SEA-LNG

SHIPPING INDUSTRY DECARBONISATION:
FUEL CHOICE AND THE COSTS OF ACHIEVING REGULATORY COMPLIANCE

INTRODUCTION

At the IMO (International Maritime Organization) in July 2023, the Marine Environment Protection Committee (MEPC 80) adopted a revised GHG (greenhouse gas) Strategy which aims to significantly curb GHG emissions from international shipping. The new targets include a 20% reduction in emissions by 2030, a 70% reduction by 2040 (compared to 2008 levels), and the ultimate goal of achieving net-zero emissions by 2050. Separately, the European Union (EU) has agreed to reduce the GHG intensity of fuels used by the shipping by sector by up to 80% by 2050.

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

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

In this paper we present analysis of the cost of compliance of different alternative fuel solutions for the container vessel sector using Z-Joule's POOL.FM evaluation model. Our analysis is focused on the LNG, methanol and ammonia fuel families, comparing their costs of compliance against the VLSFO (very low sulphur fuel oil) default. We have not considered the compliance pathway offered by liquid biofuels or bio-oils.

KEY TAKEAWAYS

Key takeaways from our analysis of container vessel and fleet scenarios operating on the Rotterdam to Singapore trade route in the period 2025 to 2040 are as follows:

- **Operational costs are likely to be significantly higher for fleet operators under IMO and EU decarbonisation regulations.**
- **The use of LNG, methanol and ammonia dual-fuel engine technologies can reduce compliance costs.**
- **An LNG dual-fuel vessel provides the lowest cost compliance solution. This is driven by the fact that it has lower GHG emissions than VLSFO in its fossil form and vessels can avoid using relatively expensive MGO (marine gas oil) for ECA (Emission Control Area) compliance.**
- **FuelEU Maritime will have a major impact on how fleet operators run their alternatively fuelled vessels. Operators will offset non-compliance by traditionally fuelled (VLSFO) vessels by ramping up the quantity of green fuels they burn in alternatively fuelled vessels to generate FuelEU Maritime credits.**

- **In terms of fleet operations LNG dual-fuel vessels are the lowest cost option for ensuring overall fleet compliance with EU and IMO decarbonization regulations.**
- **Ammonia and methanol dual fuel vessels are likely to need significant quantities of expensive green fuels to comply with GHG regulations, in particular FuelEU Maritime, from 2025 onwards.**
- **Finally, the high FuelEU Maritime penalty price will not only incentivise the demand for blue, bio and e-fuel versions of LNG, methanol and ammonia but there will also be a major impetus for bunker fuel suppliers to develop liquid biofuels at scale.**

REGULATORY OVERVIEW

KEY GHG EMISSIONS REGULATIONS

We have analysed the impact on the shipping industry of the GHG regulations set out in Table 1.

Table 1: Regulations driving shipping industry decarbonisation

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

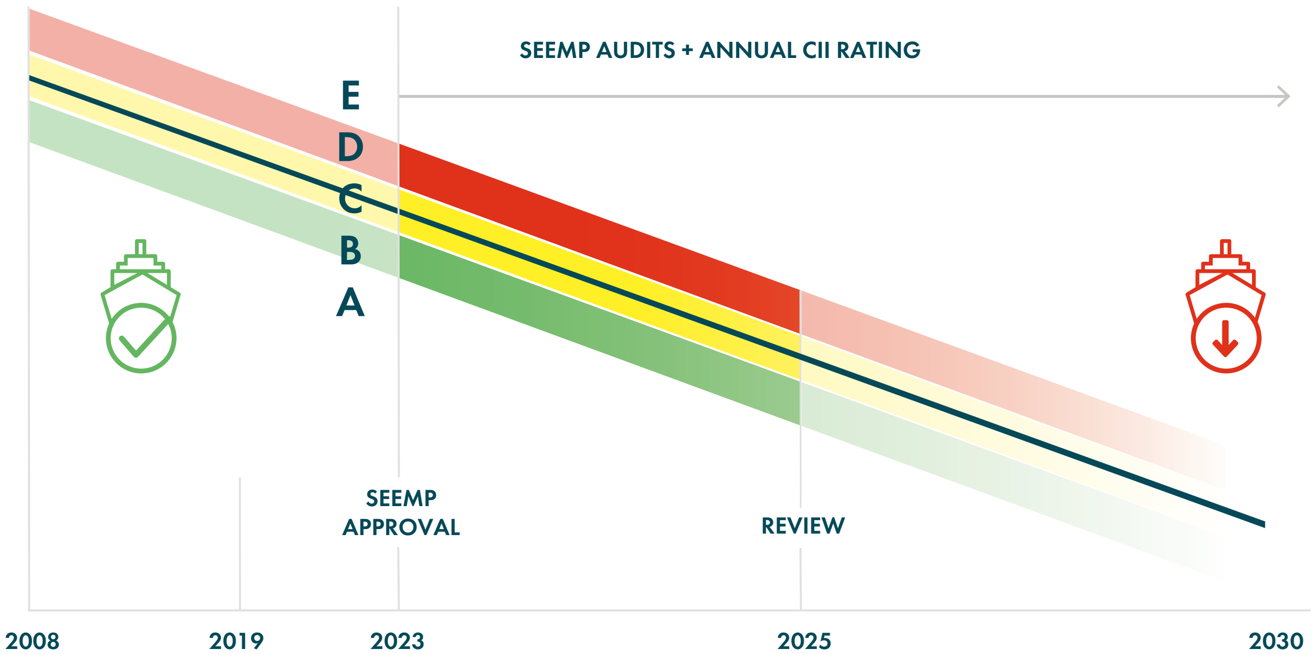
These regulations vary in terms of application, scope, emissions, geographical coverage and mechanism. Some regulations are linked to whole lifecycle emissions of marine fuels from well to wake (WtW), while others only consider emissions onboard from the tank to wake (TtW). The emissions regulated include just carbon dioxide (CO2), or multiple GHG including methane (CH4) and Nitrous oxide (N2O). In analysing their impacts, we also needed to take into account the impact of local emissions regulations such as SECAs (Sulphur Emission Control Areas) and NECAs (Nitrogen Oxides Emission Control Areas) which regulate SOX (sulphuroxide) and NOX (nitrogen oxide) emissions, and the EU's Onshore Power Supply (OPS) mandates at core TEN-T (Trans-European Transport Network) European ports which start to come into effect from 2030 onwards.

Note, we have not attempted to analyse the impact of any future Market-Based Mechanisms (MBMs) which are being discussed in relation to the IMO's revised Greenhouse Gas Strategy.

REGULATORY TRAJECTORIES

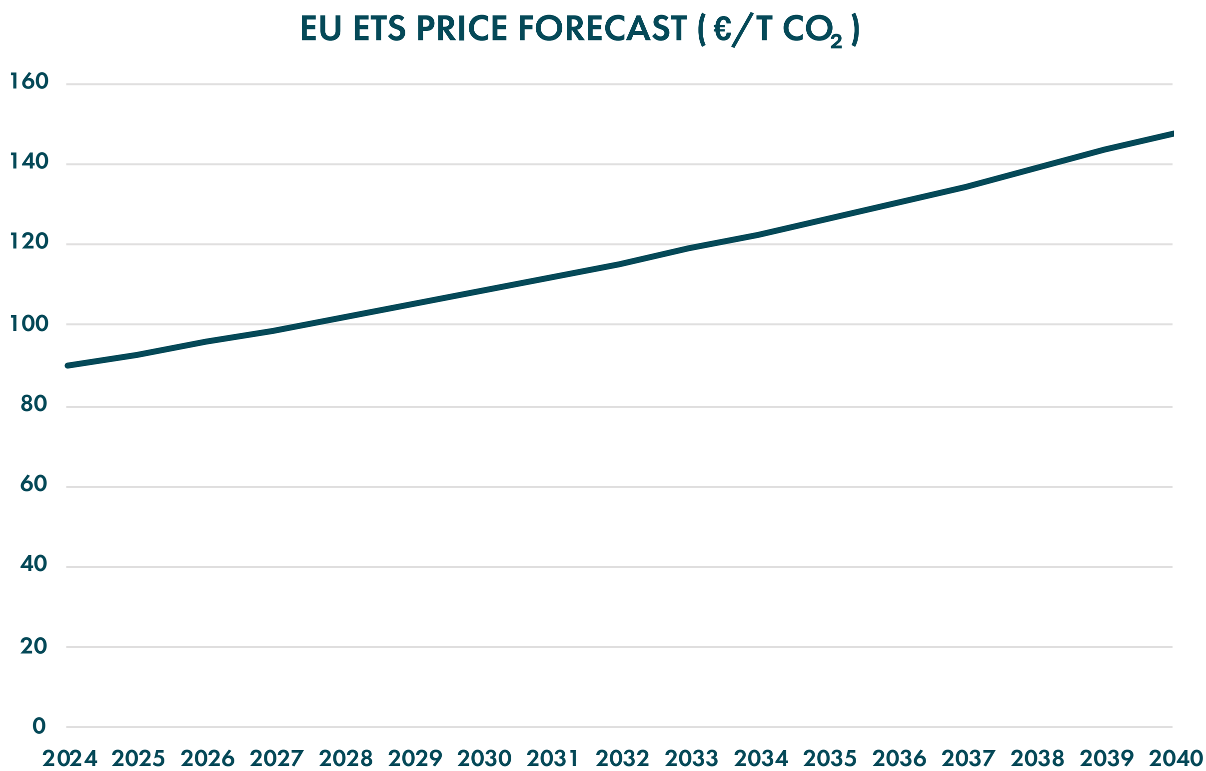
Figure 1: CII, EU ETS and FuelEU Maritime regulatory trajectories

REQUIRED ANNUAL OPERATIONAL CII RATINGS

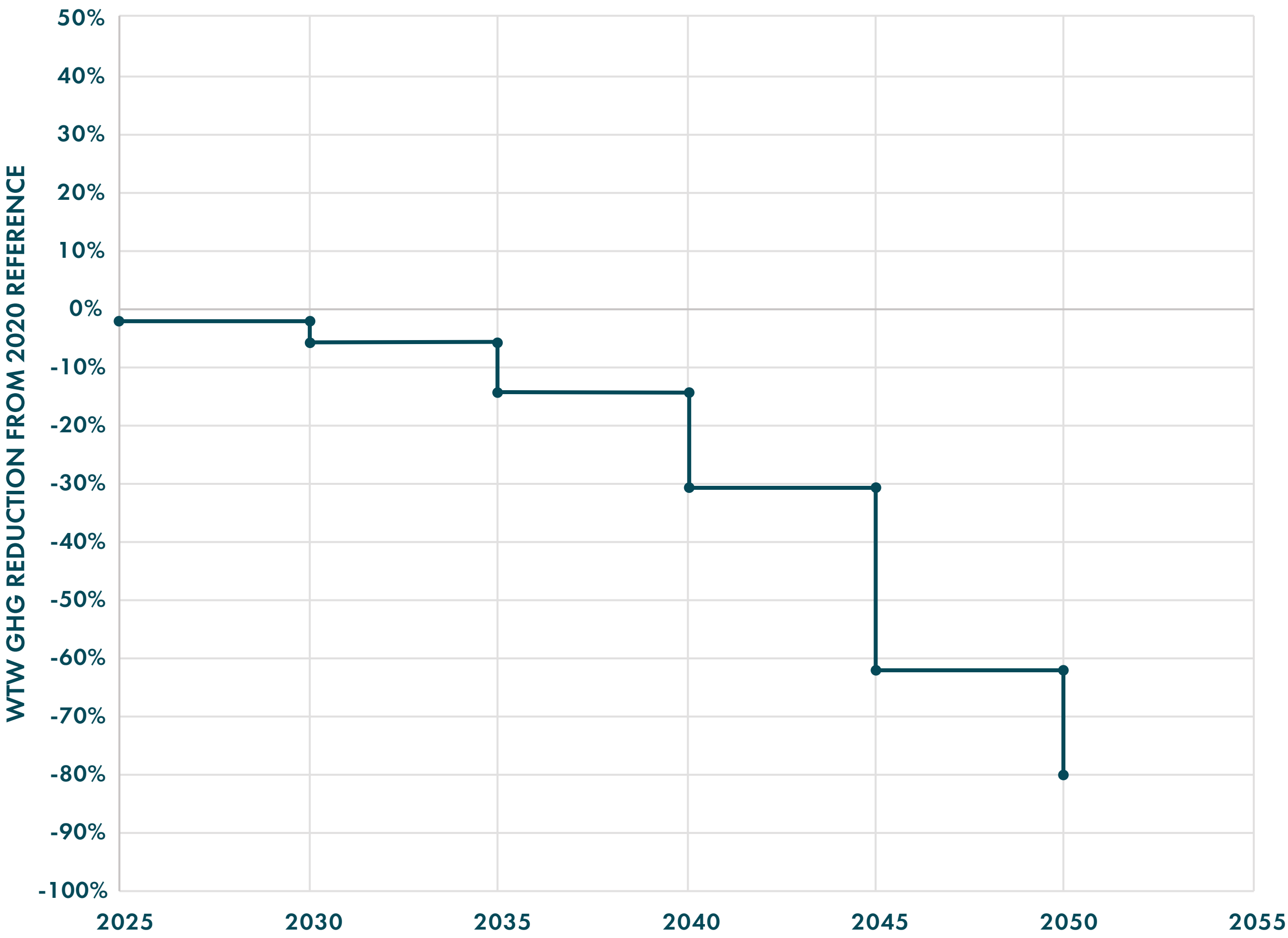


Source: DNV

EU ETS CARBON PRICE



FUELEU MARITIME CARBON INTENSITY LIMITS



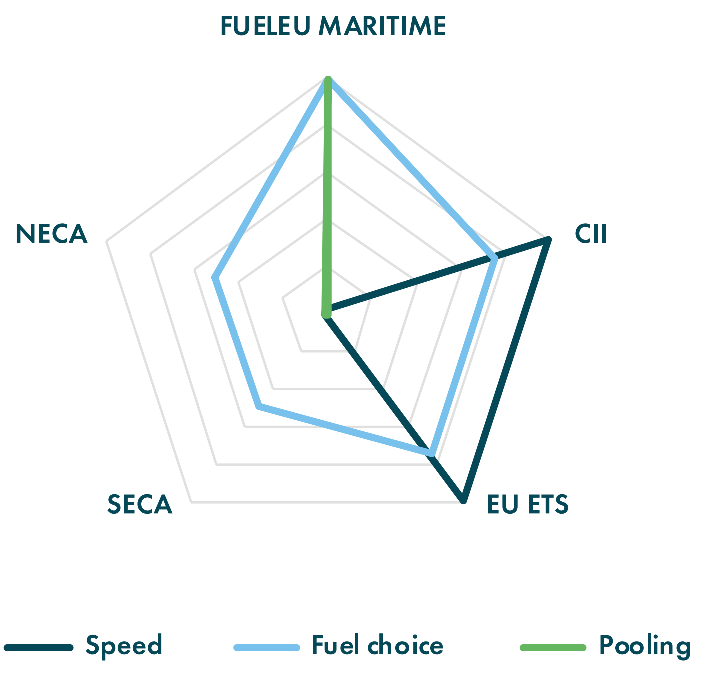
The EU and IMO share a common target of net-zero emissions for shipping by 2050. To achieve this, GHG regulations become increasingly more stringent over time as shown in Figure 1. Our assumptions on CII and EU ETS are set out in the section on Modelling Assumptions. FuelEU Maritime GHG intensity limits are set out in the Regulation.

MODELLING REGULATIONS

The interactions between regulations and individual vessel and fleet operations are complex, as illustrated in Figure 2.

Figure 2: Regulatory and operational interactions

COMPLEX INTERACTION BETWEEN LEGISLATION AND OPERATIONAL MEASURES



For example, as a fleet operator CII and EU ETS incentivise you to slow down to reduce emissions to maintain or improve your CII rating and reduce the expenditure on EUAs, (Compliance EU Allowances which are carbon allowances that allow companies to emit a specific amount of carbon dioxide and equivalent GHGs, CO2e), whereas revenue maximisation drives you to increase speed. FuelEU Maritime affects your fuel choice and how you operate an individual vessel in the context of a fleet or pool of vessels. Local emissions regulations, such as SECAs and NECAs impact your fuel choice in dual-fuel vessels.

The challenge for fleet operators is to find the optimal balance between regulatory compliance, vessel operations and commercial drivers. And these complex interactions illustrate the need for a sophisticated decision-support tool.

Z-JOULE POOL.FM MODEL

OVERVIEW

POOL.FM is a fuel-agnostic model which utilises an advanced optimisation algorithm which determines the optimal fuel mix, pooling strategy, and target speed for each vessel in a fleet (or vessel pool). The regulations currently modelled include CII, ECAs, EU ETS, FuelEU Maritime and Onshore Power Supply (OPS) mandates. Functionality to model possible IMO Market Based Measures (MBM)s is already in place and will be refined as more details about the forthcoming regulations emerge.

POOL.FM models the consumption profile of specific main and auxiliary engine types and the emissions profile of the different fuels.

MODEL OUTPUTS

Figure 3: Z-Joule POOL.FM

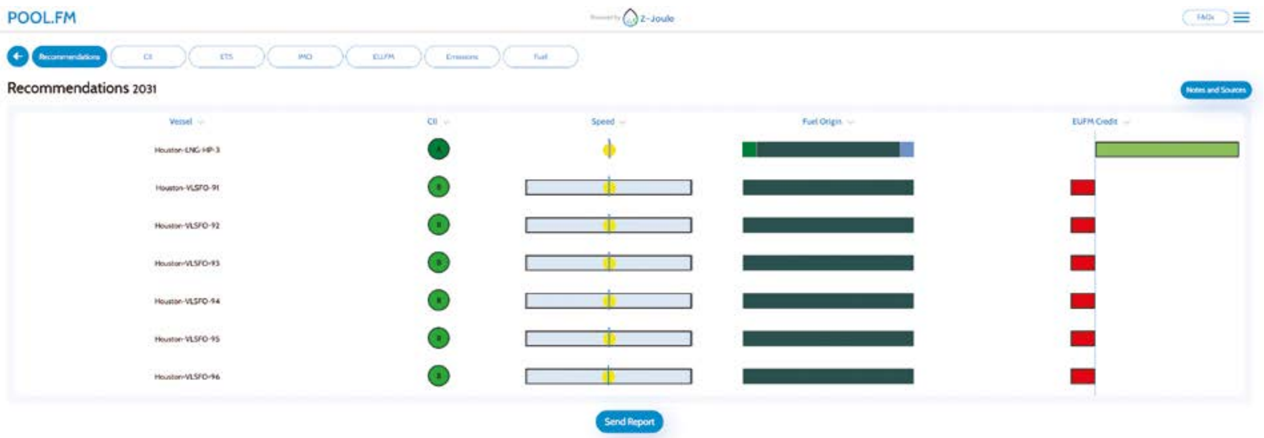


Figure 3 illustrates the outputs of POOL.FM. The model provides recommendations regarding fossil, blue, bio and e-fuel usage for each vessel, depending on the main and auxiliary engine type. Along with these recommendations it provides the associated GHG emissions and EU ETS costs. It also calculates the optimal vessel speed, which can be fixed, and the resulting CII. Finally, it determines the required transfer of FuelEU Maritime (EU.FM) credits between vessels in a fleet and any penalty payments.

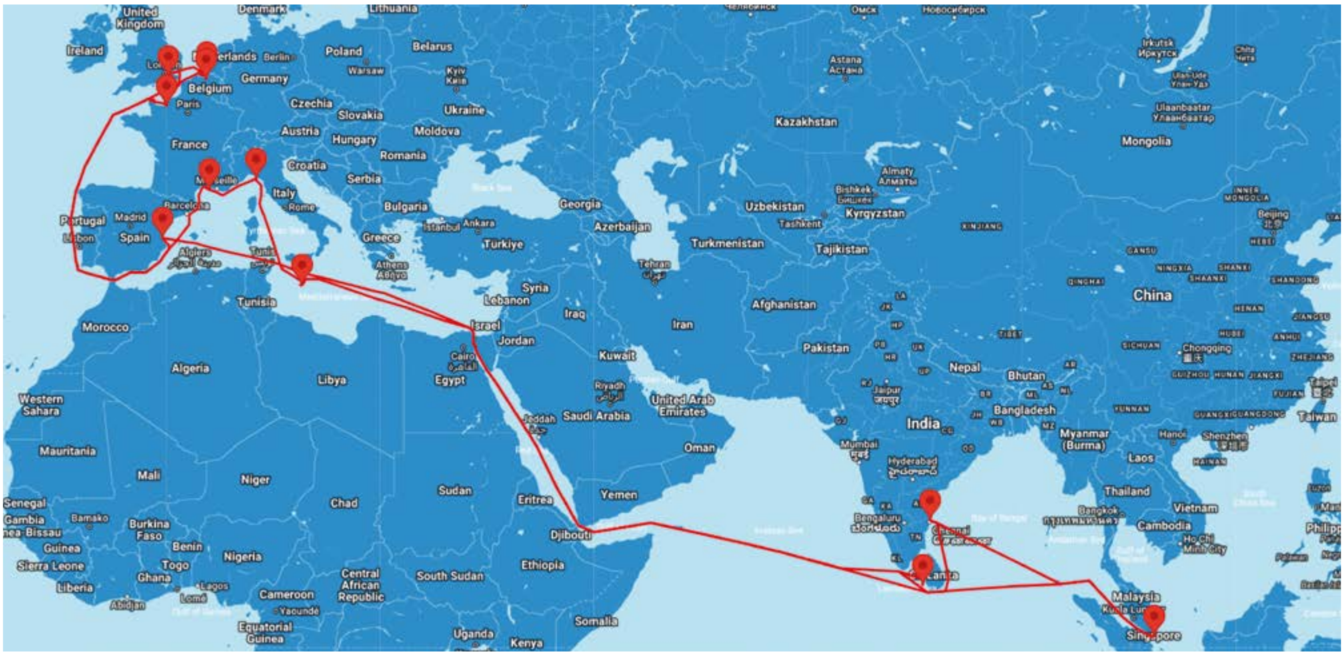
ANALYSIS

SCENARIO DESCRIPTIONS

We focused our analysis and modelling on the container vessel trade which is the most GHG-intensive shipping segment. Container vessels accounts for approximately 13% of the global shipping fleet tonnage, but consume around 30% of marine fuel. It is the segment which has seen the most investment in alternative marine fuels to date accounting for over a third of alternatively fuelled vessels in operation and on order.

We have modelled mid-sized, 14,000 TEU container vessels, in the form of single vessels and also as an eight-vessel fleet operating the Rotterdam – Singapore trade route shown in Figure 4. Such a fleet provides a weekly rotation with each vessel making a round trip of 69 to 85 days depending on vessel speed, with 22 days in port. This trade route means the vessels and fleet are subject to both EU and IMO regulations.

Figure 4: Container trade route modelled



We have examined two illustrative scenarios:

SCENARIO 1:
Analysis of single 14,000 TEU vessels using either VLSFO or LNG, methanol and ammonia dual-fuel engines for the years 2025, 2030, 2035 and 2040.

SCENARIO 2:
Analysis of a container fleet of 8 x 14,000 TEU vessels for the years 2025, 2030, 2035 and 2040. The fleet consists of six VLSFO fuelled vessels and two dual-fuel "balancing vessels" using LNG, methanol or ammonia dual-fuel engine technologies.

Table 2: Vessels and engines modelled

VESSEL	CAPACITY (TEU)	MAIN ENGINE	AUXILIARIES
VLSFO	14,000	MAN-G95ME-C10.5	4X Wärtsilä 32L
LNG High Pressure DF	14,000	MAN-G95ME-C10.5-GI	4X Wärtsilä DF 34L
Methanol DF	14,000	MAN-G95ME-C10.5-LGIM	4X Wärtsilä Methanol 32L
Ammonia DF	14,000	WinGD X72DF-A scaled using WinGD X-92 DF specifications	4X Wärtsilä Ammonia 25L scaled

Table 2 shows the main and auxiliary engines we have modelled for the four vessel types. To simplify our analysis, we have assumed that ammonia dual-fuel vessels will be in operation from 2025 onwards, when their expected in-service date is much later.

While the fuel consumption profiles and emission factors for VLSFO, LNG and methanol dual-fuel engines are available, data for ammonia main and auxiliary engines is limited as no engines are currently in operation. Therefore, we have used engine manufacturer draft specifications combined with some key "optimistic" assumptions which have major implications for GHG and local emissions. First, the WinGD ammonia engine will only use 5% MGO or VLSFO pilot fuel; and second there will be no N_2O or ammonia emissions. Should the actual performance figures of the engines prove less efficient once in service, this will adversely affect the modelled results for ammonia-powered vessels.

MODELLING ASSUMPTIONS

The analysis is illustrative with the aim to investigate the impact of fuel choice and operations on the costs of regulatory compliance. We have made the following simplifying assumptions:

REGULATIONS

- Requirements for CII ratings become tighter by 2% per annum until 2026 and 1% per annum thereafter.
- The EU ETS carbon price increases from €90/T in 2024 to €200/T by 2050.
- FuelEU Maritime GHG intensity limits fall as described in the regulation.
- Vessels within the fleet are able to exchange FuelEU Maritime (EU.FM) credits but credits cannot be banked.
- The Mediterranean SECA will be in operation from 2025 onwards.
- Onshore Power Supply will be available and mandated in core TEN-T ports from 2030 onwards.
- An IMO global MBM is not modelled.

EMISSION FACTORS

- Emission factors use those specified in regulations for different fuelling solutions where available ie emission factors specified by CII, FuelEU Maritime and EU ETS. Otherwise, values are obtained from the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (MMMCZCS) Cost Calculator.

FUEL AVAILABILITY

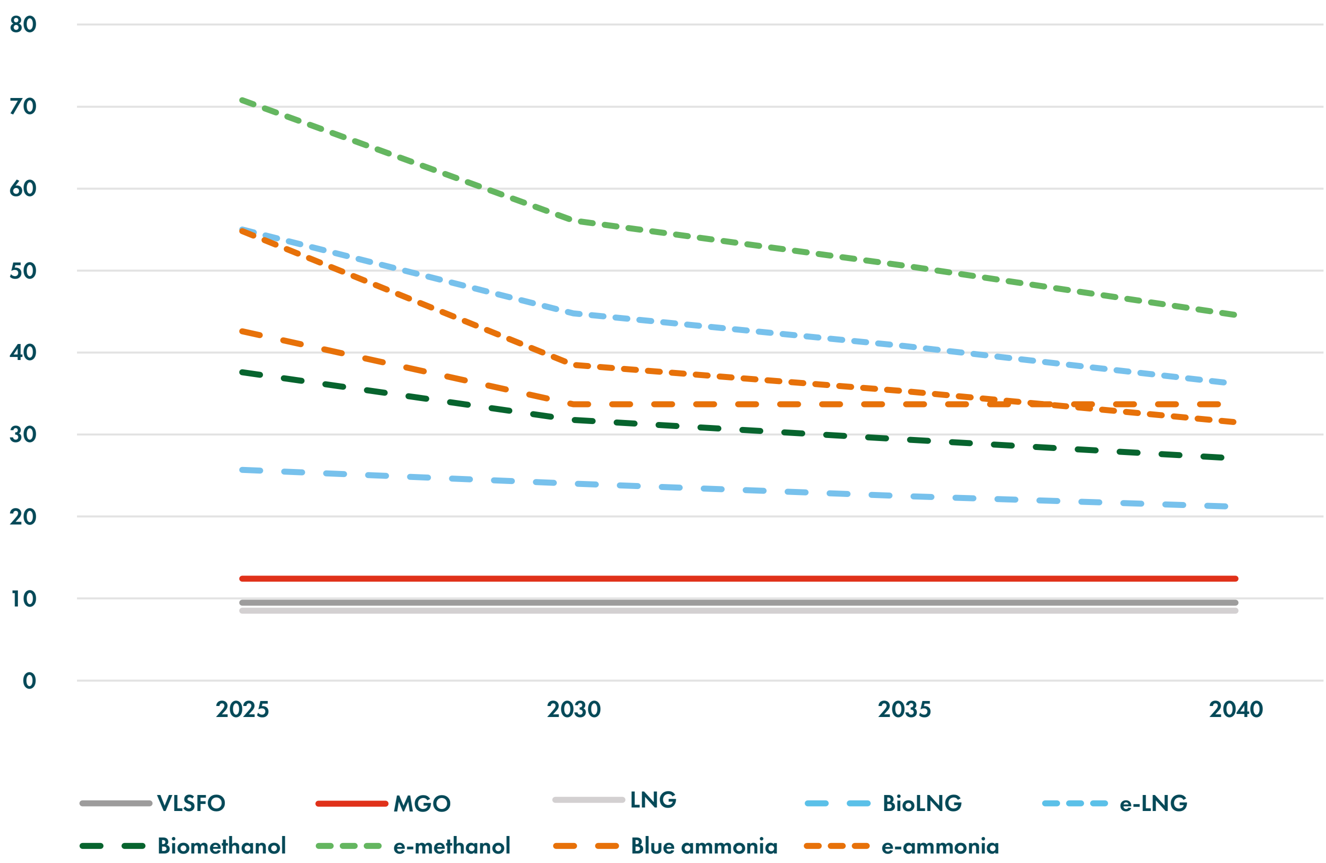
- Liquefied biomethane, biomethanol, blue ammonia, liquefied e-methane, e-methanol and e-ammonia are all available from 2025 onwards. As noted this year, supplies of biomethanol are likely to be very limited over the next few years.
- Biofuels ie bio-oils such as FAME are excluded from the analysis as availability appears to be limited. (Biomethane originates from different sources where availability is not so constrained.) Our assumption is that scarcity coupled with massive demand (only about 4% of the 60,000-vessel global shipping fleet will be dual-fuel by end of decade) will drive bio-oil prices to converge with the FuelEU Maritime penalty price.

OPERATING ASSUMPTIONS

Speeds are held constant for each year, consistent with vessels maintaining at least a CII "C" rating. This means that average vessel speeds and fleet capacity will decline over time in line with the CII trajectory.

FUEL PRICE ASSUMPTIONS

Figure 5: Fuel price assumptions ($/mmBtu)



Fuel price assumptions are set out in Figure 5. We have used historic averages for fossil fuel bunker prices ie for VLSFO, MGO and LNG. We have not included prices for fossil ammonia and methanol as these are more expensive than VLSFO and also have higher Well-to-Wake emissions. Consequently, it would make no sense to use them in a dual-fuel engine. For blue, bio and e-fuels, we have used production cost forecasts from the MMMCZCS Cost Calculator[1] plus bunkering adjustments.

1. https://www.zerocarbonshipping.com/cost-calculator/?s=0

We can see that fuels group into three price categories:

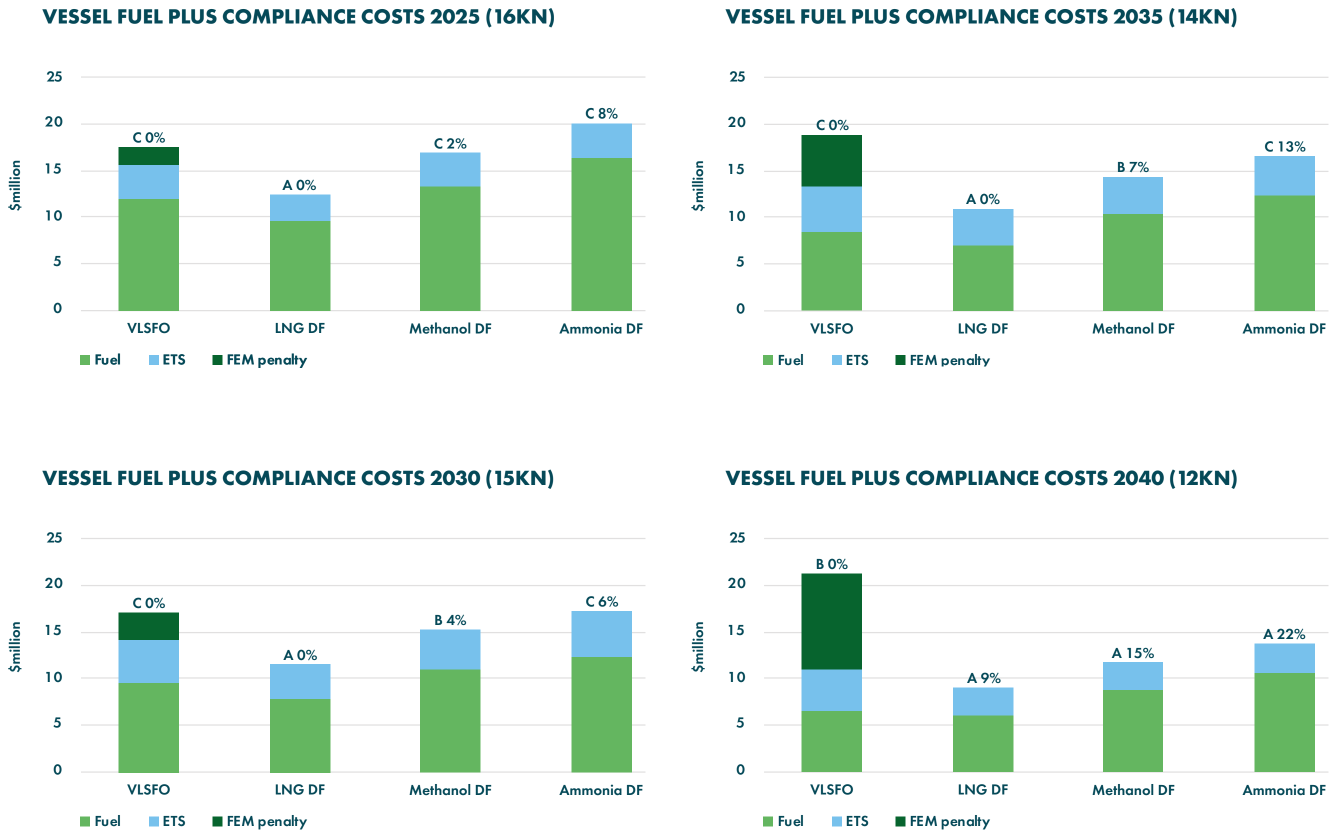
1. Fossil fuels.
2. Bio / blue fuels whose prices are currently 2.5 – 4 times higher than fossil fuel prices. These are likely to fall gradually over time as production of bio-derived fuels industrialises and scales and the costs of CO2 capture and sequestration fall.
3. e-fuels which are currently 5-7 times higher than fossil fuel prices. These have scope to fall significantly as renewable electricity and electrolysis capacity scales and costs come down.

Current MMMCZCS fuel cost forecasts show that in the period to 2040 bioLNG is the lowest cost bio or blue fuel, followed by methanol and then ammonia. In terms of e-fuels, ammonia is the cheapest to produce, followed by e-LNG with e-methanol the most costly.

RESULTS

SCENARIO 1: SINGLE VESSEL

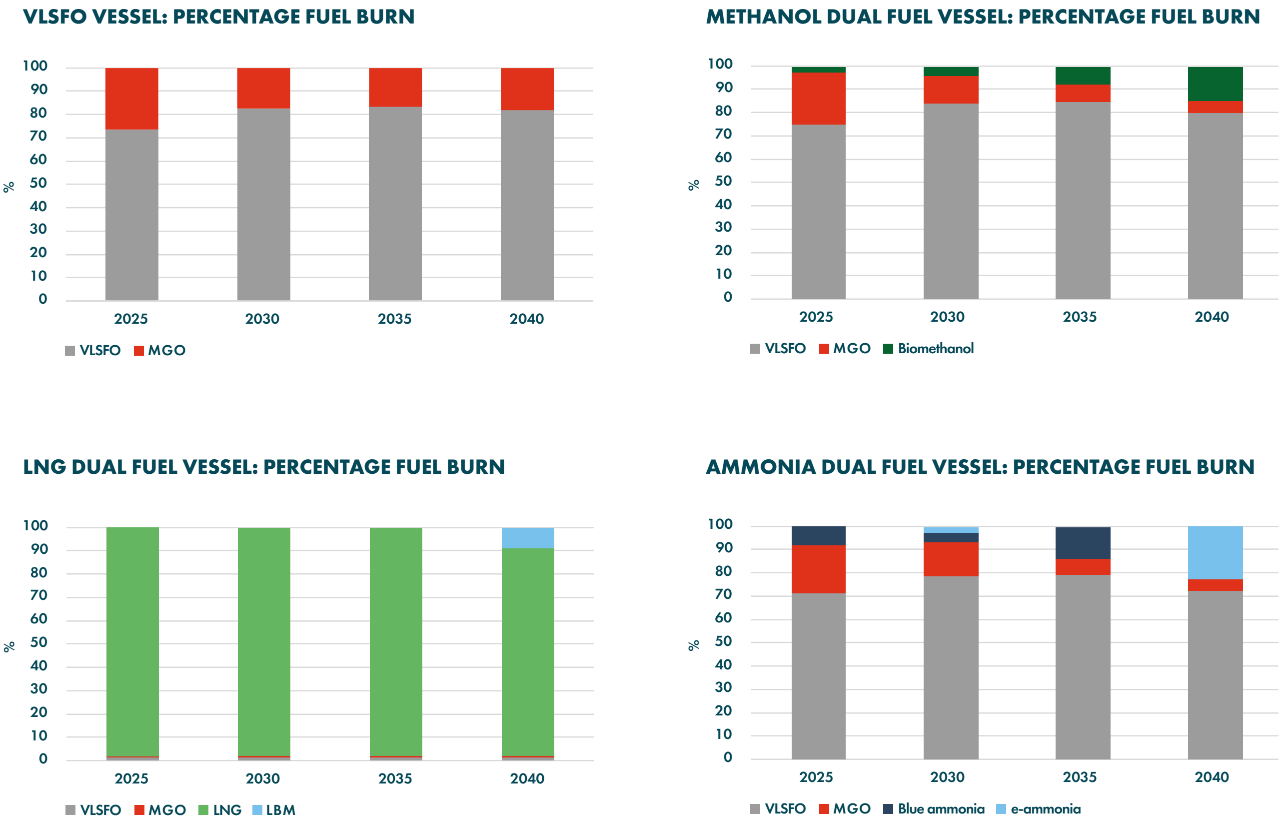
Figure 6: Cost breakdown by vessel speed, CII rating & percentage green fuels



The key takeaways from the results shown in Figure 6 are:

- **Operational costs are likely to be significantly higher for fleet operators under IMO and EU decarbonisation regulations. In the case of the VLSFO vessel regulatory compliance will increase annual operating costs by almost 50% in 2025 and by more than 200% in 2040.**
- **The use of LNG, methanol and ammonia dual-fuel engine technologies can reduce compliance costs.**
- **The LNG dual-fuel vessel provides the lowest cost option. This is driven by the fact that it has lower GHG emissions than VLSFO in its fossil form and vessels can avoid using relatively expensive MGO for ECA compliance.**
- **LNG is able to comply with FuelEU Maritime until 2039 in its fossil form. Green fuels ie liquefied biomethane are only needed for compliance from 2040 onwards.**
- **LNG fuelled vessels also have the best CII rating for same vessel speed.**
- **It should also be noted that the LNG dual-fuel results for 2025, 2030 and 2035 do not include the additional value that can be derived from FuelEU Maritime credits generated by fossil LNG's over-performance in relation to FuelEU Maritime GHG intensity limits.**

Figure 7: Scenario 1: Single vessel percentage fuel burn by year



The percentage fuel burn data for different fuel types in Figure 7 shows that ammonia and methanol dual-fuel vessels operate mainly on VLSFO and MGO to 2040. They will need to use blue, bio or electro fuels to ensure compliance with FuelEU Maritime from 2025 onwards.

FuelEU Maritime allows for double-counting of RFNBOs (renewable fuels of non-biological origin) to 2033 which means these an e-fuel may be used in preference to cheaper blue or bio-derived fuels. This is the case for ammonia in 2030. By 2035, there is no longer a multiplier, so blue ammonia is used; then in 2040 e-ammonia is used again, as the price of e-ammonia drops below that of blue ammonia. This double counting effect also shows up in the lower percentage of "green ammonia" in 2030 (6%) compared with 2025 (8%).

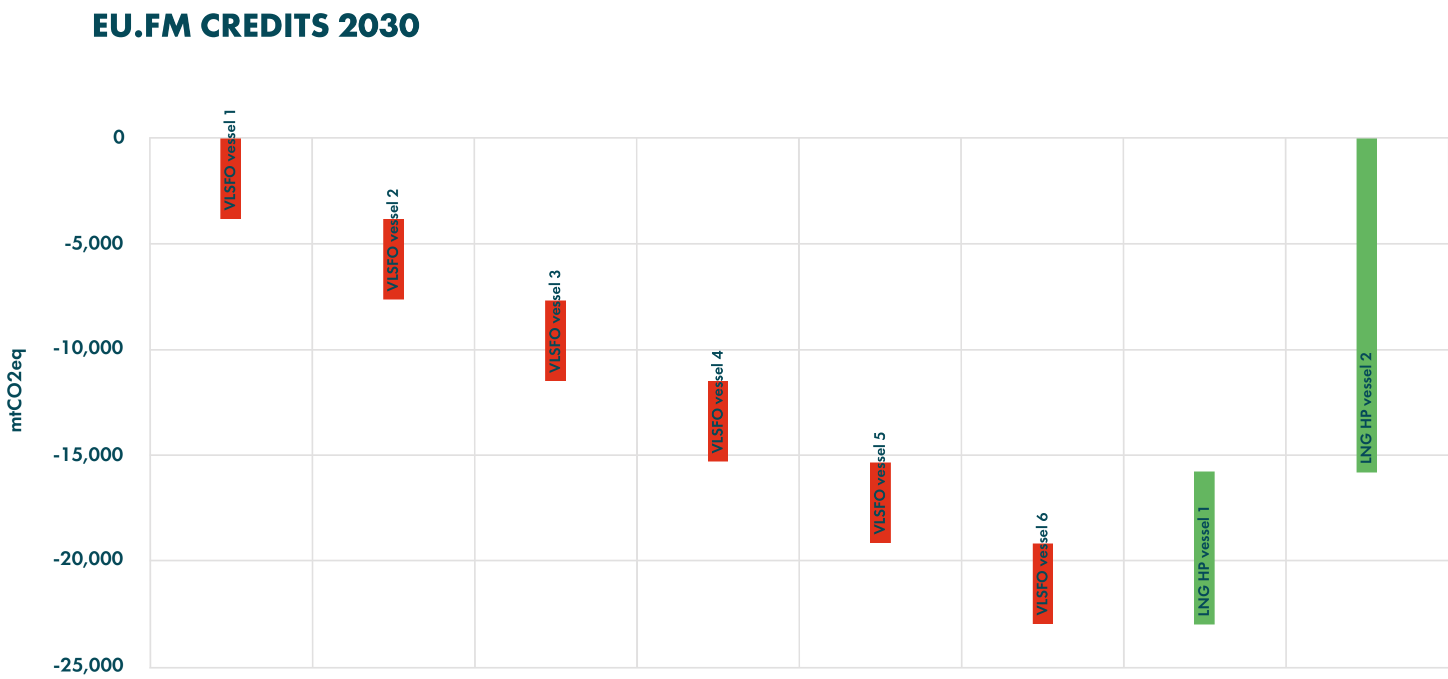
The step reduction in the use of MGO from 2025 to 2030 for VLSFO, methanol and ammonia dual-fuel vessels is due to the fact that our analysis assumes the use of onshore power is mandated for vessels in European Ten-T core ports from 2030 onwards. This means that fleet operators will not be able to use MGO for compliance during European port calls.

SCENARIO 2: VLSFO FLEET WITH TWO BALANCING VESSELS

Figure 8: Scenario 1: Fleet cost breakdown by vessel speed

Figure 8 shows that LNG dual-fuel vessels are the lowest cost option for ensuring overall fleet compliance with EU and IMO decarbonization regulations. For an 8-vessel fleet with two alternatively fuelled "balancing vessels" the overall cost of compliance with LNG will be between $5 million and $17 million per annum lower than in the case of methanol and ammonia.

Figure 9: Scenario 2: FuelEU Maritime effects



FuelEU Maritime will have a major impact on how fleet operators run their alternatively fuelled vessels as illustrated in Figure 9 in the case for LNG in 2030. Operators will offset non-compliance by traditionally fuelled (VLSFO) vessels – the red bars - by ramping up the quantity of green fuels they burn in alternatively fuelled vessels, in this case LNG, to generate EU.FM credits (the green bars).

Table 3: Percentage of liquefied biomethane used in LNG-dual fuel vessels

YEAR	PERCENTAGE OF LIQUEFIED BIOMETHANE USED	
	SINGLE LNG DF VESSEL OPERATION	FLEET OPERATION – LNG DF BALANCING VESSELS
2025	0%	0%
2030	0%	8%
2035	0%	48%
2040	9%	77%

By way of further illustration Table 3 compares the percentage of liquefied biomethane used in a single LNG dual fuel vessel with the much higher percentages used when two LNG fuelled vessels are operated to achieve overall fleet compliance with FuelEU Maritime. Note, any surplus credits will have a market value and can be traded with other fleet operators.

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

CONCLUSIONS

The interactions between IMO and EU regulations and vessel operations including fuel choice are complex. Intuition and simple rules of thumb may not always provide optimal compliance strategies and there is a need for sophisticated decision-support tools.

Key conclusions from our analysis of container vessel and fleet scenarios operating on the Rotterdam to Singapore trade route in the period 2025 to 2040 are as follows:

- **Operational costs are likely to be significantly higher for fleet operators under IMO and EU decarbonisation regulations.**
- **The use of LNG, methanol and ammonia dual-fuel engine technologies can reduce compliance costs.**
- **An LNG dual-fuel vessel provides the lowest cost compliance solution. This is driven by the fact that it has lower GHG emissions than VLSFO in its fossil form and vessels can avoid using relatively expensive MGO for ECA compliance.**
- **FuelEU Maritime will have a major impact on how fleet operators run their alternatively fuelled vessels. Operators will offset non-compliance by traditionally fuelled (VLSFO) vessels by ramping up the quantity of green fuels they burn in alternatively fuelled vessels to generate EU.FM credits.**
- **In terms of fleet operations LNG dual-fuel vessels are the lowest cost option for ensuring overall fleet compliance with EU and IMO decarbonization regulations. For an eight-vessel fleet with two alternatively fuelled "balancing vessels" the overall cost of compliance with LNG will be between $5 million and $17 million per annum lower than in the case of methanol and ammonia.**
- **Ammonia and methanol dual fuel vessels are likely to need significant quantities of expensive green fuels to comply with GHG regulations, in particular FuelEU Maritime, from 2025 onwards.**
- **Finally, the high FuelEU Maritime penalty price will not only incentivise the demand for blue, bio and e-fuel versions of LNG, methanol and ammonia but there will also be a major impetus for bunker fuel suppliers to develop liquid biofuels at scale.**

We should emphasise that this analysis is illustrative and relates to a specific trade and vessel type. Fleet owners and operators will need to plan their fuel transition strategy using assumptions and scenarios that are carefully tailored to their individual fleets.

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