ₂ /gFuel)	3.163	3.255	2.830	0.08	0.08	0.049	0.049	-	-

Assumed fuel prices (US\$/mt)

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
HFO	649	649	649	649	649	649	649	649	649	649	649	649	649
MGO	861	861	861	861	861	861	861	861	861	861	861	861	861
LNG	636	636	636	636	636	636	636	636	636	636	636	636	636
Bio-LNG	1,399	1,385	1,370	1,355	1,341	1,326	1,311	1,297	1,282	1,267	1,252	1,238	1,223
E-LNG	3,530	3,437	3,344	3,251	3,157	3,064	2,917	2,878	2,785	2,691	2,598	2,505	2,412
Bio-Methanol	636	628	620	611	603	595	587	579	571	562	554	546	538
E-Methanol	1,110	1,093	1,076	1,059	1,042	1,026	1,009	992	975	958	941	924	907
E-Ammonia	960	940	920	900	800	860	840	820	800	780	760	740	720
Blue Ammonia	438	438	439	440	440	441	441	442	442	442	443	443	444

	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
HFO	649	649	649	649	649	649	649	649	649	649	649	649	649
MGO	861	861	861	861	861	861	861	861	861	861	861	861	861
LNG	636	636	636	636	636	636	636	636	636	636	636	636	636
Bio-LNG	1,208	1,194	1,179	1,164	1,150	1,135	1,120	1,105	1,091	1,076	1,061	1,047	1,032
E-LNG	2,318	2,225	2,132	2,039	1,945	1,852	1,759	1,666	1,572	1,479	1,386	1,293	1,199
Bio-Methanol	530	522	513	5050	497	489	481	473	464	456	448	440	432
E-Methanol	890	873	857	840	823	806	789	772	755	738	721	704	687
E-Ammonia	700	680	660	640	620	600	580	560	540	520	500	480	460
Blue Ammonia	444	445	445	446	446	447	447	448	448	449	449	450	450

Carbon prices and regulatory targets

Carbon Price EU-ETS (USD/mt CO ₂) LR Estimate	86	89.44	93.738304	96.738304	100.6078362	104.6321496	108.8174356	113.170133	117.6969383	122.404816	127.301009	132.393049	137.688771
FuelEU GHG target (gCO ₂ e/ MJ)	89.3368	89.3368	89.3368	89.3368	89.3368	85.6904	85.6904	85.6904	85.6904	85.6904	77.9418	77.9418	77.9418
GHG intensity Reduction Factor (%)	0.02	0.02	0.02	0.02	0.02	0.06	0.06	0.06	0.06	0.06	0.145	0.145	0.145
Carbon tax Global (USD/mt CO ₂) LR Estimate	0	0	50	50	50	50	75	75	75	75	75	100	100

Carbon Price EU-ETS (USD/mt CO ₂) LR Estimate	143.196322	148.924174	154.881141	161.076387	167.519443	174.22022	181.189029	188.43659	195.974054	203.813016	211.965537	220.444158	229.261925
FuelEU GHG target (gCO ₂ e/ MJ)	77.9418	77.9418	62.9004	62.9004	62.9004	62.9004	62.9004	34.6402	34.6402	34.6402	34.6402	34.6402	18.232
GHG intensity Reduction Factor (%)	0.145	0.145	0.31	0.31	0.31	0.31	0.31	0.62	0.62	0.62	0.62	0.62	0.8
Carbon tax Global (USD/mt CO ₂) LR Estimate	100	100	100	125	125	125	125	125	150	150	150	150	150

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