POWERED BY LPG

THE PROSPECTS OF LPG AND LIQUID GAS AS MARINE FUEL

October 2024

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The WLGA is the authoritative voice for the global Liquid Gas industry, representing the full Liquid Gas value chain. The primary goal of the association is to add value to the sector by driving premium demand for Liquid Gas, while also promoting compliance to good business and safety practices. With over 300 members in 125 countries, the association brings together private and public companies involved in one, several or all activities of the industry, develops long-term partnerships with international organisations, and implements projects on local and global scales. The association was established in 1987 and granted Special Consultative Status with the United Nations Economic and Social Council in 1989.

The WLGA mission statement forms the four principal goals of the WLGA in the current period, namely **Advocacy**, to advocate Liquid Gas, LPG and DME as part of the solution to future energy challenges; **Safety & Business Improvement**, to support safe, efficient, and responsible business; **Sustainable Growth & Innovation**, to encourage sustainability, sustainable growth and innovation in the business and **Communications** to effectively communicate and raise awareness of Liquid Gas.

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About Watermelon

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Abbreviation list

AFIR	Alternative Fuels Infrastructure Regulation
AiP	Approval in Principle
CBM	Cubic Meters
CCC	Carriage of Cargoes and Containers
CCS	Carbon Capture and Storage
CII	Carbon Intensity Indicator, Carbon Intensity Index
DME	Dimethyl Ether
DWT	Deadweight
ECAs	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGS	Exhaust Gas Recirculation
ETD	Energy Taxation Directive
ETS	Emissions Trading System
EU	European Union
GHGs	Greenhouse Gases
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
IGC	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization

ISO	International Organization for Standardisation
LCA	Life Cycle Analysis
LG	Liquid Gas
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LPGCs	LPG Carriers
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGCs	Medium Gas Carriers
MSC	Maritime Safety Committee
NOx	Nitrogen Oxides
PM	Particulate Matter
RED	Renewable Energy Directive
SCR	Selective Catalytic Reduction
SGMF	Society for Gas as a Marine Fuel
SOx	Sulphur oxides
TNM	Tonnes nautical miles
TtW	Tank-to-Wake
VLGCs	Very Large Gas Carriers
WASP	Wind Assisted Propulsion Technologies
WtT	Well to Tank
WtW	Well to Wake

Foreword

The benefits of LPG as a marine fuel have already been demonstrated by its wide adoption as the most common alternative fuel for LPG Carriers

Nearly 90% of global freight is transported by sea, making it an essential part of all major supply chains. Although transport by ship is by far the most energy-efficient form of freight transport, the International Maritime Organization (IMO) estimates that shipping accounts for about 3% of global greenhouse gas emissions, approximately the same as the global aviation industry. There are many pathways to lowering shipping emissions, including operational, ship design, and fuel choice. As a fuel, LPG, standing for either propane or butane or a mix of these two, belongs to the category of Liquid Gas (LG) and is a unique and exceptional energy carrier. When it comes to decarbonising shipping, it has an important and growing role to play.

The term "Liquid Gas" refers to LPG and DME which are both transported and stored as a liquid under moderate pressure or cooling but are consumed as a gas. LPG and DME, as will be further elaborated on in this report, can deliver cleaner and lower emission marine transportation.

The benefits of LPG as a marine fuel have already been demonstrated through its wide adoption as the most common alternative fuel for LPG carriers. Orders for LPG-fuelled ships have recently hit record levels, with over 250 LPGCs either on order or currently sailing on LPG, and it is anticipated that 80% of new Very Large Gas Carriers (VLGCs) that enter the market in the coming years will be capable of running on LPG[1]. Although LPG is now a popular fuel for large LPG carriers, its further role as a marine fuel alternative for smaller LPG carriers and other marine segments should not be overlooked.

In a drastically transitioning world, balancing between energy security and decarbonisation, LG including LPG and DME, could have an important role to play and a gap to fill. While cleaner fuels will be focusing their scale of production and availability towards new constructed long-term user units, LG could become one of the alternatives to allow the existing fleet to complete its lifecycle in compliance with the IMO Green House Gases (GHGs) strategy or extend a pathway to sustainability through shifting to bioLPG and renewable LPG, renewable DME, ammonia, and in combination also with Onboard Carbon Capture and Storage (OCCS) and Wind Assisted Propulsion Systems (WASP).

As experience and track record on the use of LPG as fuel increase and LPG small-scale operations are widely spread in hundreds of terminals around the globe, the readiness and availability of this option remain one of its key attributes. According to recent Life Cycle Analysis (LCA) data, LPG can save 17% on a well-to-wake (WtW) basis, not only due to its combustion carbon factor but also its well-to-tank (WtT) improved profile. Despite the variance in its price, LPG can be very competitively priced, even against conventional fuels, in certain geographies. Finally, its overall pollution profile should not be overlooked, with benefits extending from SOx to NOx and PM.

With focus on the future and the ambition of the revised IMO GHG strategy towards zero shipping emissions, LPG can significantly save GHG emissions in times when zero carbon fuels will not yet be taken up, and it can also blend with cleaner future pathways. Its infrastructure and equipment compatibility with ammonia, and in components like fuel tanks, that could be purposed for dual use, but also with renewable LPG, bioLPG, DME, and renewable DME, adds to the merits for consideration.

Executive Summary

The shipping industry's actions towards decarbonisation are a reality, but there is still a long way forward to achieve targets for zero carbon emissions. Even though the transition should be completed as fast as possible, it is an ongoing global process with several intermediate steps that should be conquered and pathways that the maritime stakeholders can follow.

Out of all the available pathways, one relatively unexplored is that of Liquid Gas, and especially LPG, as a marine fuel. LPG can support stakeholders in the shipping industry in implementing emissions reduction strategies in the medium- and also into the longer-term through its more sustainable blends, synergies and pathways. The adoption of LPG as a marine fuel enables compliance with the 2020 sulphur cap and gives a remarkable advantage against the CII and the upcoming EU ETS and FUEL EU regulations due to its lower carbon-to-hydrogen ratio, which leads to a lower carbon factor. The use of LPG could result in a 13%-18% reduction in CO_2 emissions compared to Marine Diesel Oil (MDO) and Heavy Fuel Oil (HFO)[2].

Today, there are 1,679 LPG carriers of all different sizes and age groups, and 172 are following in the order book until 2027, when the total available LPG fleet capacity is expected to reach around 56.5 million tonnes, a rise of about 36% compared to 2022[1]. According to the IHS June 2024 database, the LPG carrier orderbook consists of 51% VLGCs and 25% Medium Gas Carriers (MGCs). By the time of this guide's completion, out of the total LPG carrier fleet, 151 are already equipped with LPG dual-fuel engines, and 109 more are included in the orderbook, the majority of them (72%) consisting of VLGCs.

Moreover, LPG can be proven to be very competitive in terms of pricing against other fuels as well, depending on the region and origin. Considering that there are 700 LPG terminals around the world, in some regions LPG can be found even at 360[1]$/ton, while in combination with the existing 995 LPG carriers up to 15,000 cubic meters (cbm) that could be used as bunker vessels, the hidden economic potential and supply chain are revealed.

Regarding the available LPG technology, MAN Energy Solutions (MAN ES) already provides a series of two-stroke main engines as newbuild or retrofit solutions through its variety in the dual-fuel ME-LGIP series. The installation of such engines could further lead to the unlocking of the adoption of other alternative fuels in the future due to the similarity in design with the methanol ME-LGIM and ammonia ME-LGIA engines.

Considering the value chain of LPG as a marine fuel, owners may follow a holistic approach that includes collaboration and the establishment of synergies between all stakeholders, so that they de-risk potential investments in LPG as a marine fuel.

Combined with its sustainable twins, renewable LPG or bioLPG, renewable DME and ammonia, LPG can constitute a cleaner, proven solution leading to future-proof investments.

Conventional LPG, and even more, renewable LPG and renewable DME, with their synergies also with ammonia, can constitute a cleaner, proven solution leading to future-proof investments.

[1] Chart 16

1. Introduction

The objective of the subject guide is to enhance the reader's perspective and understanding of the different aspects of LPG by describing and exploring LPG as a marine fuel supply value chain. The guide aims to inform about the market, the technology readiness level, the environmental and regulatory compliance aspects, as well as the improved carbon profile that is secured when consumed as fuel. The opportunities that are generated as a transition portfolio through the adoption of LPG are presented and analysed in this guide. The reader can find a holistic business model that is centred around the value chain of LPG to propel its global adoption and a wider high-level feasibility approach aiming to unlock the high financial potential of its use.

The information contained in the publication intends to incentivise readers from the shipping industry to explore the offering of LPG as a marine fuel, its characteristics including environmental sustainability, regulatory compliance, future-proofing, and financial feasibility, and further consider its adoption and commercial potential. This publication envisages providing readers, interested parties, and stakeholders in the maritime industry with a clear picture of the landscape of LPG as a marine fuel. The guide presents the current status of the industry and the supply chain readiness to incorporate LPG as a feasible alternative fuel, worth exploring both for gas and non-gas carriers.

2. Why LPG as Fuel and Experience So Far

Decarbonisation is a global challenge, and the maritime industry is no exception to that. Oppositely, the maritime fleet is a key polluting contributor, where, according to the IMO's 4th GHG study, shipping emits 1,076 million tonnes of CO_{2e}[3]. To address that, many significant actions have been implemented on a statutory level to deal with climate change and global warming to the extent that the shipping industry is responsible.

Undoubtedly, shipping along with the rest of the world, is already moving into a new energy transition era where the industry needs to explore fuel pathways to meet the tough environmental targets that are continuously set by the regulatory bodies and aim to reduce the industry's GHG emissions and carbon footprint. Uncertainty and pressure to improve shipping's sustainability prevail, and the next day finds the stakeholders within a complex operating environment. The fuel options to achieve these targets out there in the market seem to be too many and promising. However, many of them have been little explored or are under development.

LPG does not, however, belong to the aforementioned category. LPG is a largely explored and mature option that has been used as a fuel safely for many years in other industries and can prove to be a leader in shipping's fuel transition. Regarding the properties of LPG as fuel, insights about its bunkering, and other useful information, please refer to the previous guides issued by WLGA[2].

The development of a strategy around LPG as fuel presents great advantages. It is compliant with 2020 sulphur requirements and with IMO's lower Emission Control Areas (ECAs) limit of 0.1% sulphur and it improves the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). Moreover, it sets the ground for better performance against the upcoming EU Taxonomy, including the Maritime Fuel EU and EU Emissions Trading System (EU ETS), via its reduced carbon factor and through its compatibility with other alternative fuels, which future-proofs the users. Taking into consideration the emissions lifecycle analysis and "Well to Wake" (WtW) GHG emissions, LPG outperforms Marine Gas Oil (MGO), HFO plus scrubber, and compared to Liquified Natural Gas (LNG) as a fuel, as elaborated in chapter 4.

TABLE 1: ALTERNATIVE FUEL PROPERTIES COMPARED TO MDO

	LPG	LNG	Methanol	Ammonia	Hydrogen
Fuel tank size ratio compared to MDO	**1.5**	1.8	2.5	3	5-7
Volumetric energy density (MJ/L)	**26.5**	21.2	15.7	12.7	8.5

[2] See Appendix

In terms of fuel properties, LPG has the highest volumetric energy density compared to other alternative fuels and as a result, the most favourable fuel tank size ratio, taking MDO fuel as a baseline.

LPG has the highest volumetric energy density compared to all other alternative fuels, hence it requires the smallest tank size for storage on board, second only to MDO.

In addition, LPG presents significant pricing opportunities and a competitive option against other fuels in less explored regions, thus making it an alluring fuel for local and other operators. Investment-wise, the adoption of LPG as fuel provides CAPEX opportunities compared to other dual-fuel options, considering both newbuilds and in some cases, retrofits for the full spectrum of the installation. Indicatively, a newbuild LNG-fuelled 10k TEU containership can cost up to 125 million USD while a similar sized LPG-fuelled option for a newbuild would cost around 100 million USD i.e. almost 80% of the first. The retrofit of a conventional diesel oil engine to LNG dual-fuel costs 12-33 million USD, while the retrofit of the same ship to LPG will cost between 9.5-27 million USD, depending on the ship type and size.

LPG as a marine fuel can potentially work in great synergy with other technologies, such as wind-assisted technologies (rotor sails or rigid wing sails) and Carbon Capture Storage (CCS) onboard vessels, further improving the vessel's environmental footprint while extending asset lifetime. Even though CCS is still a hatching point for the maritime industry, its adoption in combination with the use of LPG can lead to remarkable environmental and financial benefits.

3. Global Market Overview

3.1 Market Outlook - Fleet Anatomy - June 2024

Regarding the worldwide LPG ship profile, as of June 2024, there were 1,679 LPG carriers, and 204 of them, based on the installed main engine model, could be potentially converted to LPG fuelled thus exploiting ships' cargo and existing infrastructure and minimising their operating costs. Further breaking down the June 2024 based data in the above charts, the following critical points arise and are provided below. To be noted however that the in-service dual-fuel LPGC fleet had further increased from 126 to 151 vessels by end 2024.

IN-SERVICE ANALYSIS

Chart 1: In-service VLGC fleet by class[1]

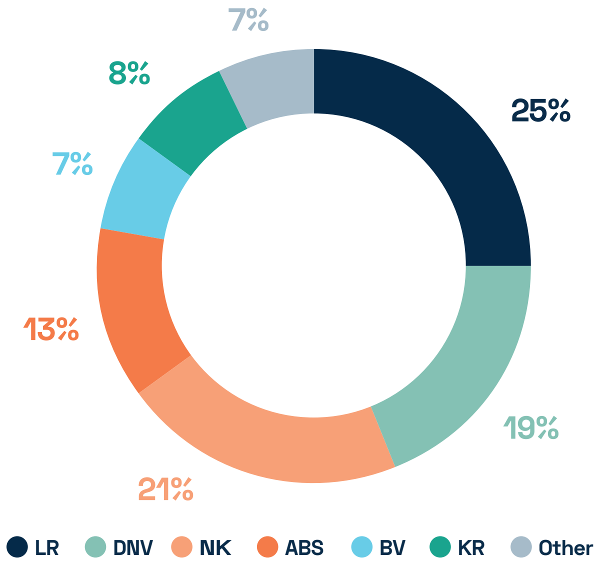
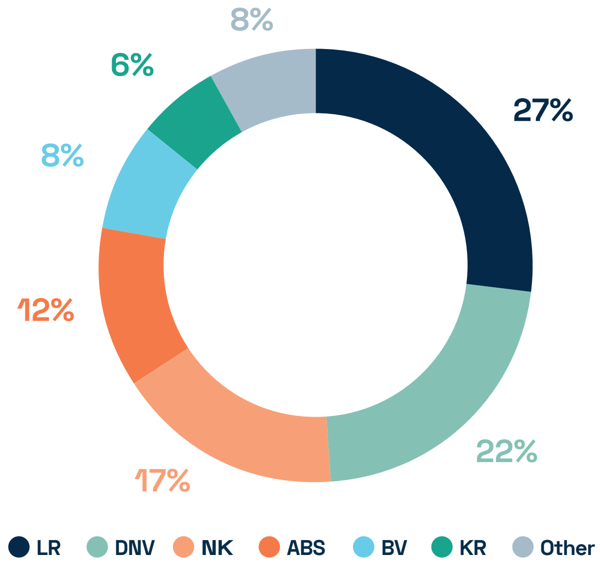
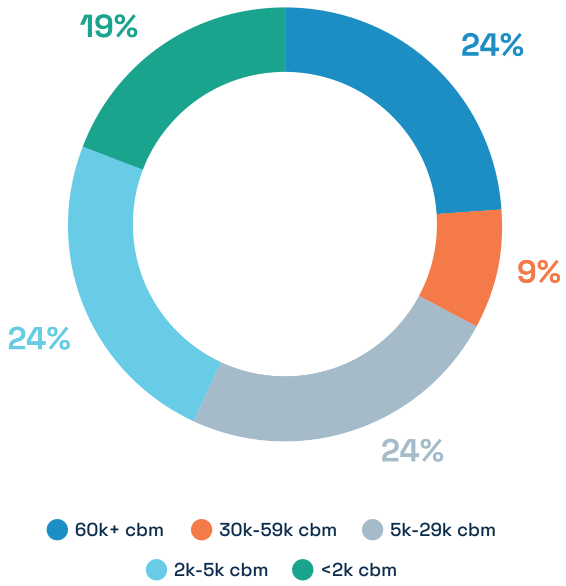


Chart 2: In-service LPGC fleet by class (>5k cbm)[1]



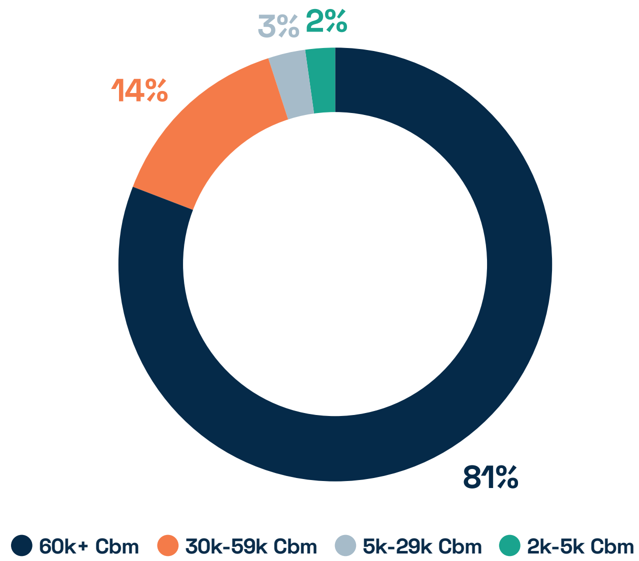
Class	LR	DNV	NK	ABS	BV	KR	Other
No of Ships	235	208	140	93	128	48	100
Gross tonnage in total (mGT)	7.6	6.0	4.6	3.2	2.3	1.7	2.1

Chart 3: In-service LPGC fleet by size[1]



Size	No. of Vessels
60k+ Cbm	**400**
30k-59k Cbm	**155**
5k-29k Cbm	**397**
2k-5k Cbm	**404**
<2k Cbm	**323**

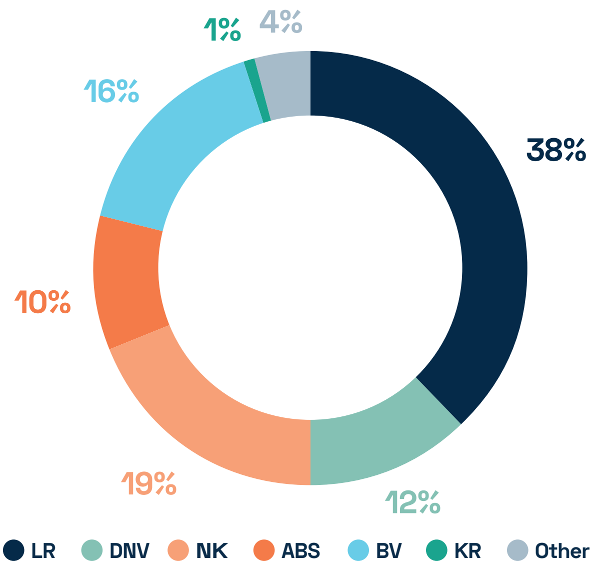
Chart 4: In-service dual-fuel LPGC fleet by size[1]



Size	No. of Vessels
60k+ Cbm	**102**
30k-59k Cbm	**18**
5k-29k Cbm	**3**
2k-5k Cbm	**3**

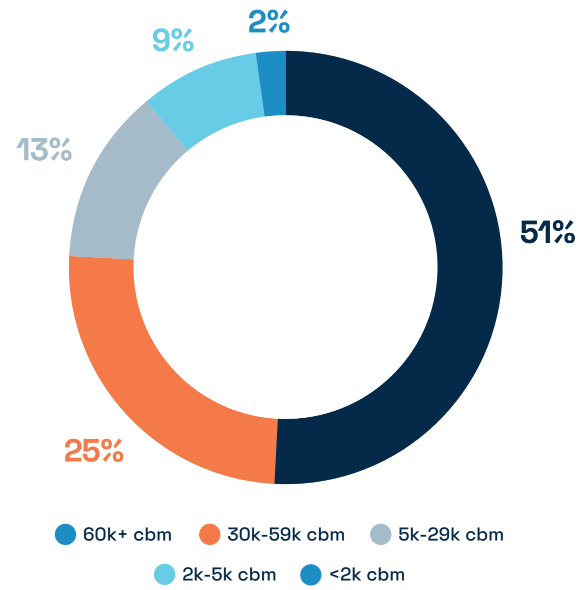
ORDERBOOK ANALYSIS

Chart 5: Orderbook LPGC fleet by class (>5k)[1]



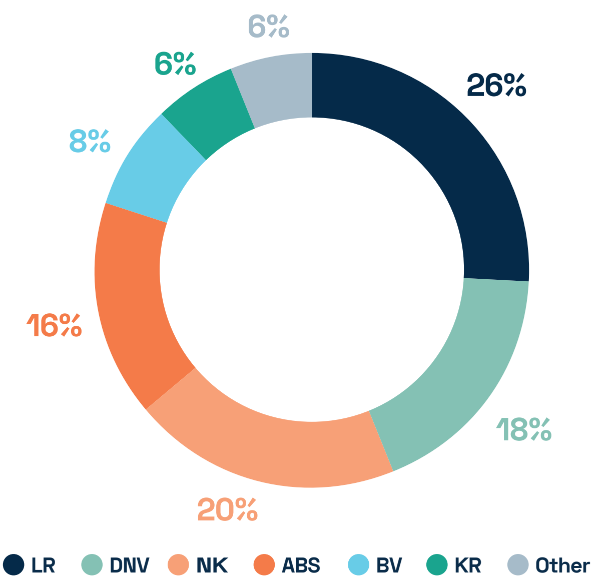
Class	LR	DNV	NK	ABS	BV	KR	Other
No of Ships	59	18	30	16	24	1	6
Gross tonnage in total (mGT)	2.3	0.8	1.4	0.6	0.8	0	0

Chart 6: Orderbook LPGC fleet by size[1]



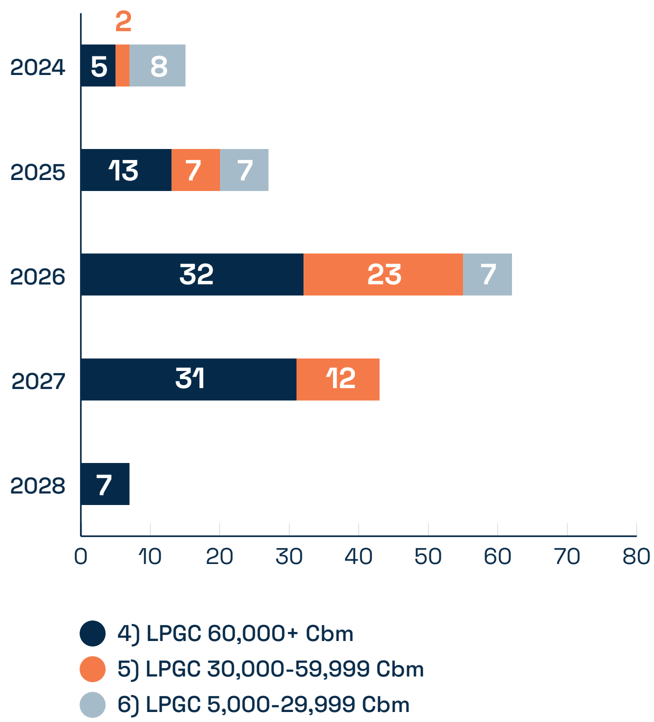
Size	No. of Vessels
60k+ Cbm	88
30k-59k Cbm	44
5k-29k Cbm	22
2k-5k Cbm	15
<2k Cbm	3

Chart 7: Orderbook and In-service VLGC fleet[1]



Age	Orderbook	0-4	5-9	10-14	15-19	20+
No.	88	120	130	34	58	58

Chart 8:LPGCS Expected Deliveries (>5k cbm)[1]



Further breaking down the data in the above charts, the following critical points arise and are provided below:

1. There are 88 VLGCs out of a total of 172 LPGCs under construction.
2. There are 400 VLGCs out of a total of 1,679 LPGCs in operation.
3. Age liability: 30% (116 out of 400) of the in-service VLGCs are currently over 15 years of age.
4. Out of 126 dual-fuel LPGCs in service, 102 are dual-fuel VLGCs (81%)

Significant rise in the LPG fleet capacity is expected in the coming years

The LPGC orderbook divided by shipbuilder and country, shows that the East shipbuilding market prevails. It is scheduled that 96 ships above 5k cbm will be constructed in Korea, 39 in China, 18 in Japan and one in Brazil until 2027, while most LPGCs are expected to be delivered during 2024 to 2026. The breakdown of the shipyards of each country is shown in chart number 9.

In addition, the LPGCs dual-fuel orderbook shows that South Korea is the leader with 59 orders, followed by China and Japan with 23 and 3 dual-fuel orders, respectively. Out of 85 dual-fuel LPGCs on orderbook, 61 are dual-fuel VLGCs (72%).

Considering both in-service and the orderbook, out of 211 dual-fuel LPGCs, 71 are LR classed dual-fuel LPGCs (34%), and their categorisation based on their main engine is given in the following chart.

Summarising the capacity of the existing and orderbook LPGC fleet, the available LPG fleet capacity arises from formulating the following chart. According to the latest data, there is 12% rise between 2022 and 2023 capacity while there will be a 26% rise in the available LPG fleet capacity between 2022 and 2026.

Chart 9: LPGC Orderbook by Shipbuilder (>5k cbm)[1]

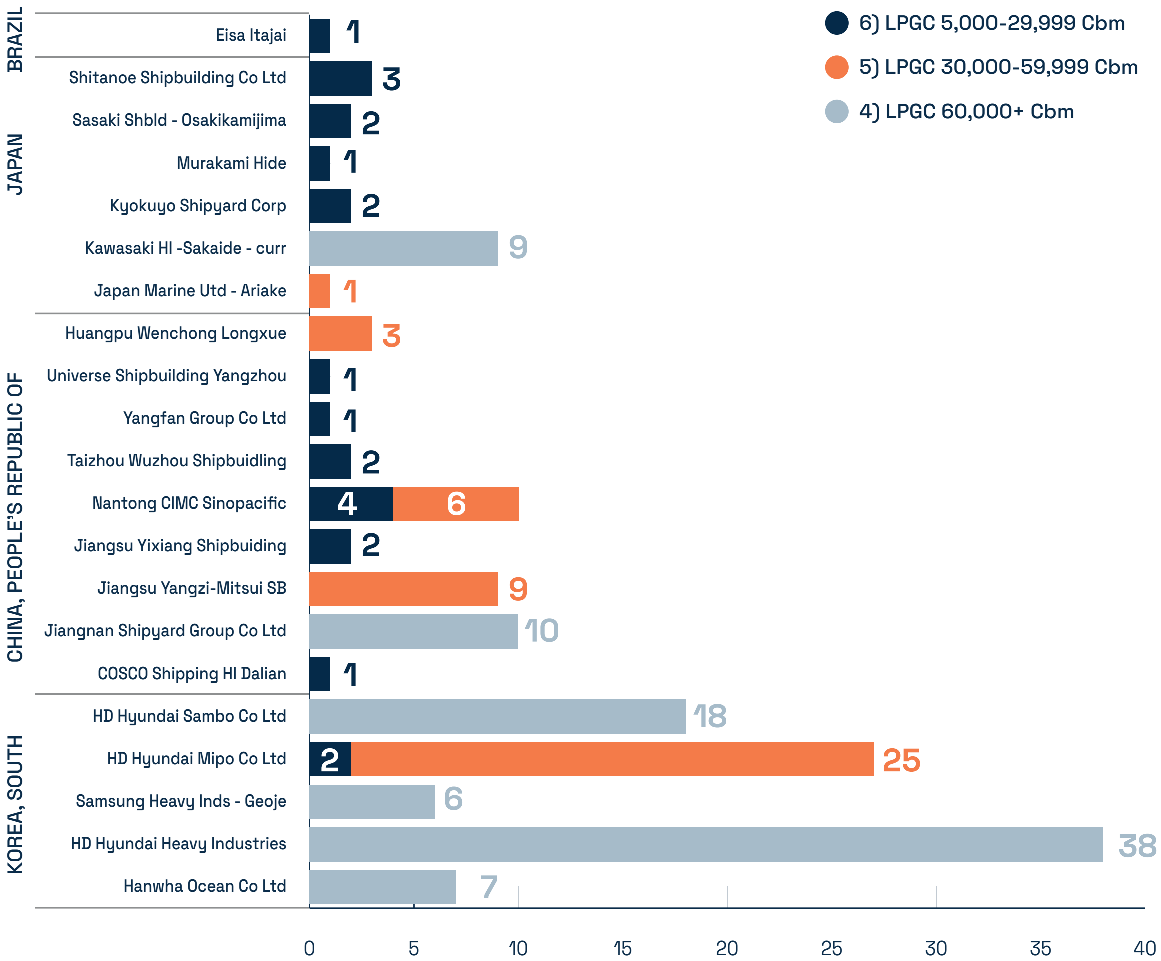


Chart 10: LPGC Dual-Fuel Orderbook by Shipbuilder[1]

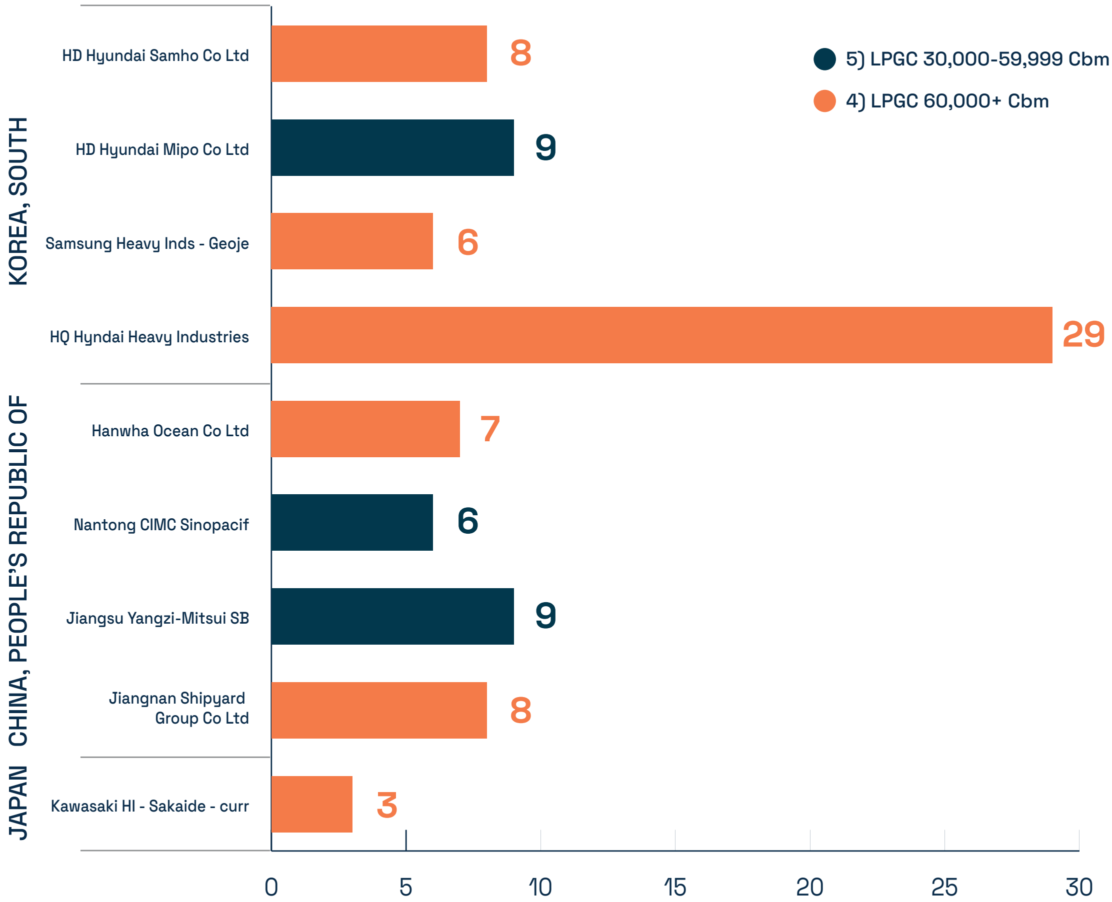


Chart 11: LPGC Dual-Fuel LPGC by M/E type[1]

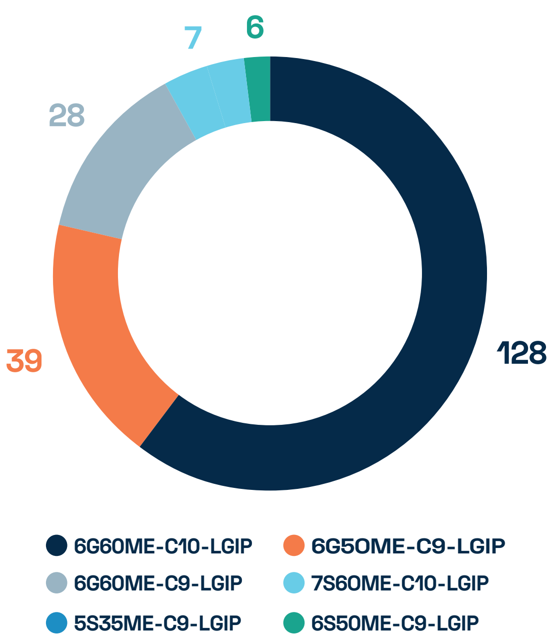


Chart 12: Projected LPG Fleet capacity (cbm)

3.2 LPG Fleet Expansion Potential

Regarding the available LPG marine engines, as can be extracted from chart 11, there are dual-fuel LPG engines for the following types:

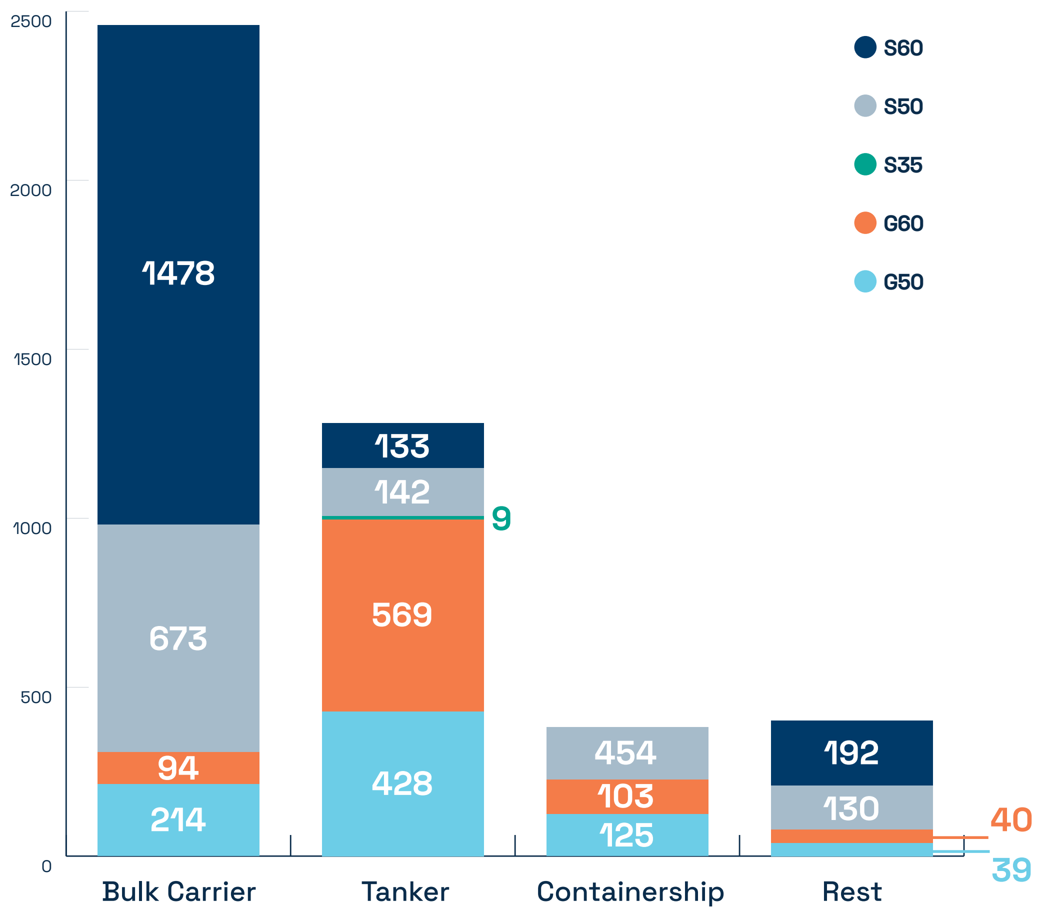
- S35ME-C
- S50ME-C
- G50ME-C
- S60ME-C
- G60ME-C

Based on the latest available data, there are about 4,090 ships equipped with those types of engines, and 747 are included in the order book, thus showing the hidden dynamics that can boost the adoption of LPG by those ships.

The following table presents a detailed breakdown of the figures of chart 13.

The analysis of the aforementioned fleet shows that tankers and containerships share 26% and 14% respectively of the total fleet. Considering the arrangement and the advantages that these types of vessels present in terms of retrofit feasibility, such as space availability on deck or in holds for accommodating the new LPG tanks, it seems that even though the subject market is still unexplored, it hides a lot of potential for the adoption of LPG as fuel.

Chart 13: Suitable M/E models for retrofit to LPG dual-fuel by type of ship and by engine[4]



Another categorisation based on the age of the subject fleet shows that the vast majority of about 76% (3,698) consists of ships of maximum age of ten years, while almost 46% (2,242) includes ships of maximum five years. Considering that ships can operate for up to 25 years, it arises that a minimum of 3,698 vessels are possible candidates for LPG retrofit and can have the maximum return on operators' investment.

The following table presents a detailed breakdown of the figures of chart 13.

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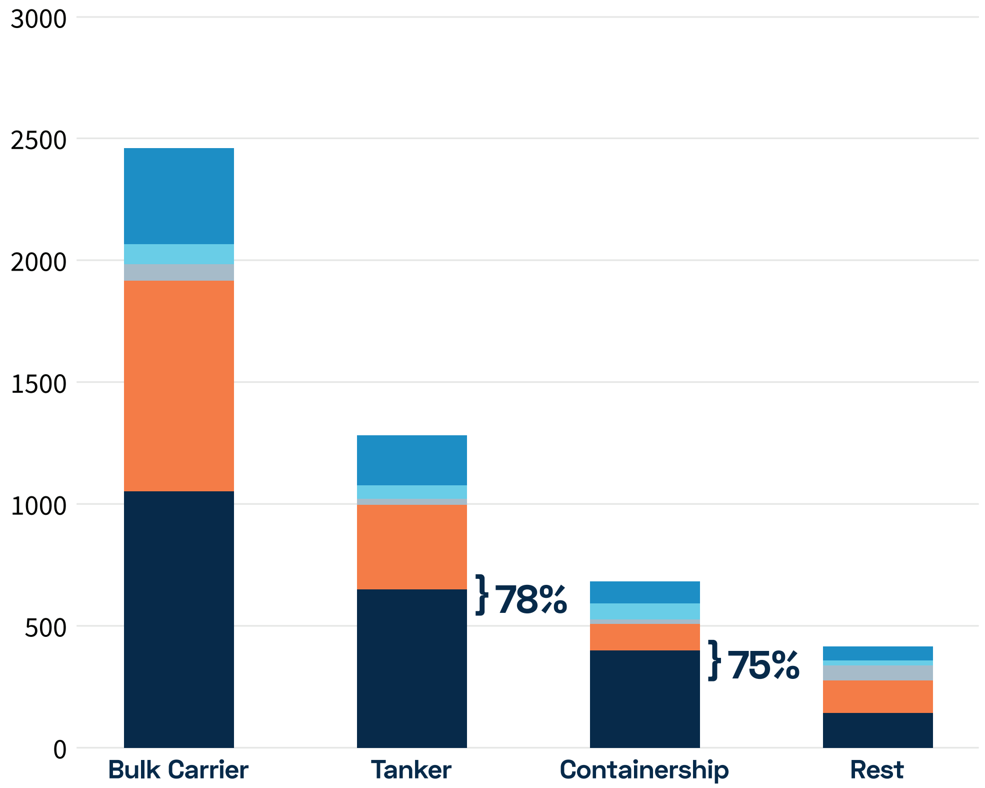
TABLE 2: BREAKDOWN OF CHART 13 (IN-SERVICE / ORDERBOOK)

Ship Type	Bulk Carrier	Tanker	Containership	Rest
S60ME-C	1418 / 60	129 / 4	399 / 55	169 / 23
S50ME-C	474 / 199	127 / 15	86 / 17	121 / 9
S35ME-C	-	5 / 4	-	8 / 6
G60ME-C	91 / 3	475 / 94	107 / 18	36 / 4
G50ME-C	82 / 132	340 / 88	-	23 / 16
Ship Category Share both In-service & Orderbook (out of 4.837 ships)	**51%**	**26%**	**14%**	**9%**

Chart 14: Suitable M/E models for retrofit to LPG dual-fuel by type of ship and by age band[4]



	Bulk Carrier	Tanker	Containership	Rest
Order	394	205	90	58
+15 yrs	81	56	65	19
11-15 yrs	69	23	18	61
6-10 yrs	864	348	109	135
0-5 yrs	1051	649	400	145

> There is a very large number of ships equipped with engine types that can be retrofitted to LPG Dual Fuel engines, demonstrating the high potential for the adoption of LPG as fuel.

The above statement is enhanced by the fact that 75% of the aforementioned containerships and 78% of the tankers are a maximum of ten years old, which means that they can have a minimum of 15 years of operation in LPG ahead.

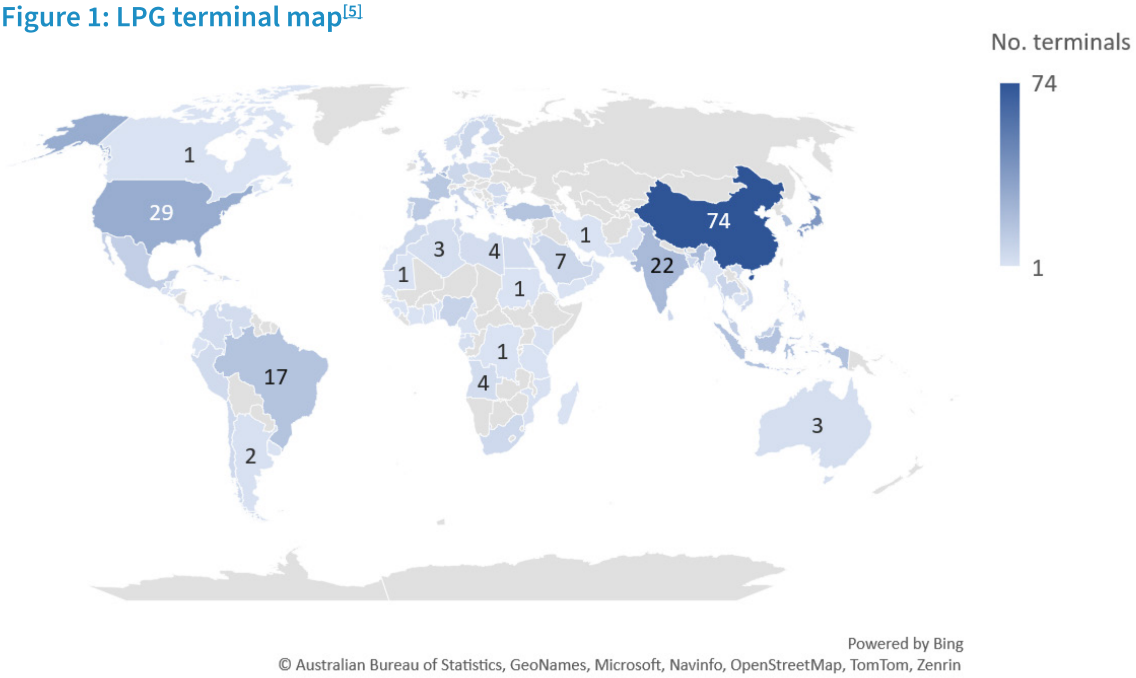
3.3 Terminals

There is a wide global distribution of LPG storage facilities, with 607 LPG terminals around the world that could potentially become LPG bunkering points for non-gas carriers as well, after considering the necessary terminal compliance aspects and covering the LPG as fuel demand[5]. One way for this to be achieved would be either directly without the need for significant initial investment from the terminal side or through the development of the bunkering supply chain via the already available small bunker vessels that will subsequently feed non-gas carriers even while undertaking cargo operations. Among the countries with the most terminals, China is at the top with 74 facilities, followed by Japan with 40, the USA with 29, and Belgium with 23. A representative map showing some countries with their respective LPG terminals that could support the LPG bunkering supply chain follows[3].

Even though LPG loading-unloading operations can be currently done at LPG terminals, LPG bunkering for non-gas carriers could potentially become a reality in due course, depending on the national framework and local legislation and a sufficient market driven by the demand for dual-fuel LPG engines by ship operators selecting LPG as fuel for non-gas carriers.

> There is a wide global distribution of LPG storage facilities, and 607 LPG terminals around the world that could potentially become LPG bunkering points also for non-gas carriers.

Figure 1: LPG terminal map[5]



[3] Considering port calls over 12hrs for Loading/Discharging operations, where the draft either increased or decreased between arrival and departure, based on AIS vessel data for vessels above 5k cbm for the period 28 August to August 2023.

3.4 Process Assurance for LPG Bunkering Operations

The transfer of LPG as fuel to non-LPG vessels, also known as LPG bunkering, is a process that has not been well documented and established. Having as a basis the guidelines on LNG bunkering such as ISO 20519 for LNG bunkering in ports, SGMF/EMSA guidelines and standards, as well as several countries' national legislation (PD 64/2019, Greece), an equivalent roadmap for LPG would be around the following pillars:

- Systems and equipment, including transfers, connections, insulation, emergency shutdown/release, maintenance, facilities, etc.
- Processes and procedures; including mooring, communication protocols, preparation/operation, risk assessment (safety zones, navigation, and traffic simulations), emergency preparedness and response, simultaneous operations protocol, etc.
- Management systems and quality assurance; including procedures, auditing, sustainability, records, port procedures manual, etc.
- Personnel training, responsibilities and familiarisation; including programmes and procedures, timetables, matrices and organograms, documentation, etc.
- Checklists, including for authorisation, preparation/pre-meetings, during and after operations, documentation and records, etc.
- Safety and compatibility studies; safety zone assessment and implementation, hazard identification workshops/studies for specific receiving/bunkering vessels, site evaluation at port/compatibilities, etc.

Apart from the regulatory framework as described above, there is a set of steps that should be followed before, during and after the bunkering process.

The so-called pre-bunkering phase begins with the ordering of bunkering and ends with the initiation of the actual bunkering process. During this preparatory phase, it is critical to make all the necessary actions to eventually achieve a safe fuel transfer. These actions include among others the following.

- Ensure that all the risk assessment findings have been properly addressed;
- Compatibility assessment between the receiving vessel and the bunkering facility;
- Emergency response plan agreed upon and in place;
- Safety instructions and training of the involved personnel;
- Engagement with the responsible authority bodies regarding any permissions that need to be granted;
- Assessment of any other processes, such as SIMOPS;
- Operational details like transfer rate, loading limits, ESD, ERS, etc.; and
- Completion of all the necessary pre-bunkering checklists.

The bunkering process starts with the connection of the receiving vessel to the bunkering facility, continues with the actual fuel transfer, and ends with all the necessary actions leading to the safe closure of the valve from the bunkering facility. During the bunkering phase, essential parts of the system should be continuously monitored, such as:

- Tank levels;
- Tanks pressure;
- Tank temperature;
- Pump transfer rates;
- Pump flow rates;
- ESD and ERS operations;
- Mooring lines and hoses adjustment; and
- The monitoring and safekeeping of other safety aspects, like the safety zones.

Upon the completion of the bunkering, attention should be paid to the following points:

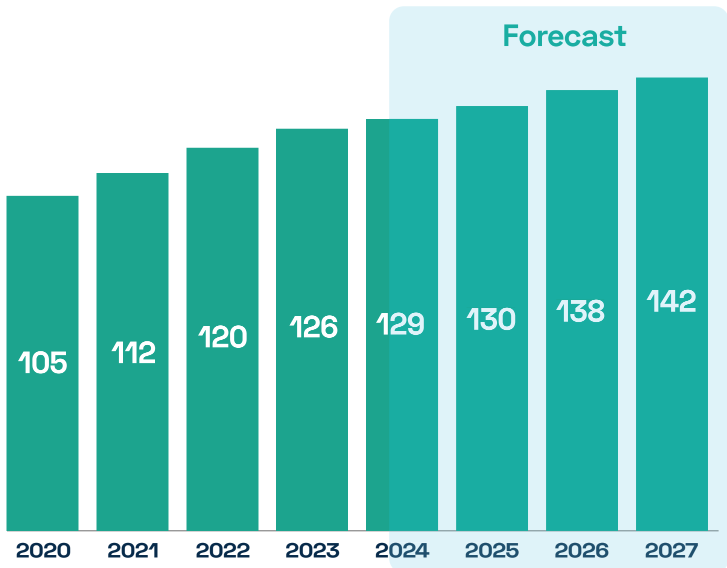
- Essential system procedures like vaporisation of the lines, inerting of the bunkering lines and hoses, etc. must be successfully done without the release of any gas into the atmosphere;
- Safe disconnection of the receiving vessel and the bunkering facility;
- Safe unmooring of the receiving or bunkering vessel from the receiving vessel and notification of the port authority.[6]

Six more million tonnes of LPG were expected to be traded in 2023 compared to 2022, corresponding to a 5% increase, and similarly for 2024, a further 2.4% increase is expected.

3.5 Availability

The LPG market continues to experience an upcoming rise in demand, as reflected in the LPG world seaborne trade. The available data show that during 2023, six more million tonnes of LPG were expected to be traded compared to 2022, corresponding to a 5% increase. Similarly, for 2024, a 2.3% rise is expected compared to 2023 and it is forecast that the trade volume will reach almost 142 million tonnes in 2027[7].

Chart 15: World Seaborne LPG trade volumes (mtonnes)[7]



> The USA, China, Qatar, and Japan play a significant role in the LPG trade and value chain as they are the top LPG exporters-importers via VLGCs

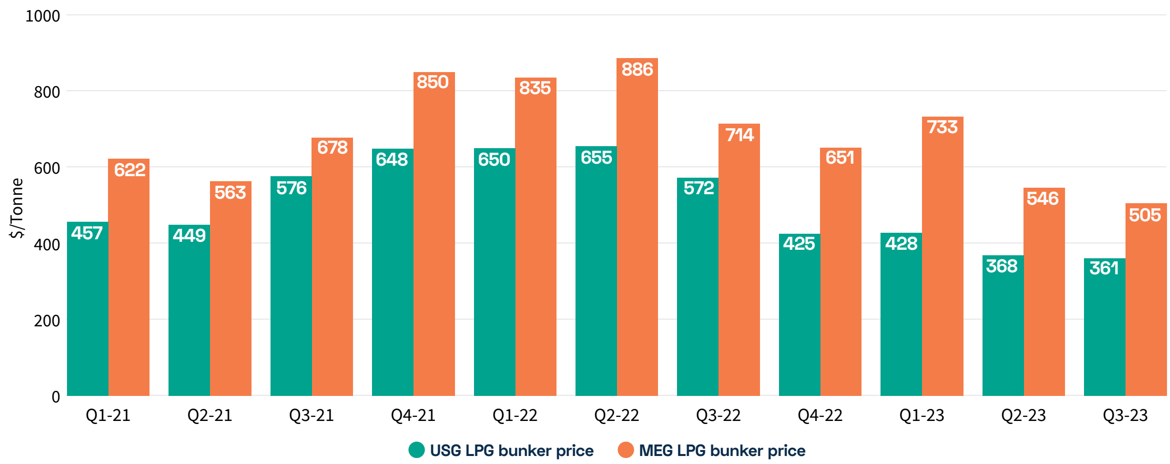
3.6 Pricing

Among other factors, the pricing of LPG, especially in some regions, makes it an attractive option for owners and operators. The following chart shows the estimated LPG bunker prices[4] for the United States and Middle East Gulf.

3.7 Trade

The USA, China, Qatar, and Japan play a significant role in the LPG trade and value chain as they are the top LPG exporters and importers via VLGCs[5]. Between August 2022 and August 2023 for the VLGCs category, the loading and discharging operations were formulated as per the following charts 17 and 18. In these charts, specifically for the loading countries, it is shown that the USA presents almost 509% higher VLCG port calls compared to the second, Qatar while for the discharging countries, China prevails with 722 port calls and Japan comes next with 479 port calls.

Chart 16: LPG bunker prices ($/ton)[8]



[4] Price represents calculated estimate of LPG bunker price in the US and Middle East Gulf, in terms of $ per metric tonne LPG, basis conversion of Mont Belvieu Propane prices using standard conversion factors and a fixed assumption for LPG bunkering delivery cost (including infrastructure costs and ship-to-ship delivery). Prices are not intended to reflect precise figures nor are basis actual transactions, but are intended to provide an approximate indication of USG LPG bunker price trends and levels.

[5] Considering port calls over 12 hours for loading and discharging operations, where the draft either increased or decreased between arrival and departure, based on AIS vessel data for vessels above 5k cbm for the period 28 August to August 2023.

Chart 17: Top 10 Loading Countries (VLGCs)[5]

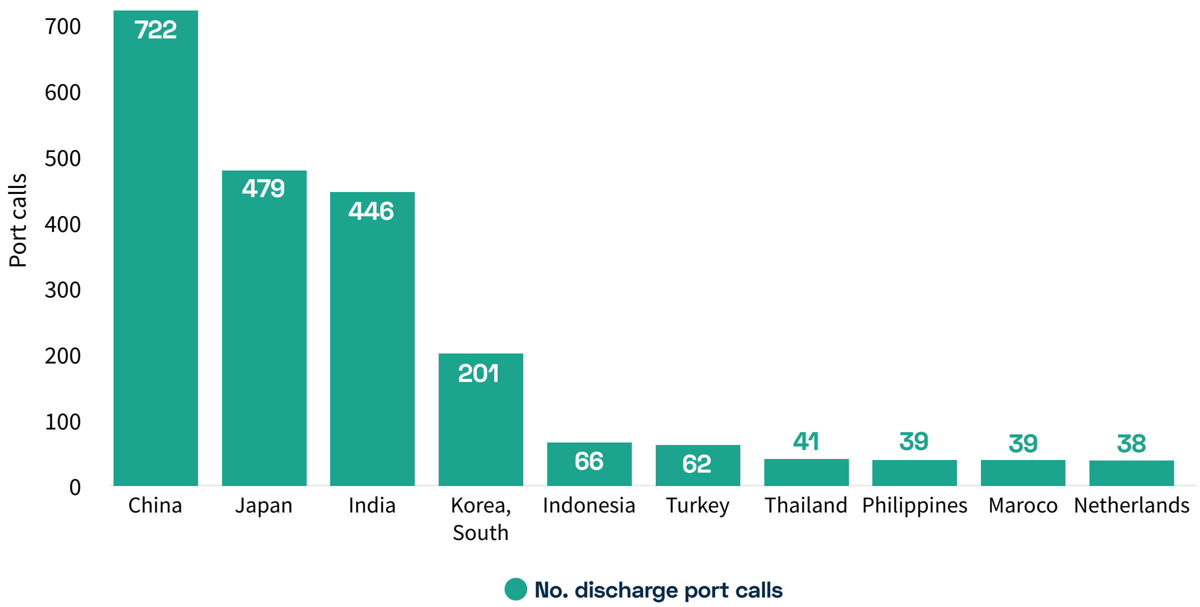
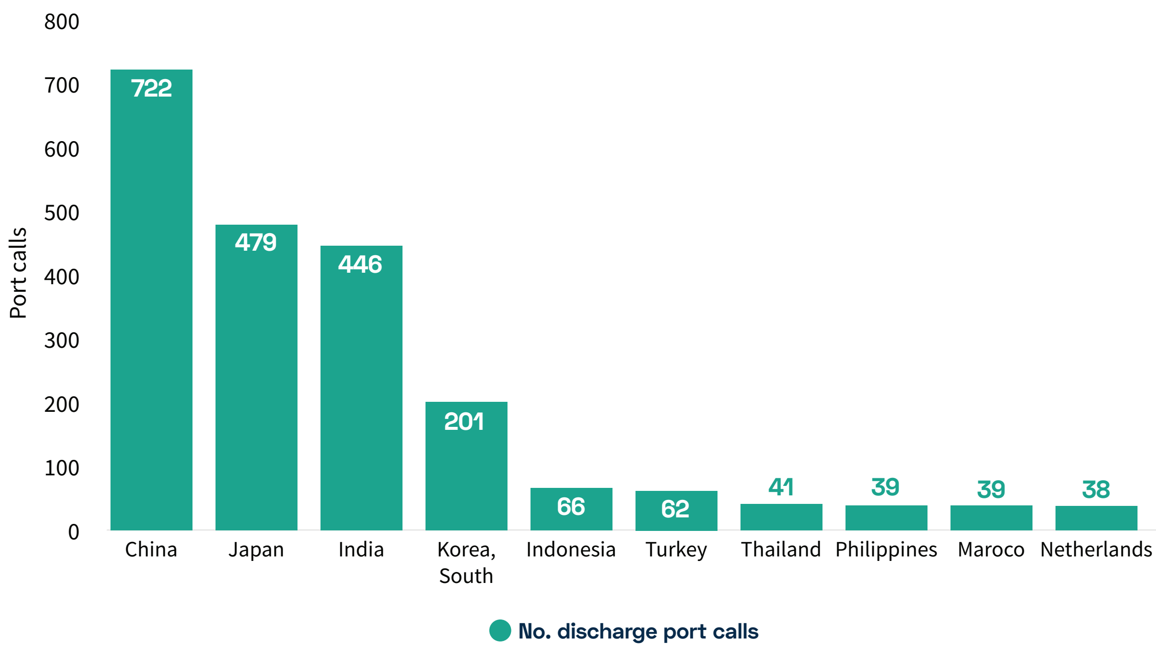


Chart 18: Top 10 Discharging Countries (VLGCs)[5]



A global distribution of the VLGCs trade routes is presented in the following picture.

For the MGCs (30k to 65k cbm) category for the same time period (August 2022- August 2023) the trade followed a more even distribution where the USA still prevailed for the exports and India for the imports.

Figure 2: VLGCs trade route heat map[5]

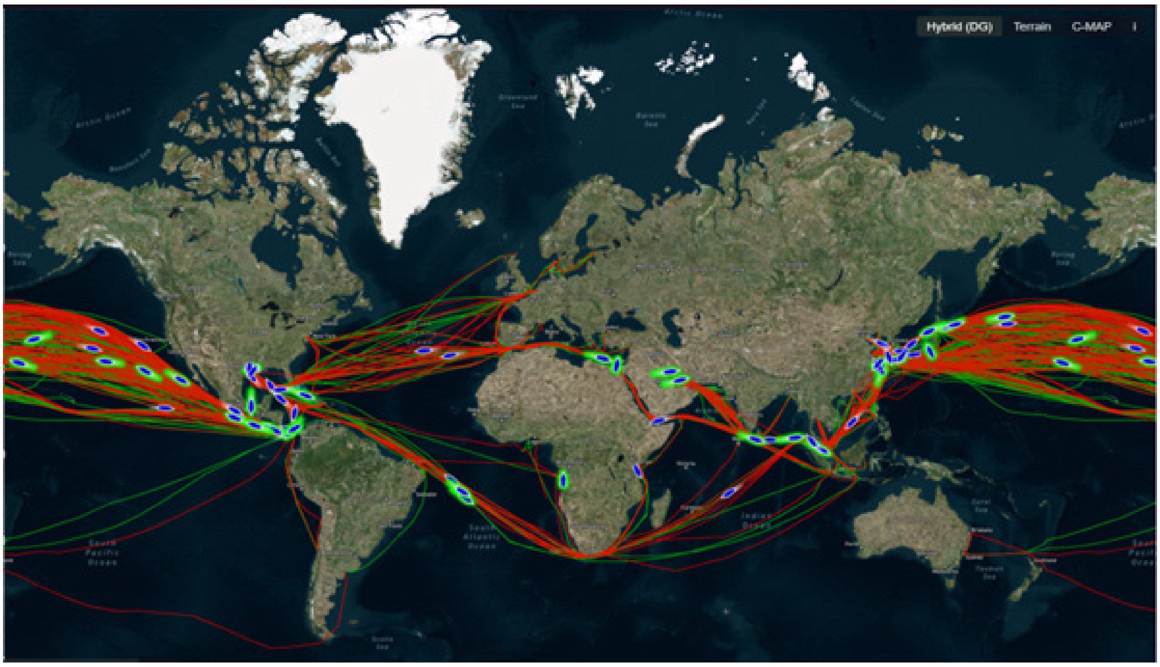


Chart 19: Top 10 Loading Countries (MGCs 30k to 65k cbm)[5]

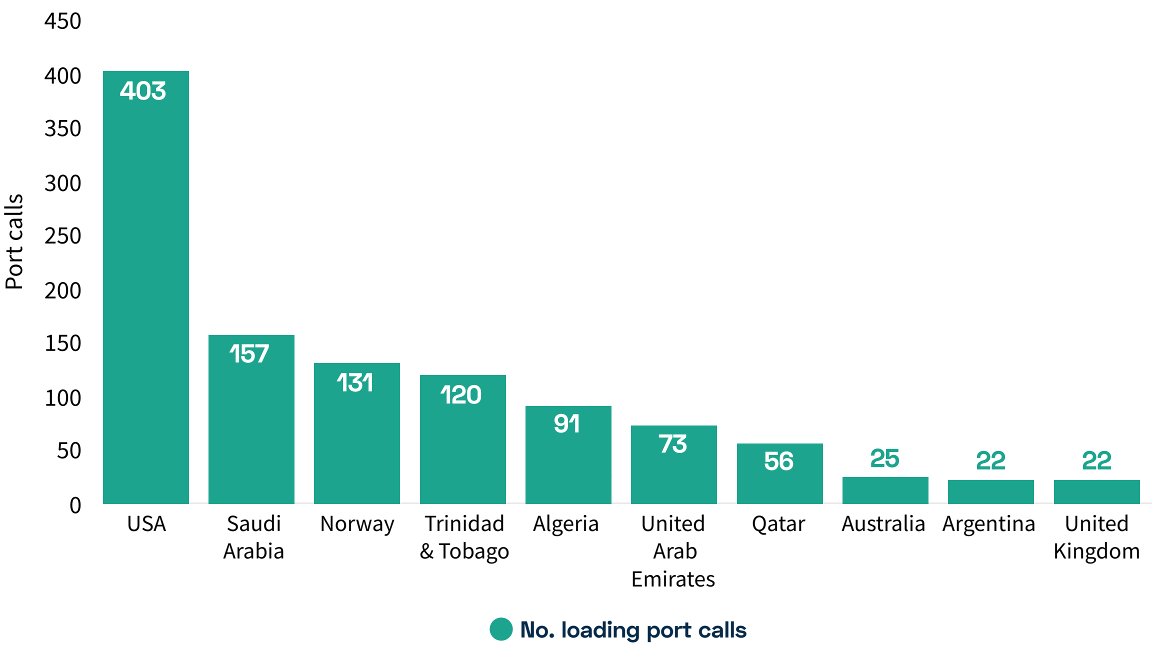


Chart 20: Top 10 Discharging Countries (MGCs 30k to 65k cbm)[5]

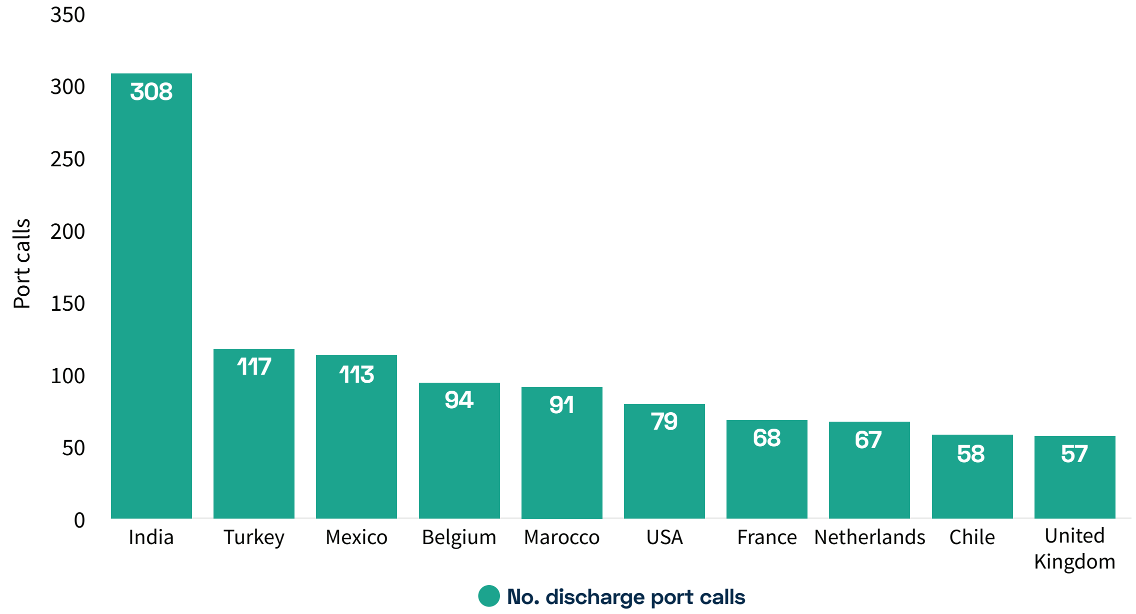
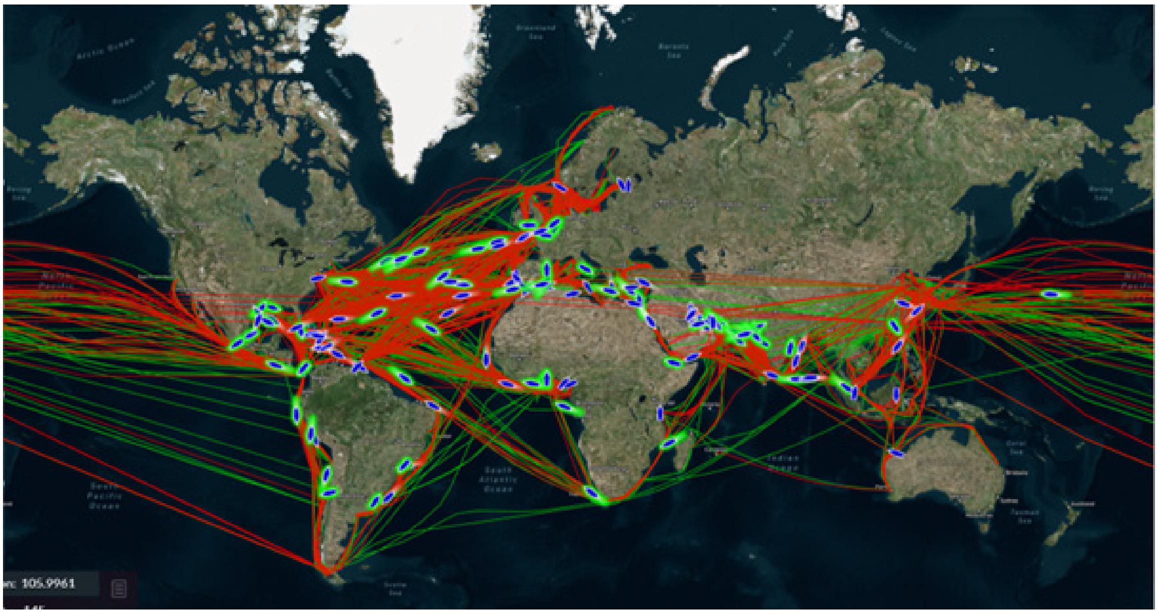


Figure 3: MGCs trade route heat map[5]



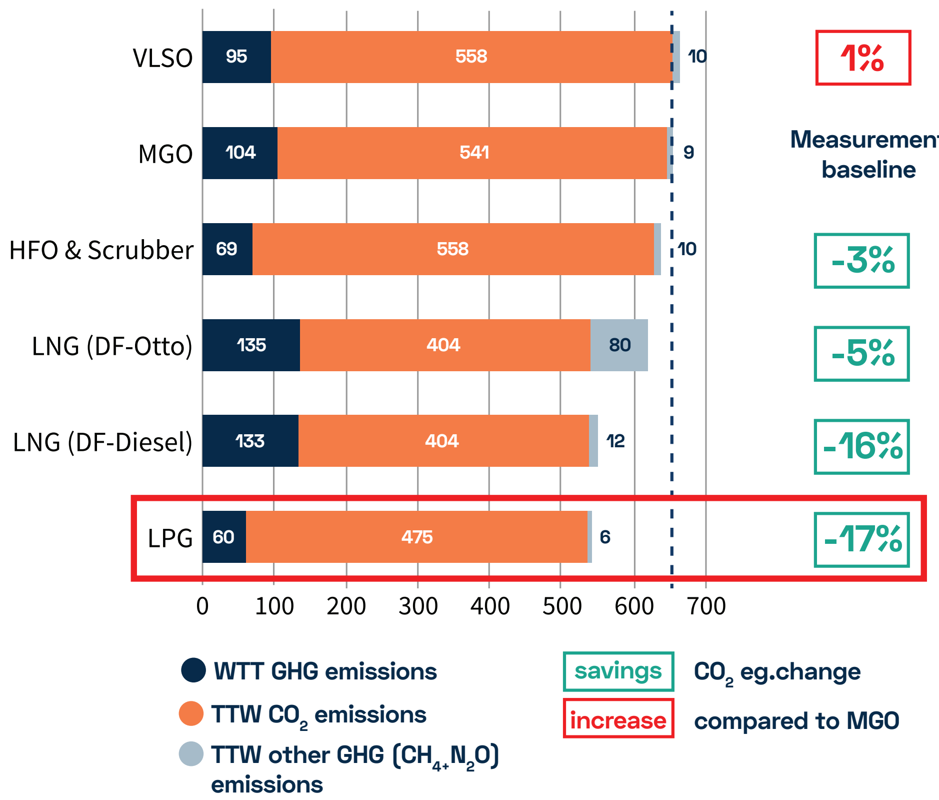
4. Carbon Footprint and Environmental Profile

As per the marine engine manufacturer MAN ES, the use of LPG as fuel can reduce CO_2 emissions by up to 13% when compared to MDO and by up to 18% when compared to HFO[2]. Another study shows that when taking into consideration the total lifecycle WtW GHG emissions, LPG can lead to 17% lower gCO_{2eq}/kWh compared to MGO, bringing it to the best position and the best choice for GHG emission reduction amongst all other options shown in Figure 4[9].

At MEPC 80, regarding the discussion of the reduction of GHG emissions from ships, the final report of the Correspondence Group on Marine Fuel Life Cycle GHG Analysis established by MEPC 78 was completed. Specifically, the MEPC adopted guidelines on the life cycle GHG intensity of marine fuels (LCA guidelines), including the fuel pathways of LPG.

LPG contains negligible sulphur meeting the IMO's 2020 and ECA fuel sulphur limit requirements. Regarding NOx emissions, even though the use of LPG can lead to a 20% reduction, compliance with TIER III needs to be secured with the subsequent use of Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR). Due to the lower carbon-to-hydrogen ratio compared to oil, LPG leads to lower CO_2 emissions and subject reduction directly affects the implementation of EEDI, EEXI and CII (expressed in gCO_2 /tonnes nautical mile), which include fuels' carbon factors in their formulas.

Figure 4: Fuels WTW CO_2 and CO_{2eq} emissions[9]



LPG is fully compliant with IMO's 2020 Fuel Sulphur Limit Requirements.

Liquid Gas is a Low-Carbon Marine Fuel Solution.

Regarding "Fit for 55" and the directives that are directly linked with the shipping industry, LPG as a marine fuel can play a crucial role there as well. Due to the lower CO_2 emissions generated using LPG, companies will find themselves in an advantageous position when it comes to considering EU ETS and FuelEU directives. Furthermore, the option of LPG and further bio or renewable LPG go in parallel to the Energy Taxation Directive (ETD) and the Alternative Fuels Infrastructure Regulation (AFIR) where the implementation of ammonia is promoted. Finally, regarding the Renewable Energy Directive (RED) and the fact that LPG can also be produced from renewable sources, thus being transformed into bioLPG or renewable LPG, interested parties can understand that through the RED, the development of the LPG supply chain is being indirectly supported and forced.

Figure 5: Generic Well to Wake supply chain[10]

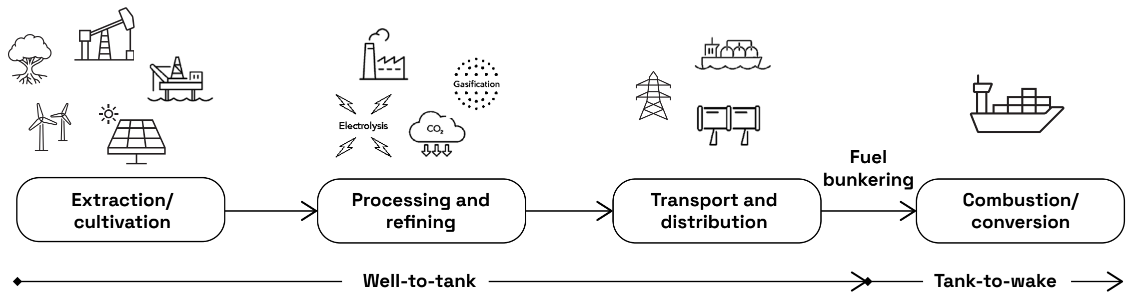
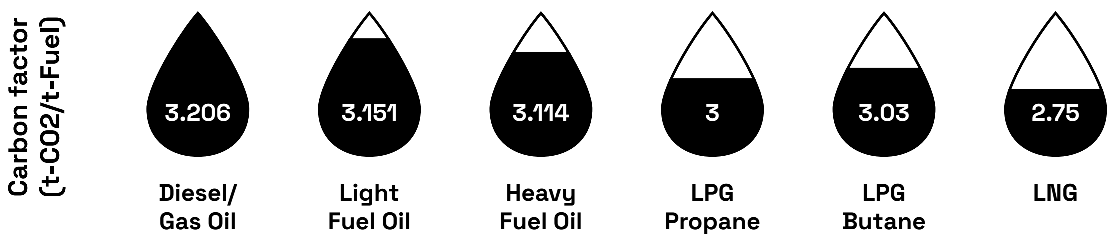


Figure 6: Fuels Carbon Factors[11]



5. Technology

As far as engines' technology readiness is concerned, MAN ES is the only manufacturer so far providing newbuilding and retrofitting LPG dual-fuel solutions for two-stroke main engines through its ME-LGIP engine series. These engine types utilise the diesel cycle combustion process to burn both fuel oil and LPG, with a small amount of compliant fuel oil used as a pilot fuel in LPG mode. Several in service ME-C engines can be retrofitted to dual-fuel ME-LGIP engines capable of burning LPG as fuel[12].

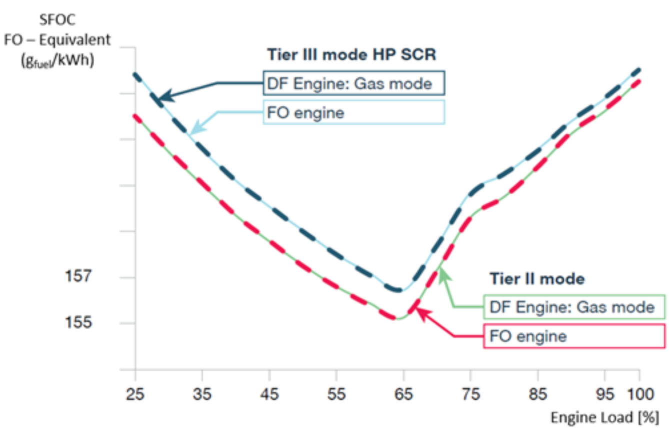
The ship's main engine modification process in the case of retrofitting includes:

- New cylinder covers
- Additional gas control block
- New LPG injection valves
- Additional gas piping
- New sealing oil pumps
- Control system upgrade

As of March 2023, MAN ES has already developed the LPG dual-fuel engine types shown below and the execution of a retrofit project presupposes their existence. In order for MAN to expand to more engine sizes, there should be strong interest and sufficient driven demand for the LGIP engines.

- G60ME-C
- S60ME-C
- G50ME-C
- S35ME-C
- S50ME-C

Figure 7: Dual-Fuel Engine (DF) vs Fuel Oil (FO) engine TIER III engine HP SCR[12]



MAN ES's LPG Dual-Fuel Technology: A Game Changer for Two-Stroke Main Engines.

Other manufacturers such as Wärtsilä have provided land-based 4-stroke solutions and have the technical knowhow to build 4-stroke engines operating on LPG, either as dual fuel or single fuel. LPG operation has already been proven, as in the case of the case of the Wärtsilä 32LG engine – a flexible, multi-fuel engine capable of operating with hydrocarbons in the range from propane to LFO, or carbon number C3 to C20 – a landmark in the company's development of engine solutions. Further, Wärtsilä can develop new upgrades for the engines running on HFO/MDO to LPG, pending market demand.

Also, recently WinGD expanded the innovative option for its X-DF-A ammonia-fuelled engines to X-DF-P, allowing them to also run on LPG vessels currently under construction to meet the anticipated growth in the ammonia trade, while maintaining the capability to transport LPG. The engine, optimised for ammonia fuel, will operate on LPG, with a simple modification allowing for future use on ammonia. WinGD X-DF-P engine sizes under development are those typically used by trade-relevant vessels, including 52- and 62-bore.

6. Regulatory Compliance

While the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) covers the construction and equipment of ships carrying liquified gases in bulk (liquefied bunker ships are within the scope of the IGC Code), the use of gases or other low-flashpoint fuels like LPG as fuel onboard for non-gas carriers is governed by the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF). Considering the nature of the fuels involved, this code indicates the necessary prerequisites for the equipment, machinery, other systems, and their arrangement on board, for the vessel to run safely on gas or low flashpoint fuels in a way that the risk to the ship, its crew and the environment is minimised. In addition to the goals, functional requirements, risk assessment and prescriptive requirements for LNG, the IGF Code also addresses operational requirements and crew training requirements.

At the Maritime Safety Committee (MSC) 107, the "MSC.1/Circ.1666 Interim guidelines for the safety of ships using LPG fuels" were approved to provide an international standard for ships using LPG as fuel, and subject to the IGF Code, to achieve the same level of safety and reliability as new and comparable conventional oil-fuelled main and auxiliary machinery installations.

The IMO Carriage of Cargoes and Containers (CCC) sub-committee has also been developing requirements for LPG cargo as fuel under the IGC Code. These are expected to be approved by MSC 108 in May 2024.

It should be noted that interested stakeholders may refer to the Society of International Gas Tanker and Terminal Operators (SIGTTO), the Society for Gas as a Marine Fuel (SGMF) and to the International Organization for Standardization (ISO) guidelines for cargo loading-unloading and bunkering operations.

In the same direction, LR has published the LFPF (GC, PG)[6] notation, which refers to gas carriers designed, constructed, and tested to operate on low-flashpoint fuels like LPG. Similarly, it has published LFPF (GC, AM)[7] and GR (AM, A)[8] which allow owners to further use ammonia on their vessels as fuel, while through the LFPF (GF, PG)[9] and LFPF(GF, AM)[10] LR addresses the adoption of LPG and ammonia as fuel by non-gas carriers.

In terms of regulatory framework, LPG bunkering still lacks an official regime that could encourage stakeholders to adopt it as a marine fuel. Developing LPG bunkering guidelines could follow a similar pathway to what has been done for other fuels, e.g. LNG and promote safety, efficiency, and environmental awareness. First and foremost, there should be extensive collaboration across the LPG industry, including shipping companies, LPG suppliers, port authorities, classification societies, equipment manufacturers and other relevant industry associations that are able to share their knowledge and expertise. Regulatory bodies and governmental agencies responsible for maritime safety and environmental regulations should be engaged with the IMO, to ensure compliance with standards and already established regulations. That would also guarantee consistency and safety across different ports around the globe.

Deep research into existing LPG handling practices should be conducted in parallel with the identification of the best practices applied to other fuels, like LNG, to provide the foundation for LPG specific bunkering guidelines. In addition, the potential hazards associated with LPG bunkering should be identified and measures to mitigate those risks should be considered.

[6] Low Flashpoint Fuels (Gas Carrier, Liquid Petroleum Gas)
[7] Low Flashpoint Fuels (Gas Carrier, Ammonia)
[8] Gas Ready (Ammonia,A)
[9] Low Flashpoint Fuels (Low-flashpoint machinery, Liquid Petroleum Gas)
[10] Low Flashpoint Fuels (Low-flashpoint machinery, Ammonia)

Moreover, the technical standards and specifications for LPG bunkering equipment such as transfer hoses, nozzles and valves should be developed and the performance criteria and safety requirements of these components should be defined. In parallel, detailed LPG bunkering operational procedures should be developed and best practices for the safe and efficient transfer of LPG should be communicated.

Having mentioned the above, a procedure for testing and certifying LPG bunkering equipment should be established, while detailed and extensive documentation and training materials to educate the different stakeholders, like operators, crew members and personnel in bunkering operations, should be issued and circulated.

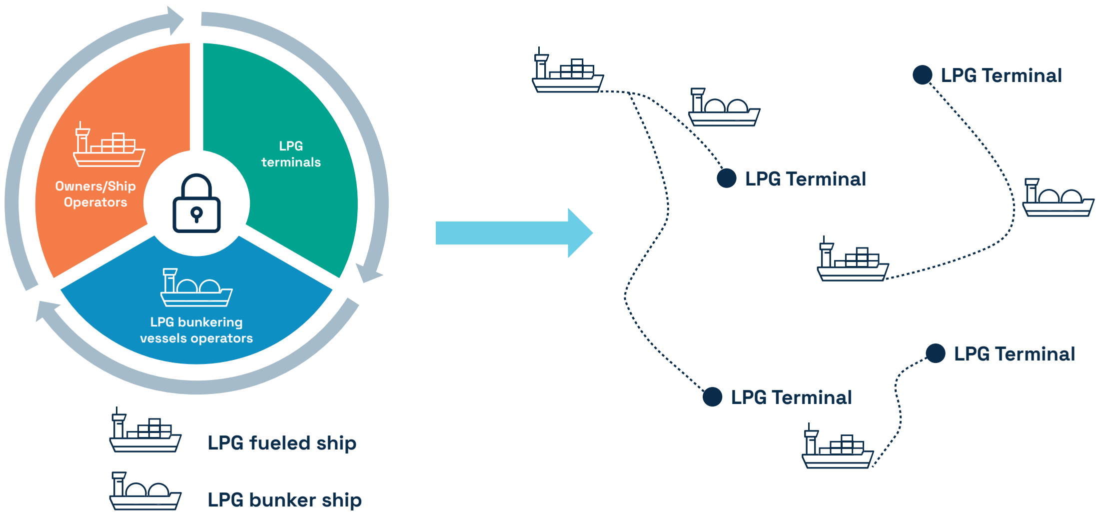
Pilot projects and demonstrations are also very important as well to validate the aforementioned framework and procedures. Potential gaps or issues would be identified through pilot projects and would lead to the refinement of procedures and the improvement of safety measures.

7. Value Chain Approach/ Business Model for Feasible Projects

For the adoption of LPG as a marine fuel, either via newbuild or retrofit, the decision makers should consider the different parts of the value chain to de-risk the project and co-develop it with other complementary stakeholders. All parties should work together to address the arising issues, such as technical, logistical, and supply barriers. First and foremost, owners should consider the available volumes of LPG as a marine fuel and the supply points for it across the globe. As mentioned previously, there are currently 607 LPG terminals available worldwide, and their trade is projected to be 142[11] m tonnes by 2027. Further focusing on the supply of LPG, there are 995 LPG carriers of up to 15.000 cbm that could be operated as bunkering vessels[1]. On that basis, ports and terminals play their own pivotal role, as they are the ones that should support the expansion of the LPG supply chain as well.

To de-risk the use of LPG as a marine fuel, owners can pre-establish a business model similar to that of LNG in the early stages of its development. It is a "chicken-egg" problem that should be approached holistically by all interested parties and stakeholders. Synergies should be developed between shipping providers and users and prior to proceeding with an order for an LPG fuelled ship, either a retrofit or a newbuild, owners can collaborate and come to agreements with charterers to bear the charter premium and small LPG carriers and LPG terminal operators that will subsequently secure the availability and price at which the LPG will be sold as bunker fuel. In this way, a resilient and financially optimised supply chain will be built, thus leading other parties to follow the same route and finally establish and expand the subject market.

Figure 8: LPG as a marine fuel initial steps



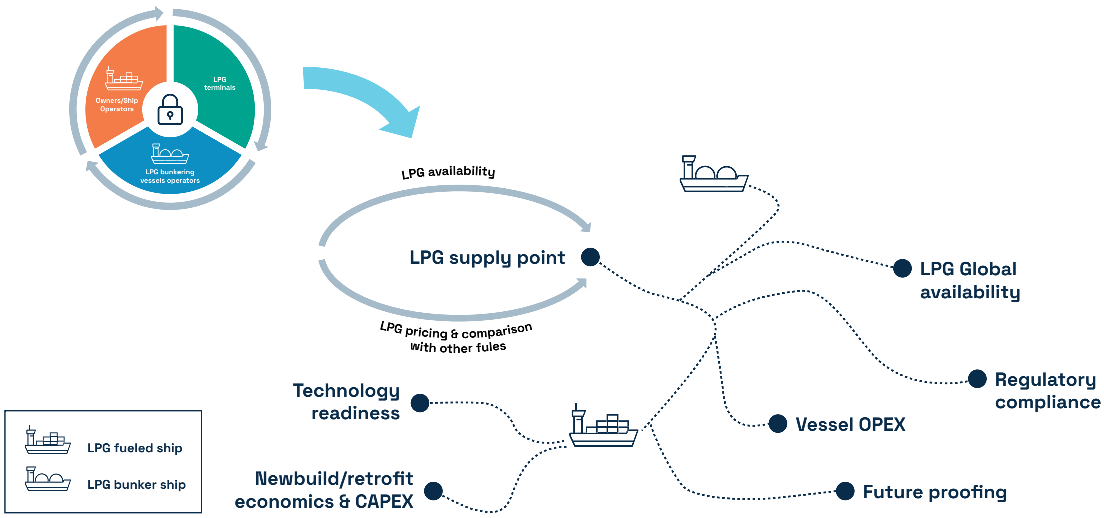
[11] Chart 15

Having considered the business model, the technology readiness level should be examined, and as of now, as stated above, only MAN ES provides models of LPG dual-fuel two-stroke engines (ME-LGIP) that can be used for propulsion purposes. The ME-LGIP engines that have been installed so far and are in the orderbook are shown in subchapter 3.1 and in case of strong market interest for other models of ME-LGIP engines, MAN ES could develop additional engine types. In the case of a retrofit, owners should consider that the whole procedure will take about six months for the engineering, nine months for production and transportation, one to two months for conversion and installation and about 20 days for sea and gas trials.

Shipowners and ship operators must consider several points to explore the feasibility of a specific project. The holistic evaluation includes, of course, the CAPEX and OPEX from the operation with LPG as fuel in parallel with the regulatory landscape and the future proofing and securing of the investment against the upcoming maritime fuel transition regulations. Owners should consider the EU's regional ETS and the FuelEU maritime that will soon come into force and will affect ships' operations and economics, something unprecedented for the shipping industry.

Shipowners and ship operators need to consider several points for the feasibility of a specific project with LPG as fuel, including CAPEX and OPEX, in parallel with the regulatory landscape and the upcoming maritime fuel transition regulations like EU's regional ETS and the FuelEU maritime.

Figure 9: LPG as a marine fuel developed value chain



8. LPG Sustainable Pathways

As mentioned above, the shipping community's actions towards decarbonisation are a reality and LPG can be utilised as a link on the fuel transition chain prior to alternative and zero carbon fuels, which for the time being are under deep research and development. Out of those fuels, bioLPG, rDME and ammonia stand out. Moreover, on the same path of decarbonisation, LPG can optimise any CCS or WASP onboard the ships, as will be explained below.

8.1 Renewable LPG and bioLPG

As it is chemically and physically identical to conventional LPG, bioLPG or renewable LPG belongs to the liquid gases category and can totally substitute LPG without any equipment or machinery upgrades or energy loss during the engine's combustion. On this basis, they can be further blended at any rate for more fuel flexibility and better environmental performance, with up to an 80% lower carbon footprint, depending on the used feedstocks, compared to conventional LPG while maintaining the same NOx, SOx and PM emissions.

BioLPG is a naturally occurring by-product and can be produced from biological sources and potentially from renewable electricity and CO_2[13]. Currently, the only commercialised production processes of bioLPG are that of hydrotreated or hydrogenation of vegetable oils, fats and biomass derived oils (HVO), where bioLPG arises as a by-product and that of oligomerisation[14][15]. Other bioLPG production pathways exist and are also promising; however, these are still not mature and commercially available. Time and more resources are needed to bring these technologies from the research and development stage to commercial scale.

Figure 10: Pathways to bioLPG and renewable LPG[13]

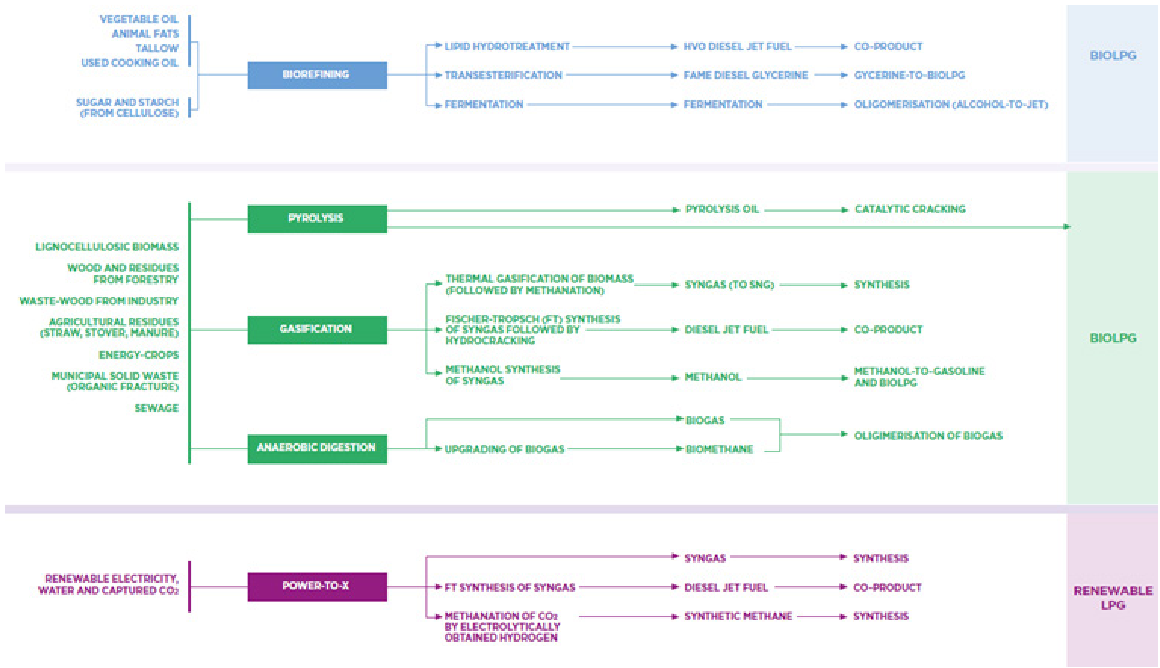
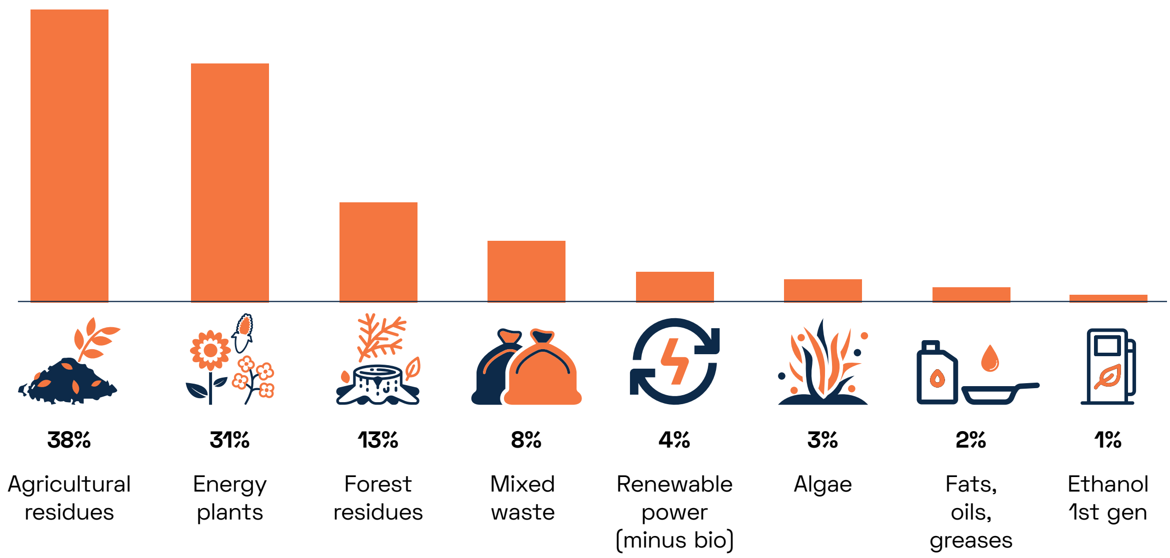


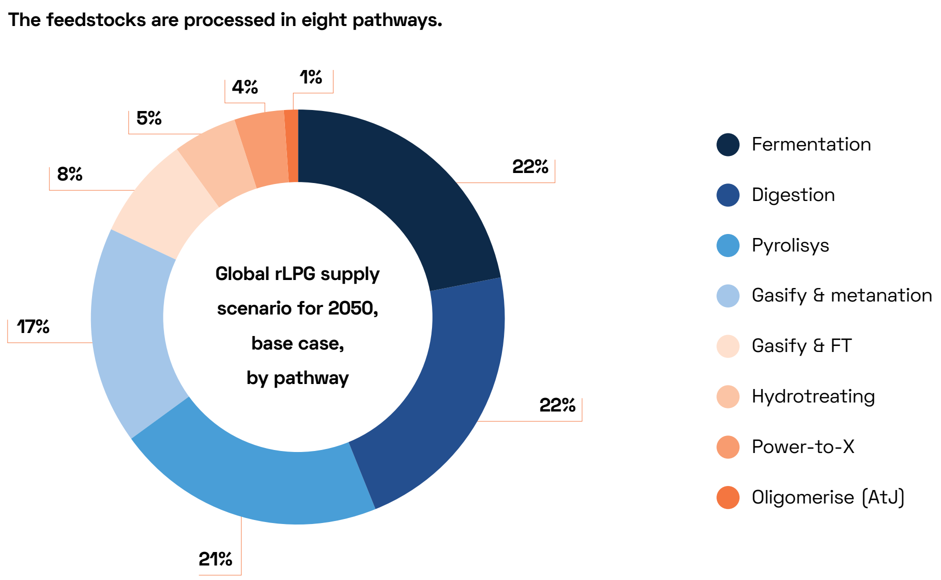
Figure 11: LPG feedstocks[15]



The Global renewable Liquid Gas production could reach 100 million tonnes by 2050 under certain scenarios

Renewable LPG, even though still little known to the shipping industry, can work as a drop-in fuel in LPG infrastructure and is already used in other sectors. It presents an enhanced environmental profile and is a readily available fuel. The engines' technology exists already, the production of it is continuously increasing and the market is upscaling, thus making it a well-established fuel and a promising pathway towards the decarbonisation of the shipping sector.

Figure 12: LPG feedstocks processing pathways[15]



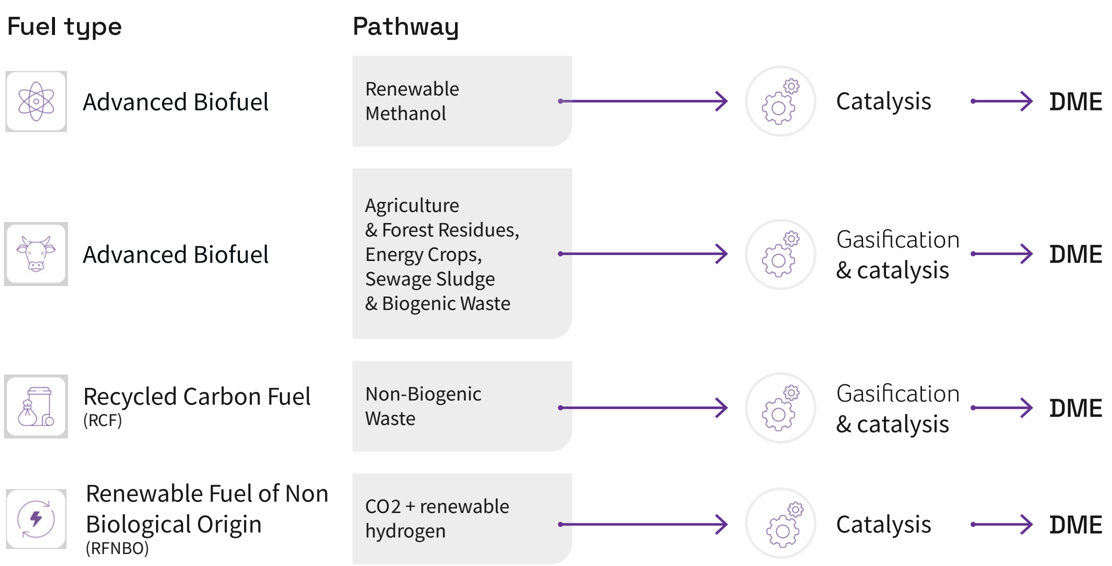
8.2 Renewable and recycled carbon DME, rDME

Dimethyl Ether (DME) is a liquid gas and synthetic fuel and not a natural resource. The exploitation of a wide range of sustainable and renewable feedstocks like manure, organic fraction of waste streams, other biomass, non-organic fractions of municipal waste like plastics and tires, and renewable hydrogen and captured CO_2 can lead to the production of renewable or recycled carbon DME[16]. Renewable or recycled carbon DME (rDME) is already produced today. Fossil DME (same molecule) has already been used for decades in industrial applications. It is a clean burning and sustainable fuel and chemical feedstock that presents very similar properties to LPG. At ambient temperature, under low-pressure application, it can be stored in a liquid state and handled similarly to LPG without the need for special or expensive technology or cryogenic tanks and pumps. Due to those similarities, blending with LPG up to 12 % mass (or up to 20% if used only in the liquid phase) can be distributed and used, utilising the same supply chain infrastructure as LPG[17].

As far as the shipping industry and the main engines are concerned, MAN ES through the ME-LGI engines that they offer, makes the adoption of DME feasible. The ME-LGIP technology used for the burning of LPG as fuel is relative to the LGI technology and the future fuel transition from LPG to DME will not be an obstacle. When it comes to combustion, DME can eliminate sulphur and particulate emissions while it reduces significantly NOx and CO_2 emissions.

DME is the underdog alternative to LPG and has lately been under the radar. Renewable DME is capable of reaching negative CIs depending on feedstock and can offer the potential for up to 85% lower CI than the average of competing fossil fuels and when it is mixed with LPG, it could reduce CO_2 emissions by up to 30%, considering max blending ratio of 30%/70% (rDME/LPG)[18][17][19]. The available production pathways for renewable and recycled carbon DME are shown in the following figure.

Figure 13: Renewable and recycled carbon DME production pathways[17]



DME blends with LPG can constitute a sustainable fuel solution for the shipping industry.

In 2022, EMSA concluded that, as far as the Well to Tank emissions are concerned, rDME under certain pathways can offer among the greatest potential for GHG reductions[20]. The same year, Dimeta was established by SHV Energy and UGI International to advance the production and use of renewable and recycled carbon DME. Dimeta targets the construction of up to six production plants of renewable and recycled carbon DME with a total production capacity of 300kt by 2027. To support the above-mentioned target, Dimeta and KEW technology formed another joint venture, Circular Fuels Ltd which will develop construction-ready rDME production plants. In June 2023 Dimeta announced the grant of planning approval for the first waste to DME plant in Teesside, UK, through Circular Fuels Ltd which will be operational by 2025 and will have the capacity to produce over 50,000 tonnes of DME per year.

The creation of Dimeta came in addition to the other already established renewable DME producer, Oberon Fuels, in California USA. Oberon Fuels developed the world's first commercial scale plant to make renewable DME and started operating in May 2021. This plant has currently a capacity of 3,900 tonnes per year while the company estimates renewable DME production from its upcoming plants to reach over 500 kT per year by 2027[21].

Renewable DME, similarly to renewable LPG, is not widely known in the maritime industry. However, it holds immense promise as a sustainable and efficient marine fuel that emerges as a compelling solution to address environmental concerns and regulatory pressures within the maritime sector. As the shipping industry increasingly seeks cleaner alternatives, DME stands out for its potential to reduce greenhouse gas emissions and improve overall operational efficiency. The adoption of DME in shipping not only aligns with global sustainability goals but also presents a tangible pathway towards a greener and more resilient maritime future.

8.3 Ammonia Compatibility

The synergies of ammonia with the LPG supply chain, infrastructure, and equipment have already been stated above.

Ammonia is a next generation clean energy source, and the maritime industry has already started considering it as a marine fuel as, under certain pathways, it can be a zero-carbon and zero-sulphur marine fuel.

Ammonia has plenty of synergies with LPG. The maritime community has a longstanding experience in transporting ammonia with LPG carriers and due to their storage similarities, maritime stakeholders are making efforts to adopt it as a marine fuel as well. Important advantages exist, for vessels utilising LPG as a fuel, to transition to ammonia in the future.

WinGD has already announced a partnership with CMB. Tech to develop ammonia-fuelled engines for ten 210,000 DWT bulk carriers while on September 2023 it was circulated that LR awarded WinGD with the first ever AiP to WinGD's X-DF-A dual-fuel range. Passing on the actions and implementation side, it is scheduled that WinGD will deliver two 52-bore X52DF-A engines in Q2 2025 for a series of two EXMAR LPG BV 46,000 m^3 LPG/ammonia carriers that will be built at Hyundai Mipo Dockyard.

As reported by MAN ES, the first ammonia fuelled engine, ME-LGIA will be delivered to the yard in post 2025. ME-LGIA engines can be retrofitted to existing ME-C and ME-LGIP, for which the latter holds a solid basis for the ME-LGIA conversion. A similar method has been implemented for the concept of LPG and methanol as fuels with the ME-LGIP and ME-LGIM engines, respectively. The ME-LGIM concept has already been used as a foundation for the development of ME-LGIP and has already dealt with some challenges such as corrosion, toxicity and low flammability, which are related to ammonia as well.

Another key point to consider is the tank size and adaptability. A technical challenge here is that ammonia presents almost half the volumetric energy of LPG, which means that even though both can be stored under similar conditions, ammonia needs significantly more space due to its lower volumetric energy density. As far as the ammonia fuel supply system is concerned, the LPG fuel supply system will need to be verified accordingly for suitability with ammonia as fuel.

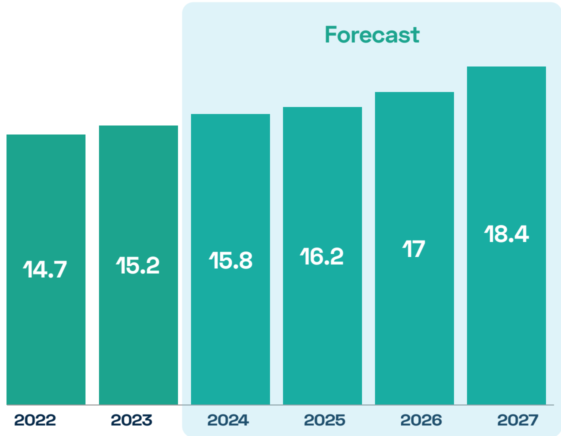
Summarising the above, by adopting LPG, as fuel it becomes easier and faster to adopt ammonia as fuel in the future when the technology and supply chain are mature enough to support such actions.

Some of the most significant initiatives and projects that promote ammonia as a fuel in the maritime industry are:

- Castor Initiative
- ShipFC (shipfc.eu)
- MS Green Ammonia
- SOFC4AMARITIME
- NH3CRAFT (www.nh3craft.com)
- Engimmonia (www.engimmonia.eu)

The worldwide trade of ammonia in recent years and a projection up to 2027 is shown below:

Chart 21: Ammonia trade volumes (mtonnes)[7]



8.4 Carbon Capture and Onboard Storage

Onboard carbon capture and storage are among the solutions that shape the future of maritime decarbonisation as they can play a significant role in the mid to long term. In combination with LPG as a marine fuel, any application of CCS onboard ships can be optimised.

The first evident synergy is for LPG fuelled ships, which can combine CCS systems with LPG propulsion systems. Not only can they reduce their environmental footprint further, but they can also reduce the required captured CO_2 storage capacity onboard due to less CO_2 emissions from LPG combustion, thus exploiting the full benefits that LPG can offer as a marine fuel. This could have a significant impact on the CO_2 storage CAPEX, which decreases due to smaller tanks, and on the OPEX, which decreases due to small power consumption for the operation of the CCS. It is worth mentioning that the adoption of CCS in combination with LPG as fuel, as observed from separate studies can extend vessel life over five years, assuming 30% net carbon capture savings, while it could lead to over USD one million reduction in annual IMO carbon pricing, assuming a carbon cost of 130 dollars per ton of CO_2[22].

On the regulatory side, classification societies, among them LR, have already issued CCS Notation & Ready, which allows owners to prepare for a future retrofit at the new building stage, thus saving time and money in the long term. Owners, yards, and classification societies have already started working on adopting carbon capture systems onboard ships, and LR has provided “Approval in Principle” for CCS technologies, including post-combustion for Value Maritime and Erma First.

8.5 Carbon Capture and Onboard Storage

The sustainability and environmental profile of LPG as a marine fuel can be further enhanced with the adoption of innovative wind assisted ship propulsion technologies. The installation of such technologies could further reduce LPG consumption, thus improving ship performance, reducing emissions, and consequently affecting a range of factors like CII, FuelEU and EU ETS.

Such technologies have been studied over the years to reach commercial readiness, with LR and other classification societies of IACS publishing guidelines to enable the installation and operation of such systems. MEPC79 references major wind propulsion technologies with quantified evidence to underpin the savings that a ship can achieve when using them[23].

TABLE 3: DUAL-FUEL LPG CARRIER CII COMPLIANCE

Year of Built	Emissions	2024	2025	2026	2027	2028	2029	2030	2031	2032
DF 2011	CO_2	B	B	B	B	B	C	C	C	C
	with CCS*	A	A	A	A	A	A	A	A	A

Year of Built	Emissions	2024	2025	2026	2027	2028	2029	2030	2031	2032
DF 2011	CO_2	D	D	D	E	E	E	E	E	E
	with CCS*	B	B	B	C	C	D	D	D	E

DWT [tonnes]	Distance Travelled [nm]	CO_2 Emissions [tonnes]
55,182	79,452	24,813

9. Conclusions

Liquid Gas, LPG, and DME present a full spectrum of competitive options on the pathway of the shipping industry's decarbonisation. The penetration of LPG as a marine fuel in the LPG carrier sector is significant today and the data shows that there is great potential for other ship categories as well. LPG, apart from its enhanced volumetric energy properties, provides a better carbon profile against other fuels and can also be found at relatively low prices as a bunker fuel, thus being a fuel that shipowners can set up their investment portfolio strategy around to face the upcoming changes in the regulatory landscape of shipping. Regarding the bunkering infrastructure, there are numerous coastal LPG terminals worldwide that, after covering the necessary compliance aspects, could support the bunkering operation of non-gas carriers while the existence of 995 LPG carriers up to 15,000 cbm that could be used as bunker vessels further promotes its adoption.

The LPG main engine technology is already commercially available through different engine sizes provided by MAN ES and given that interest is shown by different stakeholders, the relevant portfolio could be further expanded.

To attain a developed LPG value chain and de-risk the investment in LPG as a marine fuel, coordinated work should be executed by different parties and collaborations between them should be established. The charterers will have to bear the charter premium while the small LPG carriers' and terminal operators should secure the availability of LPG at certain price.

Finally, the adoption of LPG leads to sustainable pathways through its compatibility with other liquid gases like bioLPG, renewable LPG, renewable and recycled carbon DME. Moreover, LPG synergises well with the alternative fuel of ammonia and technologies such as CCS and WASPS which will play a major role in shipping's decarbonisation future.

Investing in Liquid Gas, LPG and DME as a propulsion fuel in the marine industry, is a viable option for shipowners and operators

APPENDIX

LPG as a Marine Fuel

Techno-Economic Feasibility Case Study on a 4,800 TEU Containership

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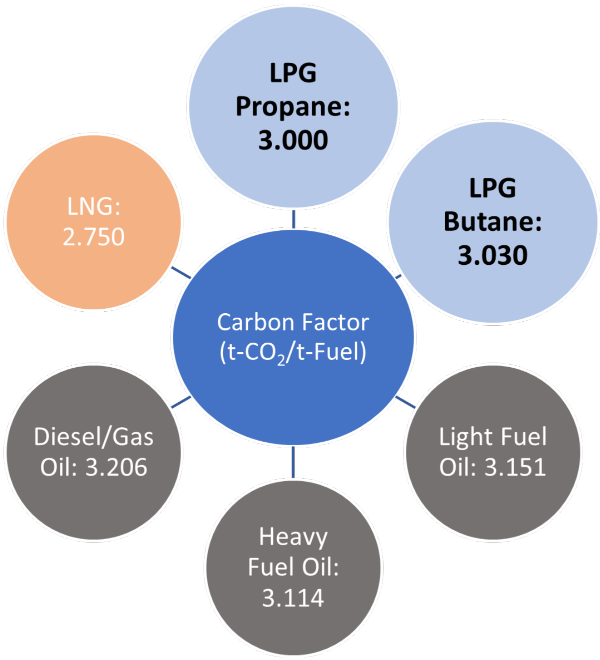
Introduction

In order to halt climate change, the need to accelerate the decarbonization of the global economy in the maritime industry is part of this process. It is calculated that global shipping accounts for more than one billion tons of carbon dioxide (CO_2) and 3% of the annual global greenhouse gas emissions (GHG) in CO_2-equivalent terms[1]. To address this issue, the regulatory landscape on maritime emissions is developing with increasingly strict requirements. The International Maritime Organization (IMO) imposed a global cap of 0.5% sulphur content in marine fuels, a regulation that entered into force from 1st January 2020. Furthermore, the IMO recently announced a revised strategy for GHG emissions in international shipping, setting a goal of net-zero GHG by 2050. In addition, the European Union's legislative bodies have agreed to a revision of the emissions trading system (EU ETS), which is set to include shipping from 2024, and set a cap on GHG emissions, and have also adopted the FuelEU Maritime regulation, to come into force in 2025, which aims to increase the share of renewable and low-carbon fuels in the fuel mix of international maritime transport in the EU. As a result, the global shipping industry needs to seek how to adopt alternative fuels, moving away from the heavy-pollutant fuel oil, which most large vessels rely on currently.

Ship owners, operators and other maritime stakeholders act in an environment full of uncertainties and continuous change. Fuel adoption strategy is at the forefront of this process, and addresses both newbuilds and retrofit projects. Well-informed decisions must be taken at every project stage. At the same time, the alternative marine fuels market is immature and underdeveloped.

Figure 1. Emission factors of different fuels



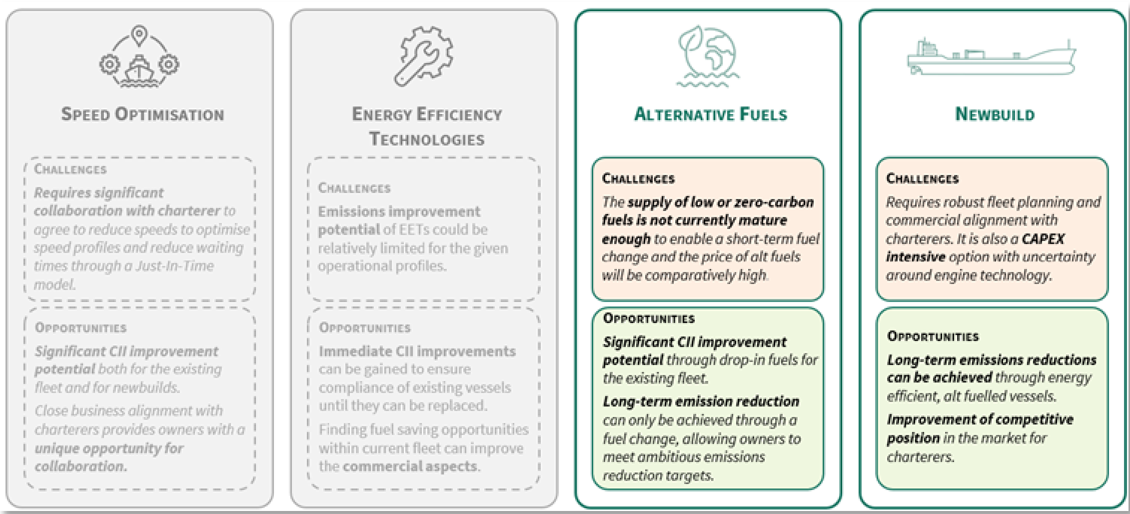
Through its well-established presence in other industries LPG can play a crucial role in the maritime industry's decarbonization efforts as LPG offers a significant emissions reduction compared to conventional fuels. The lower carbon-to-hydrogen ratio of LPG leads to lower CO_2 emissions from combustion compared to traditional oil-based fuels. In addition, LPG emits lower CO_2 in production phase, resulting in a lower well-to-tank greenhouse gas footprint when compared to natural gas, especially when methane slip is taken into account. LPG is poised to become one of the primary alternatives to traditional marine fuels in the industry's efforts to comply with the IMO 2030 and 2050 ambitions, as well as with the EU ETS and FuelEU Maritime regulations.

Through this feasibility study, the World Liquid Gas Association (WLGA) and Lloyd's Register (LR), have made efforts to support maritime stakeholders and inform them about the hidden financial and future-proof aspects of LPG as fuel. This comparative case study is based on a 2014 built 4,800 TEU containership and examines:

a. retrofit of the Main Engine (ME) to run on LPG,
b. retrofit of the ME to run on LNG, and
c. a newbuild of identical specs capable of running on LPG benchmarked against the Business-As-Usual (BAU) scenario for the timeframe 2024-2035.

The scope of this study covers two of the four levers with its challenges and opportunities as shown in figure 2.

Figure 2. Pathways for energy transition in shipping



Approach & Methodology

The methodology is designed to provide a holistic understanding of alternative fuel adoption through examination and analysis of fuel economics and their decarbonization potential. The key activities and methodology, are:

- Comparative assessment of the total cost of ownership of an LPG and an LNG-powered vessel based on pre-defined scenarios and operational profiles.
- The period under consideration spans 12 years (2024 to 2035) and takes into account all major cost factors, such as fuel cost, taxation, carbon penalties, retrofit cost, etc.
- The analysis examines (i) the as-is scenario of the vessel consuming conventional fuel, (ii) a DF LGIP (LPG) retrofit scenario, (iii) a DF LNG retrofit scenario and, (iv) a newbuild DF LGIP (LPG) vessel scenario.
- The fuel consumption estimates were based on the most recent energy consumption data of the reference vessel.
- The EU trade profile was based on the most recent EU MRV data submitted for the reference vessel.
- A CII assessment was conducted to evaluate the decarbonization potential.

The key outputs of the study, are:

- The impact of EU ETS & FuelEU Maritime regulations on each scenario
- The financial implications (CAPEX, OPEX) and Payback Analysis
- The evaluation of CII performance

Case Details, Scenarios and Key Assumptions

Project Scope

Each of the scenarios drafted represent possible options for owners that are considering LPG adoption. The following considerations have been included in the modeling:

In the case of dual-fuel engines, there is a cost associated with the development of the parent engine for the bore sizes not widely available. This cost is factored into the maker's sale price and spread over the number of units sold to newbuilding and retrofit projects.

TABLE 1: DUAL-FUEL LPG CARRIER CII COMPLIANCE

Scenarios	As-Is /Conventional	DF LGIP Retrofit	Newbuild with DF LGIP	DF LNG Retrofit
One-off costs/Initial Investment (CAPEX)	-	▶ Engine Cost[12] ▶ Tank and Supply System ▶ Engineering Costs ▶ Yard and Installation Costs ▶ Off-Hire Days	▶ DF LGIP Feeder Newbuild Price ▶ Deduction of the price of the Current Vessel	▶ Engine Cost ▶ Tanks and Supply System ▶ Engineering Costs ▶ Yard and Installation Costs ▶ Off-Hire Days
Yearly Costs (OPEX)	▶ Fuel Costs ▶ EU ETS Compliance Cost (starting from 2024) ▶ Fuel EU Maritime Compliance Cost (starting from 2025) ▶ Maintenance Cost			

[12] For this case study, the assumed parent engine development cost is associated with the retrofit installation under consideration, whereas for newbuild scenario, such a cost is absorbed into the asset price assuming a number of fifteen newbuilding orders placed.

Case Details, Assumptions and Inputs for the Models

To analyse the different scenarios, we have considered the vessel specifications, the current regulatory framework and a pre-defined operational profile.

The techno-economic environment that dictates vessel operation in each case is presented and analysed along with the necessary assumptions. The impact of the CII, FuelEU Maritime and EU ETS regulations is shown in detail so the reader can understand their significant impact on the timeline of the investments.

Vessel Parameters and Operation

TABLE 2: VESSEL PARAMETERS

4,800 TEU Containership	
DWT	60,500 t
ME MCR	One-off costs/Initial
Fuel Tank Capacity	4,300 m^3
Fuel Mix	34% MGO, 66% LFO
Annual Fuel Consumption	11,800 t
Emissions within EU Scope	48%

Emission Factors and LCVs

The emission factors and Lower Calorific Values (LCV) of each fuel are sourced from *FuelEU Annex II: Table 1 Default factors & Directive (EU) 2018/2001 (RED II) for GWPs*

TABLE 3: EMISSION FACTORS AND LCVS

Fuel	LCV (MJ/g)	CO_2 TtW (tCO_2/t_{fuel})	GHG TtW (tCO_{2eq}/t_{fuel})	GHG WtW (tCO_{2eq}/t_{fuel})
Diesel/Gas Oil	0.0427	3.206	3.261	3.876
Light Fuel Oil	0.0410	3.151	3.206	3.747
Heavy Fuel Oil	0.0405	3.114	3.169	3.716
Fossil LNG	0.0491	2.750	2.827	3.736
Bio-LNG	0.0491	2.750	2.827	3.348
Fossil LPG (Propane)	0.0460	3.000	3.000	3.3.359

EU Regulatory Costs

The 2024 average EUA price is 78.61€/tCO_2[13]. We assume a 4% YoY price increase to account for general expectation of EUA price increase.

The GHG limits imposed under the FuelEU Maritime are shown in table 4.

TABLE 4. FUELEU MARITIME GHG INTENSITY LIMITS

Year	2025	2030	2035	2040	2045	2050
GHG Intensity Limit (gCO_{2eq}/MJ)	89.34	85.69	77.94	62.90	34.64	18.23

Projected Fuel Prices and Assumed Fuel Mix Cases

Fuel prices are a major cost item that affects the choice of investment. Bunker prices carry inherent volatility that depends on supply/demand factors and geopolitical events. To determine fuel prices going forward, we consider a six-month average (May 2023-Oct 2023) price for HFO, LFO, MGO and Fossil LNG.

For Bio-LNG, we considered the delta between Fossil LNG and Bio-LNG, as defined by SEA LNG. For Fossil LPG, we defined a low price based on rates provided to sophisticated owners that can leverage bunkering significant amounts. This assumption considers the trading pattern of the vessel, indicating a potential cost advantage when assessing LPG.

The Total Cost of Ownership model incorporates a dynamic fuel mix for each scenario that reflects the evolving industry trends towards alternative fuels. One key component of our fuel mix for the LNG DF Case is Bio-LNG, for which we have allocated a percentage set to increase over time. This reflects the anticipated growth and availability of Bio-LNG in the market, driven by advancements in sustainable energy technologies and regulatory incentives.

With time, the availability also of Bio-LPG will increase in the market, which will provide additional benefits, but this has not been taken yet into account.

[13] Price as of Nov 5, 2023.

Figure 3. Fuel price projections

(Sources: https://shipandbunker.com/prices, SEA-LNG, Nanyang Technological University, LR Consulting)

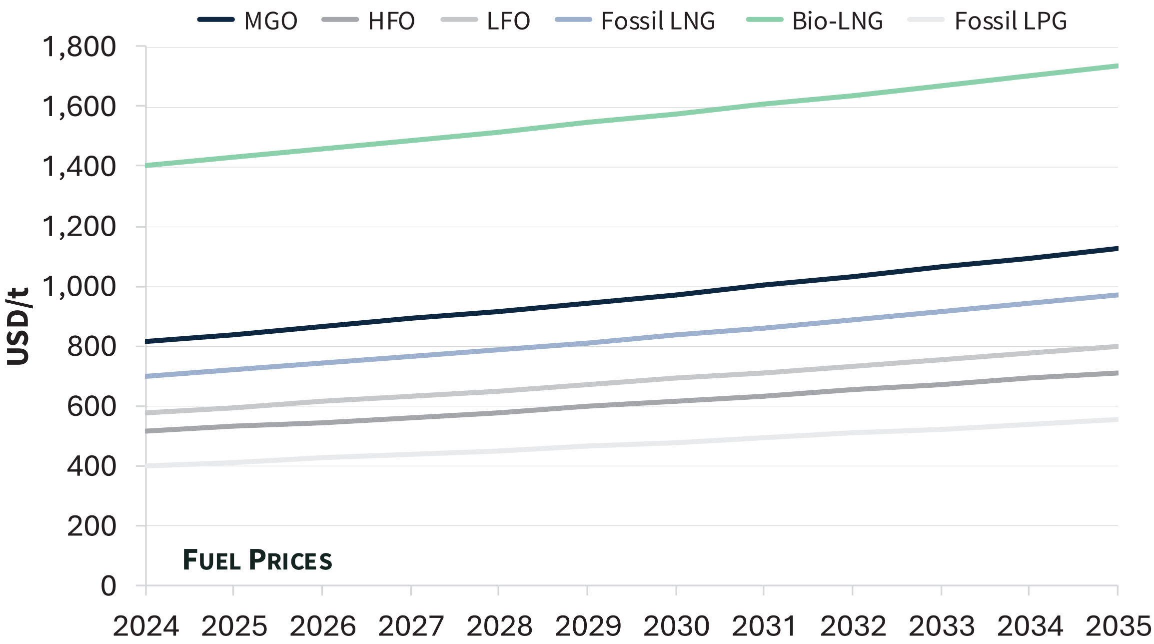
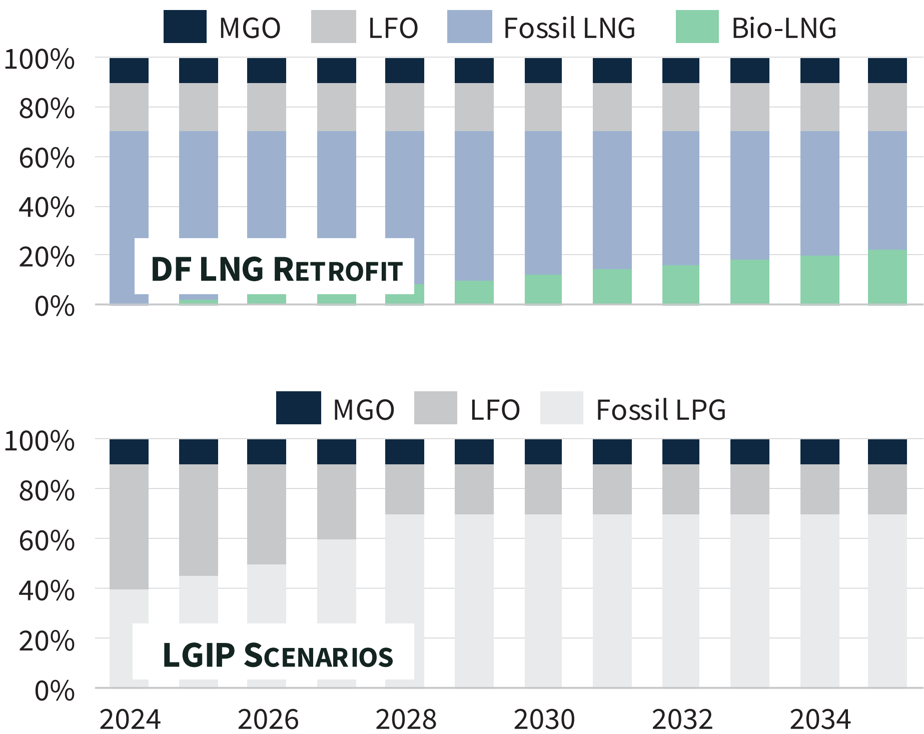


Figure 4. Projected fuel mix scenarios



Financial Impacts

Projected Emissions-Related Costs

Each scenario chosen carries an environmental compliance cost stemming from the different emissions output and the fuel used. LR has forecasted the EU Regulatory Cost impact below.

Figure 5 shows the cost of compliance with the EU ETS regulation. The operating profile of the vessel is assumed to be constant throughout the period. The steep increase between the years 2024 and 2026 is due to the phase-in period built into the regulation. In 2024, 40% of the emissions in scope are to be surrendered, rising to 70% in 2025 and 100% from 2026 onwards. After 2026, the mild increase is due to the assumption of rising EUA prices by 4% YoY.

Figure 5. Projected EU ETS cost of compliance.

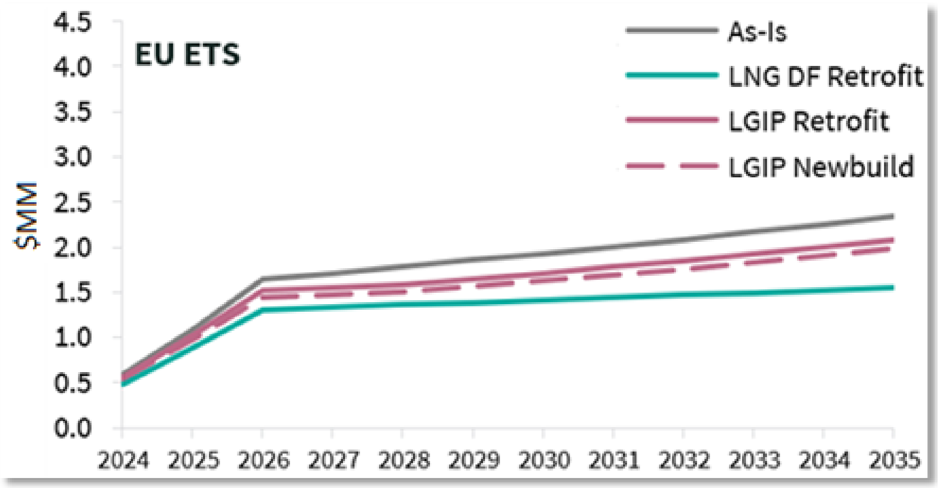


Figure 6. Projected FuelEU Maritime cost of compliance

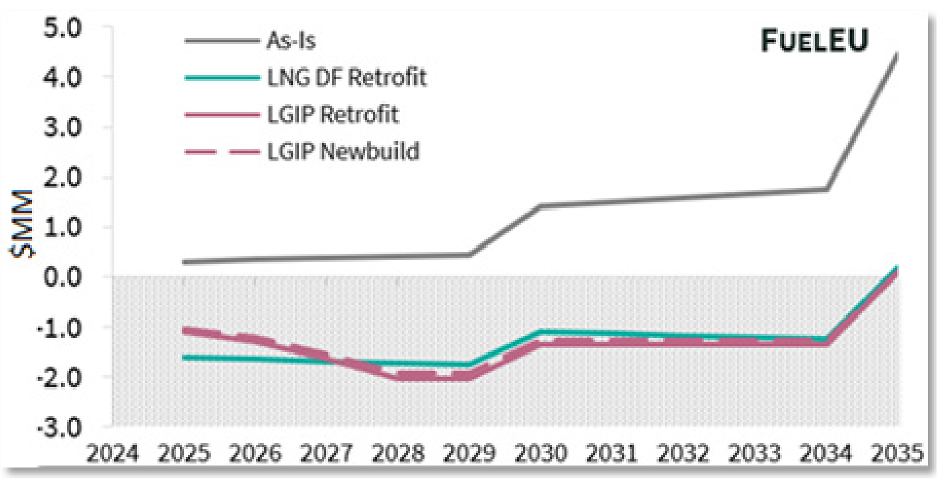
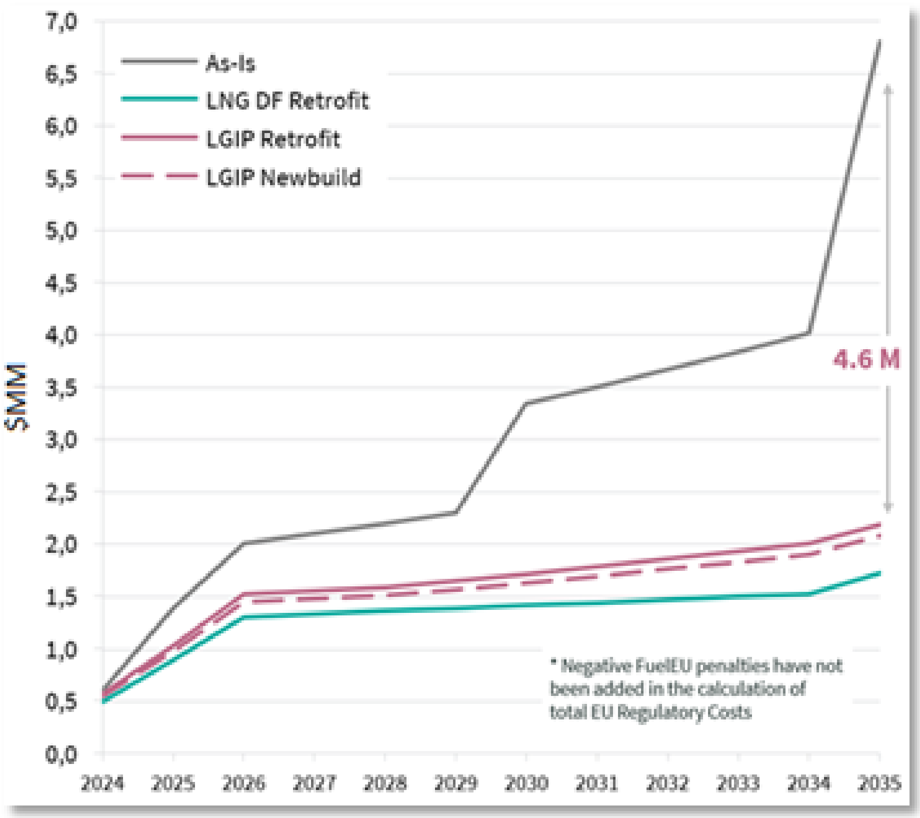


Figure 6 depicts the cost of complying with the FuelEU Maritime regulation that will enter into force in 2025. For vessels burning LNG or LPG, we see that the GHG intensity is below the corresponding thresholds for each year until 2035, meaning that no penalty fees must be paid. While owners do not receive monetary rewards by operating below GHG intensity thresholds, compliance surpluses can be pooled for all the ships in the fleet. This means that ill-performing ships can use the compliance surplus saved from better-performing ones, effectively saving on penalties they would have otherwise incurred. This is shown in the grey area of the chart as a 'negative' compliance cost.

The total cost of compliance is the sum of the above (see figure 7 below). In this case, the negative FuelEU Maritime costs have not been added to the calculation. We see that the As-Is scenario becomes exponentially uneconomic. The other three cases yield similar costs, with the LNG DF retrofit scenario being the most profitable. This is the result of LNG's lower emission factor (LNG: 2.750, LPG-Propane: 3.000, LPG-Butane: 3.030) in combination with its high energy density (i.e. less fuel must be burned to achieve the same energy output).

Figure 7. Total cost of EU carbon compliance

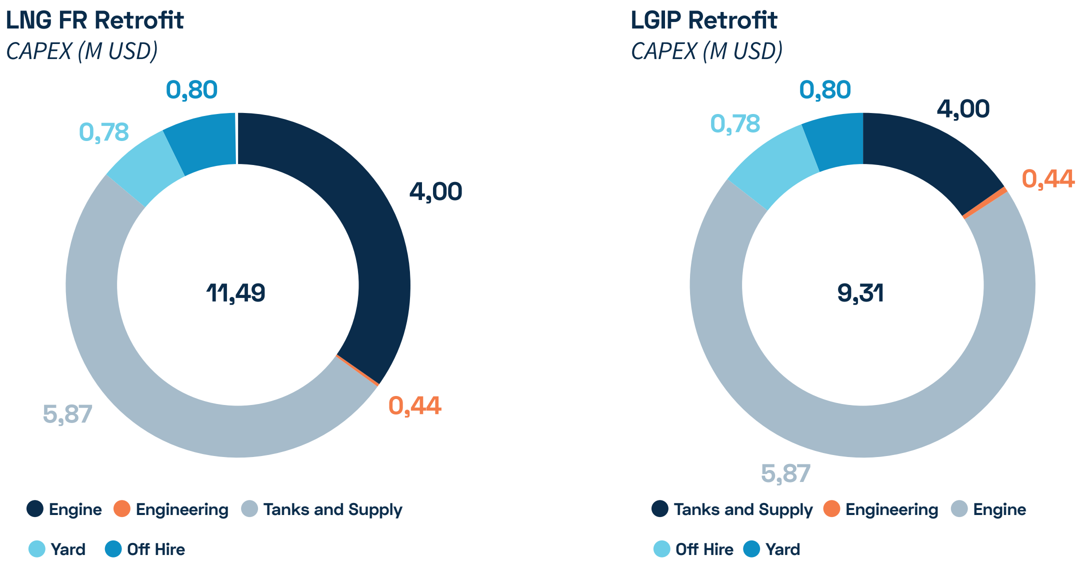


CAPEX

The estimated CAPEX for the LNG DF retrofit stands at $11.49MM and includes the cost of the engine, tank and supply system, shipyard and installation, engineering and off-hire days.

For the LGIP DF retrofit, the cost is estimated at $9.31MM.

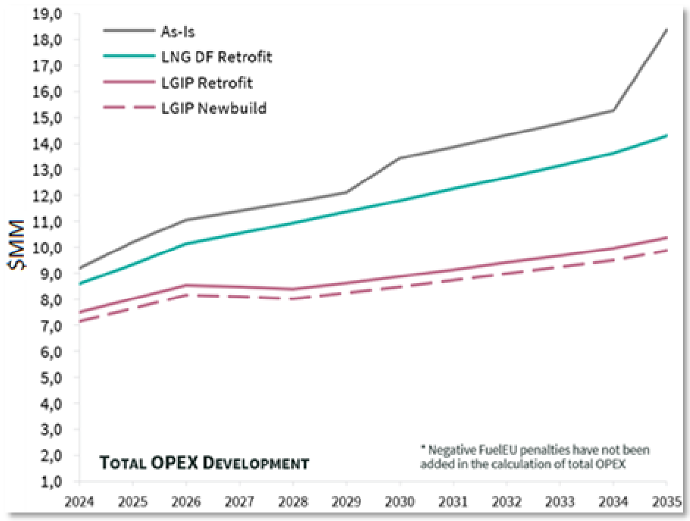
Figures 8a and 8b. LNG and LPG retrofit CAPEX (in $MM)



Projected Total Costs

LR has forecasted the total OPEX cost, which includes fuel cost, EU ETS and FuelEU Maritime compliance cost, and maintenance cost.

Figure 10.Projected total OPEX

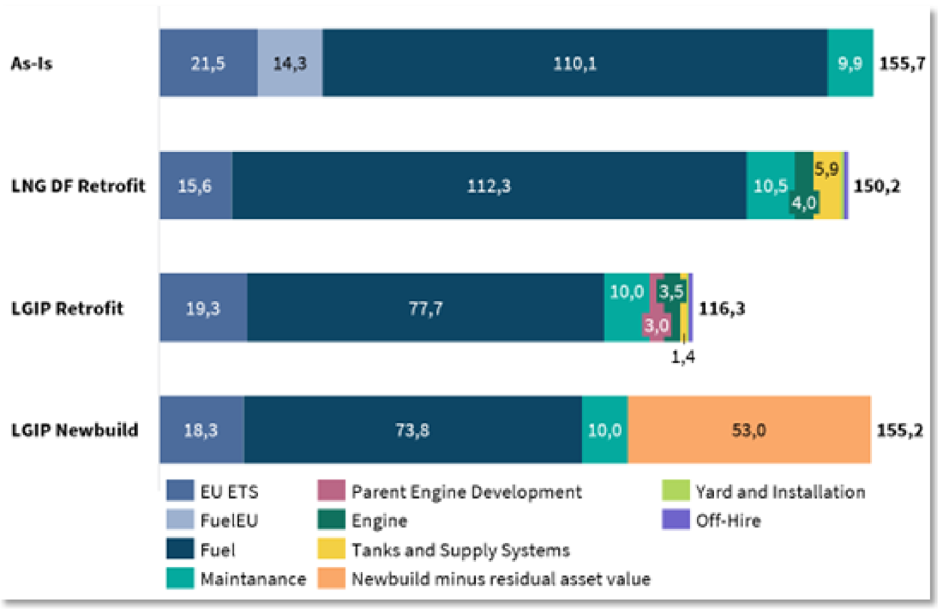


The following observations should be noted:

- Across all scenarios, we anticipate an increase in OPEX costs. This is attributed to the combined effects of escalating EU Emission-related costs, projected increase in fuel prices, and the necessity to adopt greener fuels, particularly Bio-LNG, which comes at a premium compared to fossil LNG.
- Total costs in the As-Is scenario are notably higher due to the substantial carbon taxes and penalties associated with traditional fuel sources.
- While LNG presents a more cost-effective option in terms of yearly OPEX, both fossil and Bio-LNG adoption face challenges. The high prices associated with these LNG variants limit the potential for significant savings compared to the As-Is scenario.
- The LGIP (Low LPG Price) scenarios emerge as the most compelling options, especially after 2026 when LPG adoption increases. If the assumption of low LPG price materializes, it presents a dual advantage:
  - LPG offers a lower emission factor compared to LFO and MDO/MGO, better aligning with environmental goals.
  - LPG proves to be a more economical choice, outperforming both LFO and MDO in terms of cost. This cost-effectiveness is further amplified by LPG's higher energy density, which translates into reduced fuel consumption for the same energy output.

Over the whole 12-year period, the total costs amount to the figures below.

Figure 11. Total costs for the 12-year period (in $MM)



Cost-Benefit Analysis

In Figure 12, the annual OPEX savings of the three scenarios (LNG DF retrofit, LGIP DF retrofit, LGIP newbuild) are presented compared to the As-Is scenario, in order to assess which option is preferable.

Regarding the yearly OPEX Savings, the LGIP scenarios outperform LNG, due to the favorable pricing of LPG. However, it's crucial to highlight that beyond 2035, the escalating FuelEU penalties could potentially shift this dynamic, making LNG a more financially compelling option.

Based on the findings above and the CAPEX estimated, the Payback Period for the three scenarios is depicted below.

An LGIP Retrofit presents a shorter payback period of just 3 years, making it an attractive investment compared to the 10-year payback period associated with an LNG DF Retrofit. The analysis strongly suggests that committing to the LGIP Retrofit investment early, particularly in 2024, is strategically advantageous. This ensures that one capitalizes on the substantial short to mid-term savings offered by LGIP before the financial benefits of LNG become more pronounced.

Figure 12. Annual OPEX savings compared to As-Is scenario.

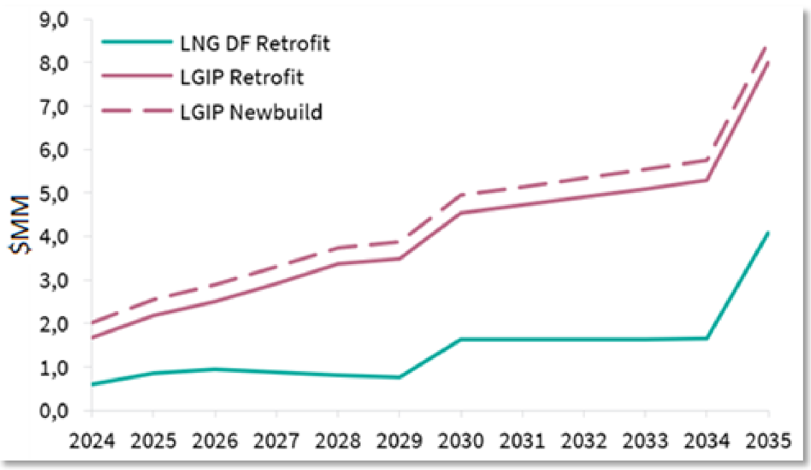
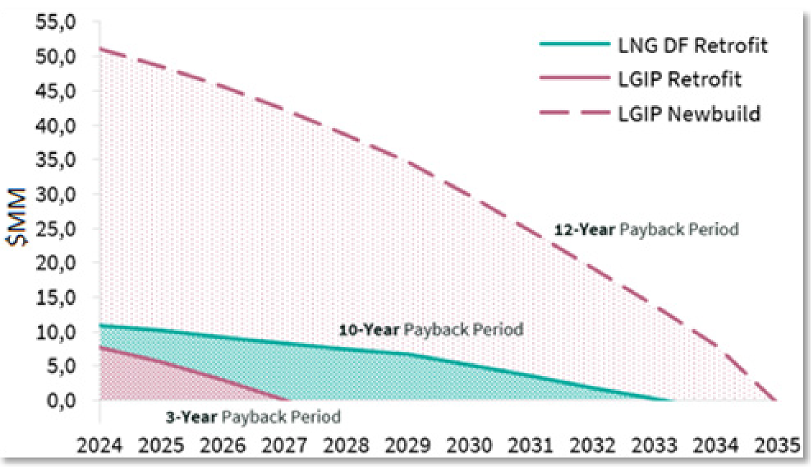


Figure 13. CAPEX Phasing and Payback Period



CII Benchmarking and Projections

Using the 2022 IMO DCS data and the reference CII for this ship type and size, we forecasted the environmental performance of each vessel up to 2035.

For the years beyond 2026, where CII reduction factors have not yet been decided, a 3% annual reduction rate was applied (2027-2030), rising to 4% from 2031 onwards.

The vessel shows strong performance even under the As-Is scenario. The vessel is able to maintain a C rating until 2031, showcasing its inherent efficiency. The first E rating is expected in 2034, signaling the need for improvements to bring the vessel back to an acceptable C rating, or better. The LGIP Retrofit scenario shows a significantly better trajectory, with the vessel maintaining its B rating until 2030 and the first D is expected in 2034. However, it rapidly deteriorated to E in the subsequent year, showcasing the need for further efficiency gains to restore compliance.

For the years beyond 2026, where CII reduction factors have not yet been decided, a 3% annual reduction rate was applied (2027-2030), rising to 4% from 2031 onwards.

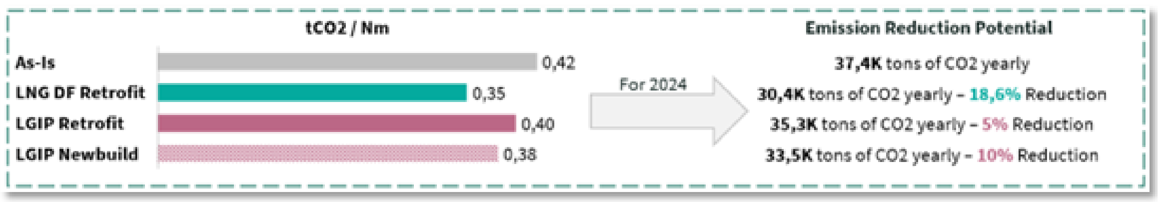
The vessel shows strong performance even under the As-Is scenario. The vessel is able to maintain a C rating until 2031, showcasing its inherent efficiency. The first E rating is expected in 2034, signaling the need for improvements to bring the vessel back to an acceptable C rating, or better. The LGIP Retrofit scenario shows a significantly better trajectory, with the vessel maintaining its B rating until 2030 and the first D is expected in 2034. However, it rapidly deteriorated to E in the subsequent year, showcasing the need for further efficiency gains to restore compliance.

The LNG Dual-Fuel Retrofit scenario exhibits the best decarbonization potential, showing an 18.6% emission reduction from the As-Is case. This is attributed to the lower emission factor and the high energy density of LNG compared to conventional fuels like MGO and LFO, which translates into reduced fuel consumption for the same required power output. Next, the LGIP newbuild vessel follows with a 10% reduction from the As-Is case. Finally, the LGIP LPG engine retrofit on the existing vessel shows a moderate 5% reduction in emissions.

Figure 14. CII projections under different scenarios

Scenario	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
As-Is	A	B	B	B	B	C	C	C	D	D	E	E
LNG DF Retrofit	A	A	A	A	A	A	A	B	B	C	C	D
LGIP Retrofit	A	A	A	A	B	B	B	C	C	C	D	E
LGIP Newbuild	A	A	A	A	A	A	B	B	C	C	D	D

Figure 15. Emissions reduction potential



Conclusions

The upcoming environmental regulations, both at IMO and at EU level render ship carbon emissions increasingly important. This is reflected in the structure of the CII and the FuelEU Maritime regulations, both of which use fixed period intervals to decrease the threshold of acceptable vessel emissions. At the same time, the cost of EU ETS allowances is expected to increase due to the decreasing number of auctioned EUAs every year, as well as competition faced by other industries striving to decarbonize.

In this case study, the benefits were split into two categories: (a) the Payback Period of the investment and (b) the emissions reduction potential. The best scenario economically does not necessarily align with the best scenario from an emissions perspective. For this particular case study, the optimal choice is the LPG Dual-Fuel engine retrofit, yielding a Payback Period of about 3 years. It is worth noting that depending on the vessel type, its trading pattern, fuel availability and costs, other fuel/engine options might prove more advantageous.

LPG is an attractive fuel choice due to its emissions profile: it has a lower TtW emission factor and a higher energy density compared to Fuel Oil and Gas Oil, meaning less consumption is required for the same power output. Besides CO_2, burning LPG emits virtually no SOX, significantly reduced PM and lower NOX. On a WtW basis, its emissions factor is lower than that of Fossil LNG and comparable to that of bio-LNG. Moreover, LPG is priced favorably, there is ample supply (mainly from the US), there is an extensive network of storage facilities and STS-capable vessels across the world, and crew experience in handling it. As a result, as it has already been an obvious fuel of choice for LPG carriers (over 90% of newbuild VLGCs on order have Dual Fuel capability), it can also be a fuel of choice to other ship types.

The cost of the LGIP retrofit is expected to go down as technology adoption increases. This will make the investment even more economical. Widespread use of LPG in transportation dates back in the 1970s, showing that LPG is a tried-and-tested fuel with wide experience from its use. LPG as marine fuel follows the IGC and IGF Codes which set out the standards for safe carriage of liquefied gases by sea and the burning of said gases as fuel, respectively.

Despite the above, environmental compliance is not a one-size-fits-all exercise. Depending on existing vessel parameters, trading routes, fuel availability, pricing, time of implementation (regulations change and equipment becomes cheaper as the technology reaches commercial maturity) and investment horizon, different owners might opt for different solutions. Generally, both LNG and LPG are excellent transition fuels. They present lower emission factors and higher energy density compared to fuel oil. Moreover, there are abundant reserves, can be easily produced and especially for LPG, there is ample handling experience over decades of use. When alternatives like bio-LNG and renewable LPG reach the desired output, liquid gases can play a key role in decarbonization even in a long-term horizon. A very recent incomer in the renewable liquid gases family, the renewable Dimethyl Ether (DME), can also bring significant additional opportunities and advantages to LPG fueled vessels.

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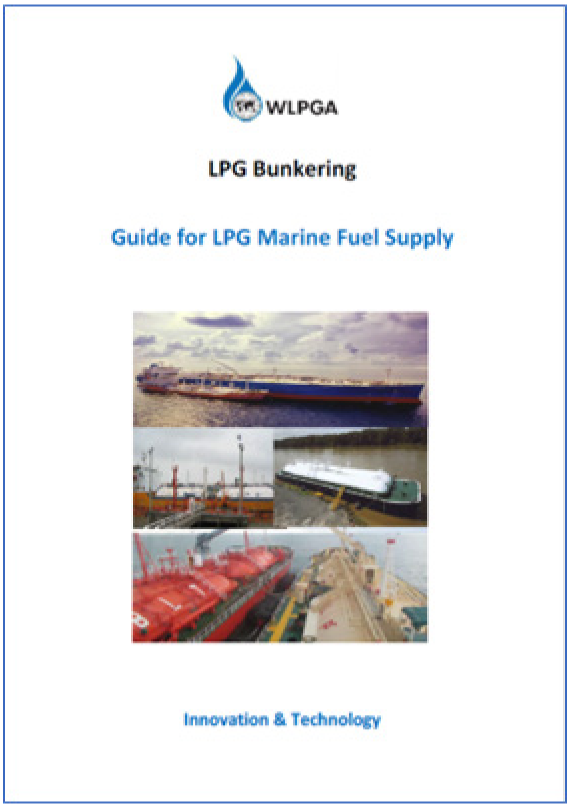

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