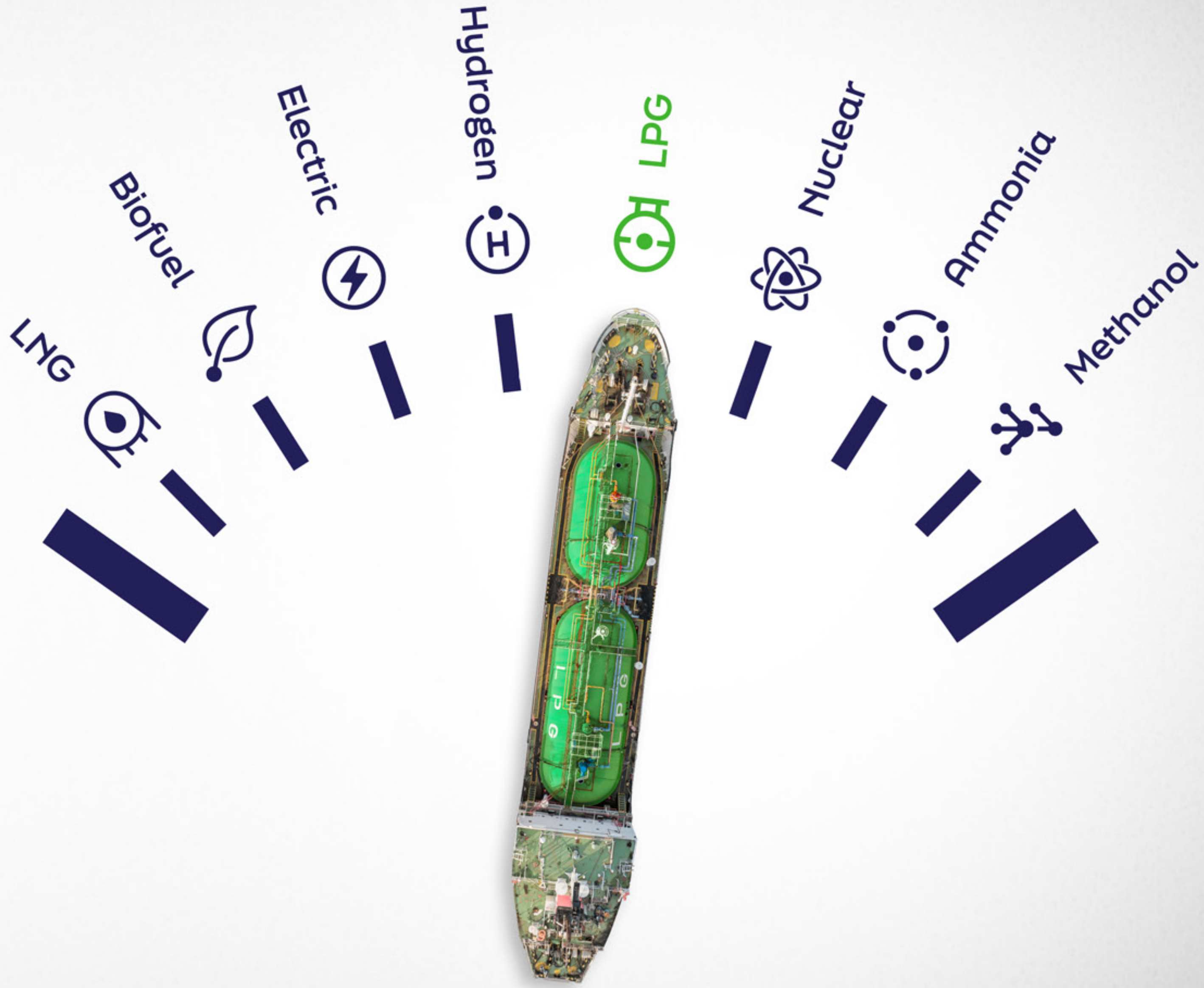
Fuel for thought

LPG

Expert insights into the future of alternative fuels

Your trusted adviser in alternative and low carbon maritime fuel



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Preface

The challenge of maritime decarbonisation is not that it is happening, but that it needs to happen so quickly.

The evolution of sail to its heyday of the great tea clippers took centuries, and the transition to coal-powered steam ships was driven by greater supply chain mobility and speed. The arrival of diesel-fuelled engines led to a new type of vessel propulsion, but this took close to one hundred years to emerge.

Each shift had a dramatic impact on the cost, speed and efficiency of shipping. The energy transition the maritime industry faces today is distinct from those earlier evolutions. It is not driven solely by technological advances or economics, but by an environmental imperative, increasingly underscored by social pressure, policy and regulatory demands to reduce emissions.

Decisions are being made today without commercial certainty, but in the knowledge that regulations, rather than economics, will push forward change. In this context, shipowners, charterers, insurers, financial markets and technology suppliers are seeking a better understanding of where the industry is heading.

Lloyd's Register (LR) is committed to providing trusted advice and to leading the maritime industry safely and sustainably through the energy transition. Our Fuel for Thought series puts decarbonisation options under the spotlight, analysing policy developments, market trends, supply and demand mechanics and safety implications. Each edition focuses on a specific fuel or technology, creating a reference point for the industry to overcome upcoming challenges as it faces the next great shift in ship propulsion.

This edition of Fuel for Thought focuses on liquefied petroleum gas (LPG), a widely available fossil fuel that offers emissions benefits compared to other fossil options. LPG could offer further benefits in conjunction with onboard carbon capture and if the emerging production of renewable, potentially zero- or near-zero emissions variants is scaled up.

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

1.1

Chapter 1: Introduction

Introduction from World Liquid Gas Association (WLGA) Technical Director Nikos Xydas

There are many pathways to lowering shipping emissions, including operational, ship design and fuel choice.

As a fuel, LPG is a unique, exceptional energy and when it comes to decarbonising shipping, LPG has an important and growing role to play. Transported and stored as a liquid, but consumed as a gas, LPG can deliver cleaner, lower emission marine transport than many alternatives currently available.

These benefits are already recognised with LPG being one of the most commonly accepted alternative fuels in the world today. Orders for LPG-fuelled ships have recently hit record levels, with 117 VLGCs either on order or currently sailing on LPG; and it is anticipated that 86% of new VLGCs that enter the market in the coming years will be capable of running on LPG. Although LPG is now a popular fuel for large gas carriers, this segment accounts for only 8% of shipping emissions, leaving a massive 92% from other types of vessels. The conversion of these ships represents a great opportunity to reduce global emissions even further.

As many countries in the world pursue deep decarbonisation targets, there is a growing move towards lower, and ultimately zero emissions shipping. LPG is an ideal fuel for all types of vessels, from the largest VLGCs, to container ships, from commercial fishing boats to recreational vessels. LPG presents a clean pathway today and a cleaner pathway in the future as near-zero renewable LPG (rLPG) and renewable dimethyl ether (rDME) are being developed. Suitable as a drop-in fuel into existing fuel systems, the promise of rLPG and rDME provides a future-proof solution for shipping owners, regardless of the ship's size and service.

Our world is becoming increasingly low-carbon and all sectors of the economy need to address emissions. In the shipping sector LPG should be the fuel of choice for all types of vessels. Why? Because with its low emissions and low cost, LPG can quickly improve the environmental performance of the shipping sector. LPG is flexible, with established supply chains already in place across the world which makes bunkering infrastructure easier to implement than many other alternative fuels. There are no technology barriers to overcome with LPG fuelled propulsion systems. Whether for the world's largest ships or for the smallest outboard motors, LPG delivers a low-carbon, low-emissions fuel today, and with the introduction of renewable LPG, low-cost deep decarbonisation into the future.

1.2

LPG fact file

What is it?

Propane C_3H_8

Butane C_4H_{10}

LPG stands for Liquefied Petroleum Gas and the term is used to describe two natural gas liquids: propane and butane, or a mix of the two.

Propane and butane are chemically quite similar, but the small differences in their properties mean that they are particularly suited to specific uses. Often, propane and butane will be mixed to get the best energy yields and properties. As such, the chemical composition of LPG can vary. Typically, commercially traded LPG contains 90% or more propane and less than 10% butane.

The mixture of light hydrocarbons in LPG can be liquefied under moderate pressure at normal temperature but is gaseous under normal atmospheric conditions. Since LPG can be liquefied at low pressures at atmospheric temperature, its storage and transportation is easier than that of other gaseous fuels. It is stored under pressure in tanks or cylinders.

According to WLGA[1], global production of LPG in 2023 reached 344 million tons, slightly exceeding demand of 342 million tons. Of this, 45% was used for domestic consumption (cooking and heating), with 56.9% of that demand coming from the Asia-Pacific region. Community and industry heating and power and petrochemical production represent the other major uses of LPG fuel, with lower demand from road transport (8%), and agriculture (1%).

Given its widespread use, there is a sizeable international trade in LPG, with global imports growing by 3% in 2023 to 128.3 million tons and forecast to keep the same growth rate until 2025, when imports are forecast to reach 136.3 million tons[2]. With more than 1,000 existing storage facilities and terminals, LPG infrastructure is well-developed globally, with international transport facilitated by pipeline and a shipping network consisting of more than 1,600 LPG carrying vessels.

LPG is currently produced from mainly fossil sources, with butane and propane being byproducts of crude oil, natural gas and coal extraction and refining. Around 60% of current LPG production comes from natural gas extraction. Renewable LPG (rLPG) can be produced from biomass and from renewable electricity to deliver a zero- or near-zero emission fuel. Although current supply of rLPG is in the low hundreds of thousands of tons, production investments are scaling up rapidly.

Compared to heavy fuel oils, fossil LPG emits approximately 97% less SOx, 20% less NOx and 90% less particulate matter while cutting carbon emissions by roughly 20%[3]. Therefore, LPG available today is compliant with existing emission standards including the IMO's sulphur cap of 0.5% and requirements regarding operating in emission control areas (ECA).

Those environmental benefits and the cost advantage of using cargo as fuel have led to several LPG carrying vessels installing LPG-capable engines, with 80 dual-fuel ships already in service and a further 70 on the orderbook. Based on main engine sizes installed on the existing fleet and the availability of corresponding LPG-capable engines, a further 200 or so vessels could be retrofitted to use LPG.

The wider uptake of LPG as a marine fuel – on gas carriers and potentially in other merchant segments - will depend on current efforts to extend its environmental benefits. WLGA has proposed a global pathway to rLPG satisfying up to 50% of global demand for LPG in 2050, while the use of onboard carbon capture could support mid-term compliance with IMO and other decarbonization targets while using mainly fossil LNG.

LPG typical properties

Boiling temperature

-42 °C (pure propane)
to -0.5 °C (pure butane)

Vapour pressure

1.8 bar (pure butane) to 7.3 bar (pure propane) at 15°C / 4.3 bar (pure butane) to 15.3 bar (pure propane) at 45°C

Density (as gas)

1.89 kg/m^3 (pure propane) to 2.54 kg/m^3 (pure butane) at 15°C / 1.69 kg/m^3 (pure propane) to 2.25 kg/m^3 (pure butane) at 45°C and atmospheric pressure.

Lower flammability limit (by volume in air)

1.4% (butane) to 1.7% (propane)

Upper flammability limit (by volume in air)

9.4% (butane) to 10.8% (propane)

Auto-ignition temperature

392°C (butane) to 459°C (propane)

Minimum ignition energy

0.25 mJ

Volumetric energy density

26.5 MJ/l

Fuel tank size ratio (vs MDO)

1.5

Source: WLGA Guide for LPG Marine Fuel Supply

2.1

Chapter 2:
General safety issues

There are several potential hazards to the storage, use and transportation of LPG that need to be mitigated in all industrial scenarios:

LPG is approximately twice as heavy as air when in gas form and will tend to sink to the lowest possible level and accumulate there.

LPG in liquid form can cause severe cold burns to the skin owing to its rapid vaporisation. Vaporisation can cool equipment which may also be cold enough to cause cold burns if not properly insulated.

LPG forms a flammable mixture with air in concentrations of between 2% and 10%. It can, therefore, be a fire and explosion hazard if stored or used incorrectly.

Vapour/air mixtures arising from leakages may be ignited some distance from the point of escape and the flame can travel back to the source of the leak.

At very high concentrations when mixed with air, vapour is an anaesthetic and subsequently an asphyxiant by diluting the available oxygen.

A storage vessel that has contained LPG is nominally empty but may still contain LPG vapour and be potentially dangerous.

Due to these hazards, the use of LPG in a marine fuel context requires safeguards relating to ship design and construction, machinery and technology arrangements, bunkering technologies, onboard procedures and crew training.

2.2

Maritime safety regulations

While the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) covers the construction and equipment of ships carrying liquified gases as bulk cargoes, including the use of such cargoes as fuel, 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 Code).

Considering the nature of the fuels involved, the codes indicate the necessary prerequisites for the equipment, machinery, other systems and their arrangement on board in order for the vessel to run safely on gas or low-flashpoint fuels in a way that minimises the risk to the ship, its crew and the environmen. In addition to goals, functional requirements, risk assessment and prescriptive requirements, the IGF Code also addresses operational requirements and crew training requirements.

At the Maritime Safety Committee (MSC) 107, the 'Interim guidelines for the safety of ships using LPG fuels (MSC.1/Circ.1666)' 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, at MSC 108, has also recently approved "Interim guidelines for the use of LPG cargo as fuel" (expected to be MSC.1/Circ.1679).

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

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

To support LPG as a fuel application on ships subject to the IGF Code, LR has added a new appendix to the Rules and Regulations for the Classification of Ships Using Gases or other Low-flashpoint Fuels that incorporates IMO's Interim Guidelines for the Safety of Ships using LPG Fuels (MSC.1/Circ.1666).

2.3

Specific bunkering considerations

Historically, carriage and transfer of maritime LPG cargoes have a good safety record, and the safeguards associated with LPG import/export terminals are proven. While LPG bunkering would involve far lower quantities and transfer rates when compared to import/exports, many of the same safeguards are applied to ensure safety.

LPG has a higher density than air and any spillage will collect in lower spaces, requiring a different approach to leak detection and ventilation compared to conventional fuel. LPG is a low-flash-point liquid, and when used in a high-fire-risk space of the ship with a constant personnel presence, such as the engine room, a double-walled pipeline must be used as secondary containment. Hydrocarbon detectors will detect any leakage and contain the fuel within the secondary containment before it reaches areas where humans are present. Double-walled pipelines must be used below the deck line.

Although LPG in its liquid form cannot burn or explode, if spilled it can form a pool on the water. Since LPG boils at ambient temperature, a vapour cloud would then be formed in the air and easily dispersed with the winds. While the risk of fire or explosion increases in confined spaces like a ship or building, there is relatively little evidence of LPG fire or explosion in open spaces.

Leakage of LPG during bunkering can pose several hazards. Extreme care must be taken to ensure that LPG does not drip or spill onto ship hulls or decking because it could lead to brittle fracture, seriously damaging a ship or bunkering barge.

LPG spilled onto water can pose a more serious hazard as it will rapidly and continuously vaporize into natural gas, which could ignite. The resulting ‘pool fire’ would spread as the LPG spill expands away from its source and continues evaporating. A pool fire is far hotter and burns far more rapidly than oil or gasoline fires, and it cannot be extinguished; all the LPG must be consumed before it goes out. Because an LPG pool fire is so hot, its thermal radiation may injure people and damage vessels or property a considerable distance from the fire itself. Many experts agree that a large pool fire, especially on water, is the most serious LPG hazard.

Leaks can also release LPG into a port area and cause fires or explosions. While a bunkering barge or a vessel using LPG for fuel contains far less LPG than large LPG carriers, LPG spills in bunkering operations could still be a significant concern.

In terms of regulatory framework, LPG bunkering still lacks the official regime that would further 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 share their knowledge and expertise. Regulatory bodies and governmental agencies responsible for maritime safety and environmental regulations should be engaged along with IMO, in order 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 to the identification of the best practices applied in other fuels like LNG, in order 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.

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 safe and efficient transfer of LPG should be communicated.

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, personnel in bunkering operations should be issued and circulated.

Pilot projects and demonstrations are 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 improvement of safety measures.

Process assurance for LPG bunkering operations

Using guidelines on LNG bunkering as a basis - including ISO 20519 for LNG bunkering in ports, SGMF/EMSA guidelines and standards, as well as several countries' national legislation - an equivalent roadmap for LPG should focus on 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 programs and procedures, timetable, 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 zones 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 prior to, during and after the bunkering process.

Before bunkering

The pre-bunkering phase begins with the ordering of bunkers 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.

During bunkering

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.

After bunkering

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. to 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.

2.4

Fuel quality/ specifications

While no specific marine fuel standard has been developed for LPG, the commercial trade in LPG uses the International Organization for Standardization's ISO 9162:2013 standard. This specifies required characteristics and additional information to be supplied to the purchaser by the vendor of those products commonly referred to as liquefied petroleum gases and is intended to apply to international transfers of commercial propane and commercial butane.

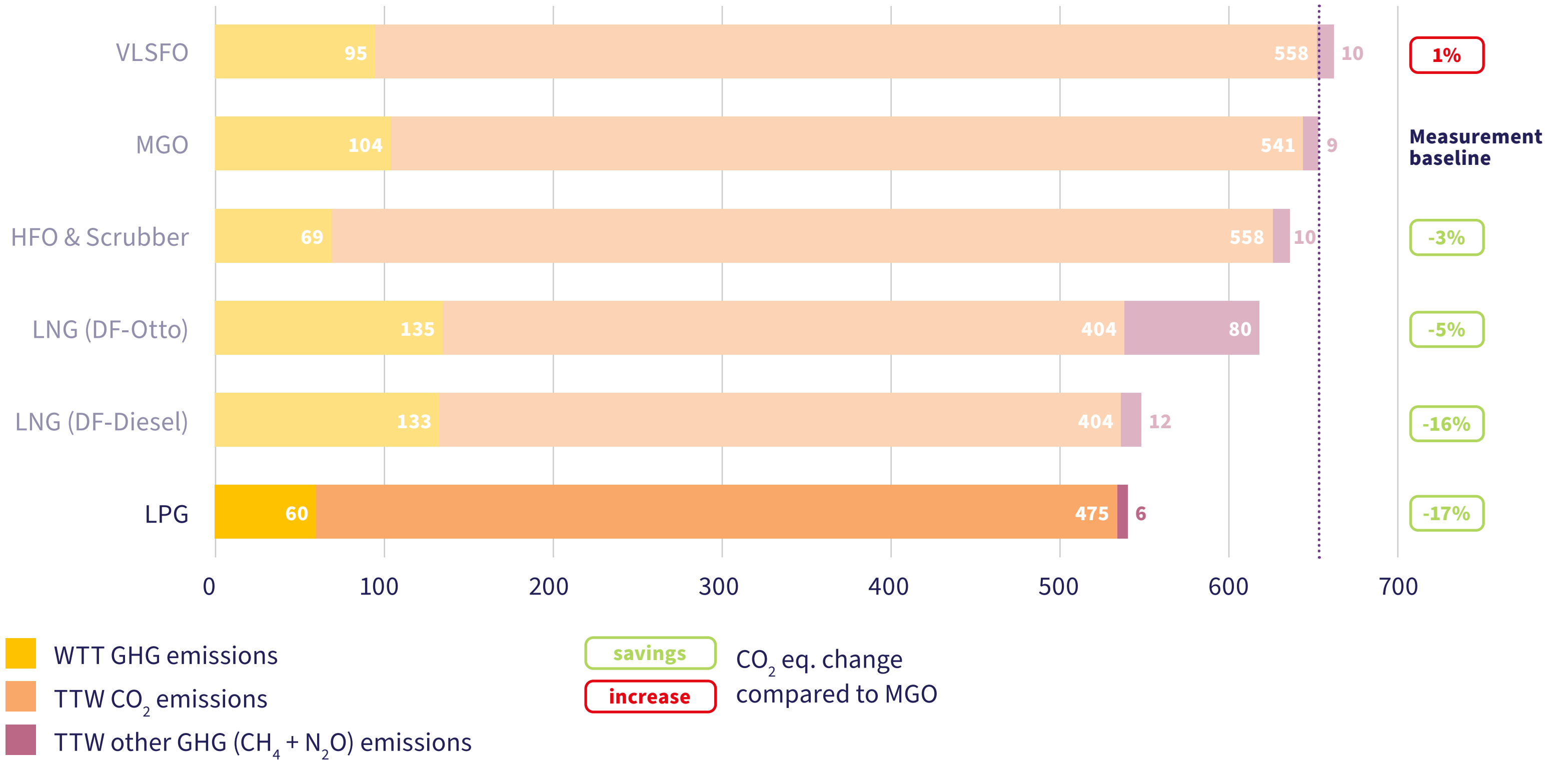
3.1

Chapter 3: Drivers for LPG

Regulations and lifecycle assessment

Engine manufacturer MAN Energy Solutions has stated that the use of LPG as fuel can reduce the CO_2 emissions by up to 13% when compared to MDO and by up to 18% compared to HFO[4]. Another study shows that when taking into consideration the total lifecycle Well-to-Wake (WtW) GHG emissions, LPG can lead to 17% lower gCO_{2eq}/kWh compared to MGO[5].

Fuels WTW CO_2 and CO_{2eq} emissions

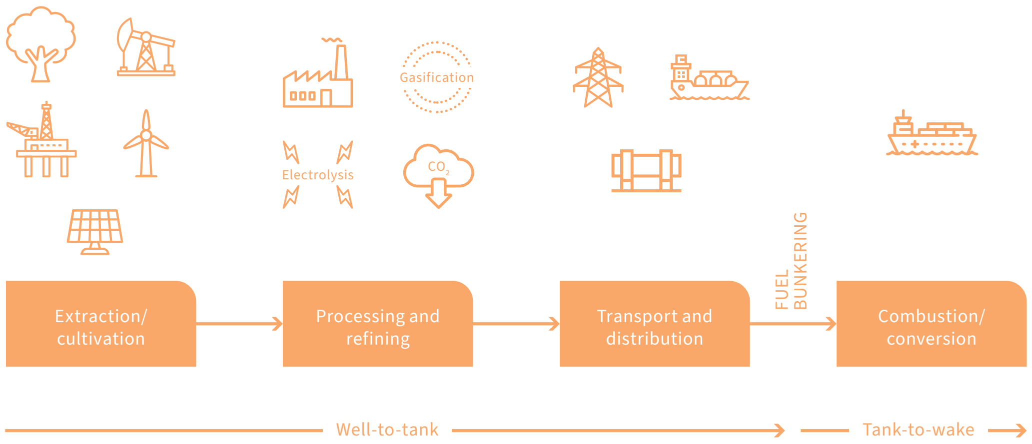


IMO's *Guidelines on the life cycle GHG intensity of marine fuels* (LCA guidelines) (MEPC 376(80)) were adopted at MEPC 80 (MEPC.376(80)). The guidelines include the fuel pathways for producing and using LPG as a marine fuel, covering all the links of the supply chain highlighted in the figure below.

The guidelines were revised at MEPC 81 by the *2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels* (2024 LCA Guidelines) (MEPC.391(81)) to include revised calculations for default emission factors, an updated template for well-to-tank default emission factor submission and a new template for Tank-to-Wake (TtW) emission factors.

Further development of the framework continues, with work planned to be undertaken at ISWG-GHG 17 in September 2024, ahead of MEPC 82.

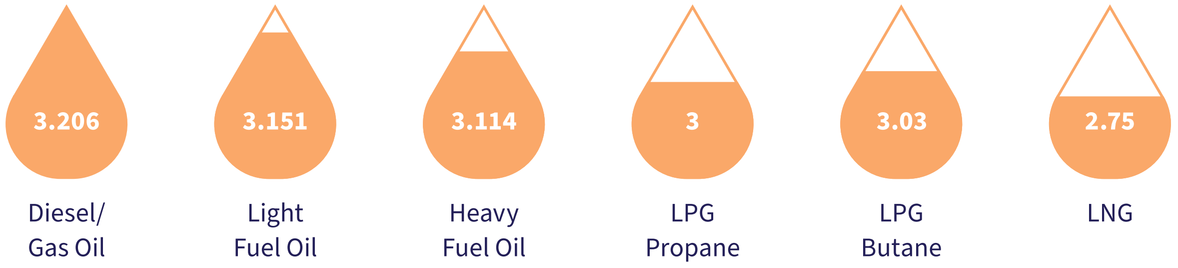
Generic Well-to-Wake supply chain[6]



LPG contains negligible sulphur, meeting IMO's Sulphur 2020 and Sulphur Emission Control Area (ECA) requirements for sulphur content in fuel oil. 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 directly affects the implementation of EEDI, EEXI and CII (expressed in gCO_2 /tonnes nautical mile) which include fuels' carbon factor in their formula.

Fuels Carbon Factors[7]

Carbon factor (t-CO_2/t-Fuel)



The use of LPG as a marine fuel must also be considered in light of the European Union's Fit for 55 package of regulations and the legislation included which is directly linked with the shipping industry. Due to the lower CO_{2eq} emissions generated using LPG, companies could view LPG use as one means of reducing exposure under both the EU Emissions Trading System and the FuelEU Maritime legislation in the early years of the regulations.

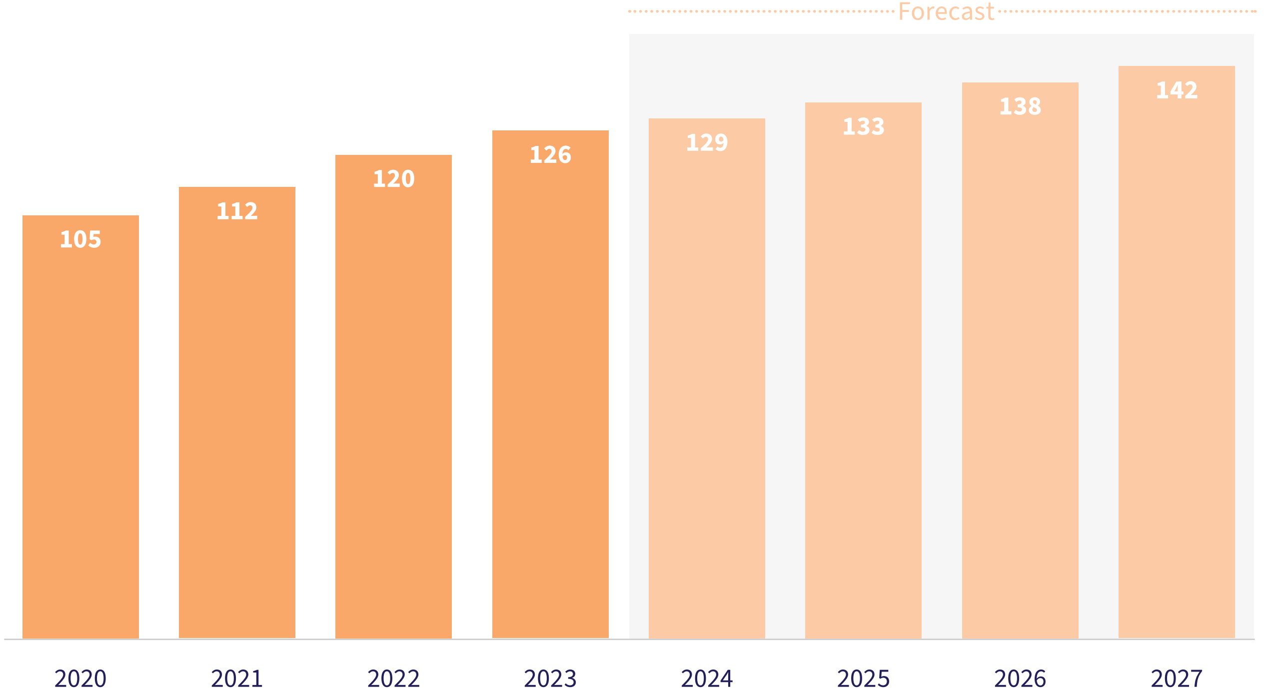
LPG, and in particular the future use of bio-LPG or renewable LPG (r-LPG), is also supported by the Alternative Fuels Infrastructure Regulation (AFIR), which promotes the implmentation of alternative fuel bunkering and onshore power. LPG can also be compatible with the EU's latest Renewable Energy Directive (RED III) when it is produced from renewable sources, such as bio-LPG or r-LPG. Thus, the development of the LPG supply chain is being indirectly supported by RED III.

3.2

Ship operator demand and interest

The LPG market continues to experience a rise in demand and consequently in world seaborne trade. In 2022, the total global LPG demand grew by 3.5%, taking global demand to a record level of 342 million tons[8]. The available data shows that in world seaborne LPG trade volumes during 2023, six more million tonnes of LPG were expected to be traded which corresponds to a 5% rise compared to 2022. Similarly, for 2024 a 2.3% rise is expected compared to 2023 and it is forecasted the trade volume will reach almost 142 million tonnes in 2027[9].

World Seaborne LPG trade volumes (million tons)

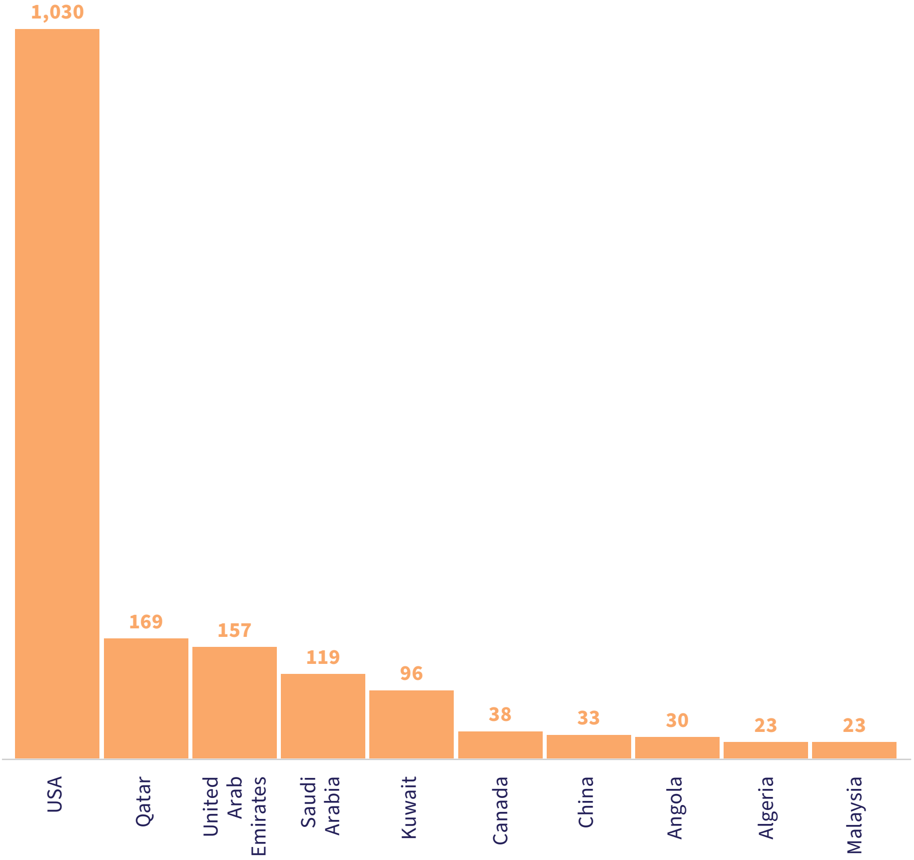


Source: GlobalPetrolPrices.com, MSI LPG trade data

The US, 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. Between August 2022 and August 2023 for the VLGCs category, the loading and discharging operations were formulated as per the following charts. In these charts, specifically for the loading countries, it is shown that USA presents almost 509% higher VLCGs 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.

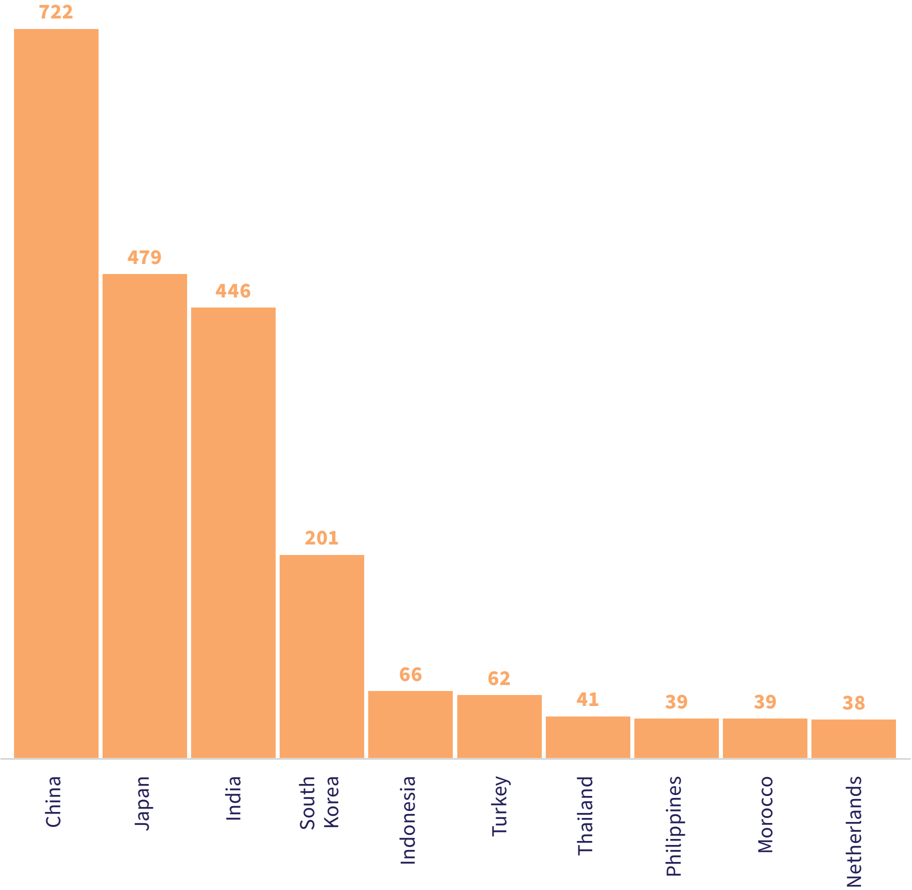
Top 10 Loading Countries (VLGCs)

No. loading port calls



Top 10 Discharging Countries (VLGCs)

No. discharge port calls

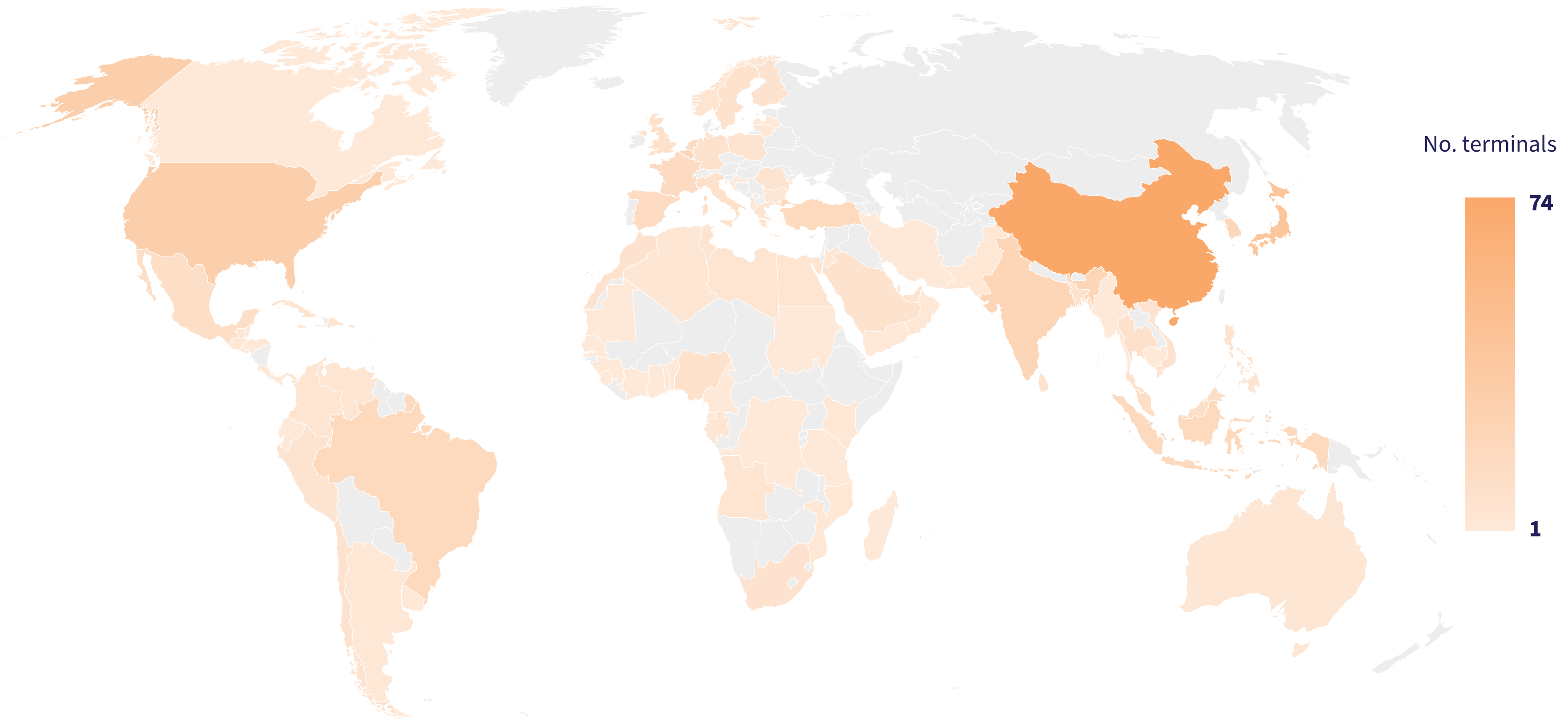


Terminals

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 cover the LPG as fuel demand. 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 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 found at the top with 74 facilities, Japan with 40, US 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[10].

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 on a sufficient market driven by the demand for dual-fuel LPG engines by ship operators selecting LPG as fuel for non-gas carriers.

LPG terminal map[11]



LPG carrier fleet

As of December 2023 there were 1,644 LPG carriers (LPGCs), 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. A thorough analysis of the LPGC sector is shown through the following charts[12].

In-Service analysis

Chart 1: In-service VLGC fleet by class

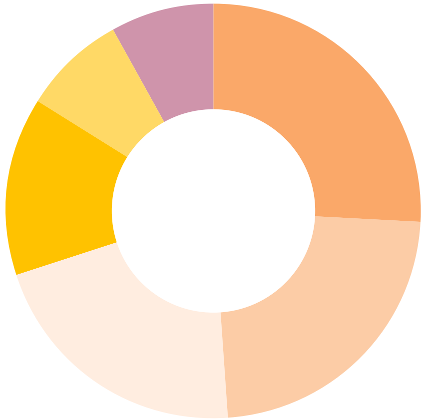
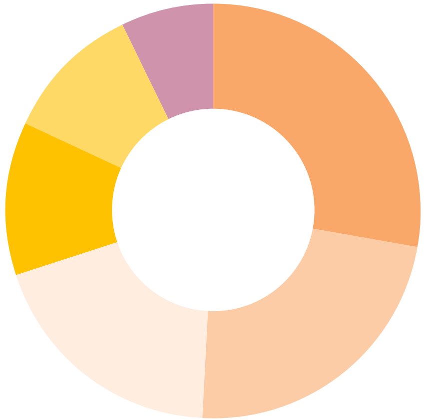


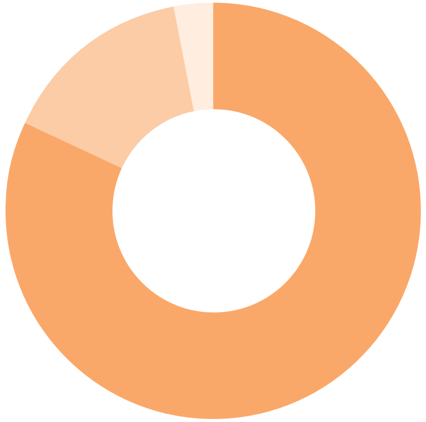
Chart 2: In-service LPGC fleet by class (>5k cbm)



Class	LR	DNV	NK	ABS	BV	KR
No of Ships	239	214	235	99	210	93
Gross tonnage in total (mGT)	7.3	6.0	4.9	3.0	2.7	1.8

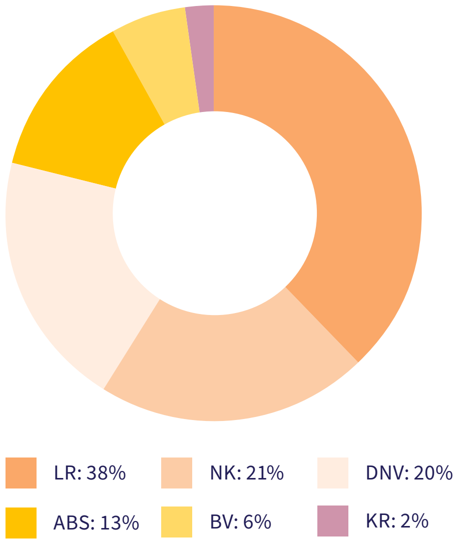
Chart 3: In-service LPGC fleet by size

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



Orderbook analysis

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



Class	LR	NK	DNV	ABS	BV	KR
No of Ships	1.7	0.7	1.0	0.7	0.1	0.1
Gross tonnage in total (mGT)	46	26	25	16	7	2

Chart 6: Orderbook LPGC fleet by size

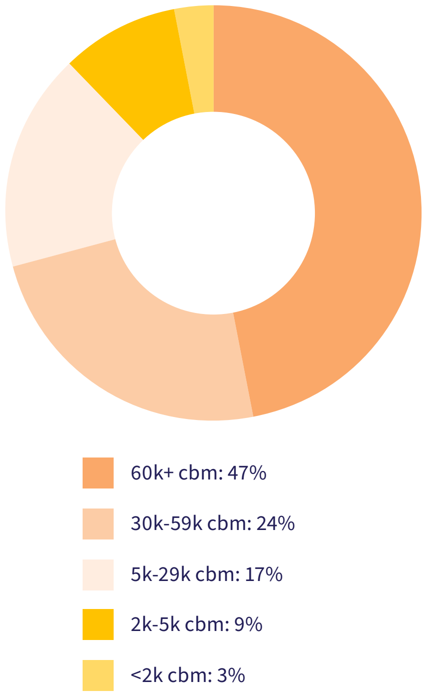
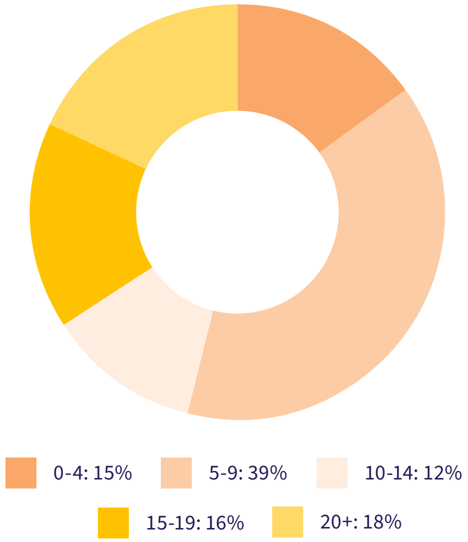
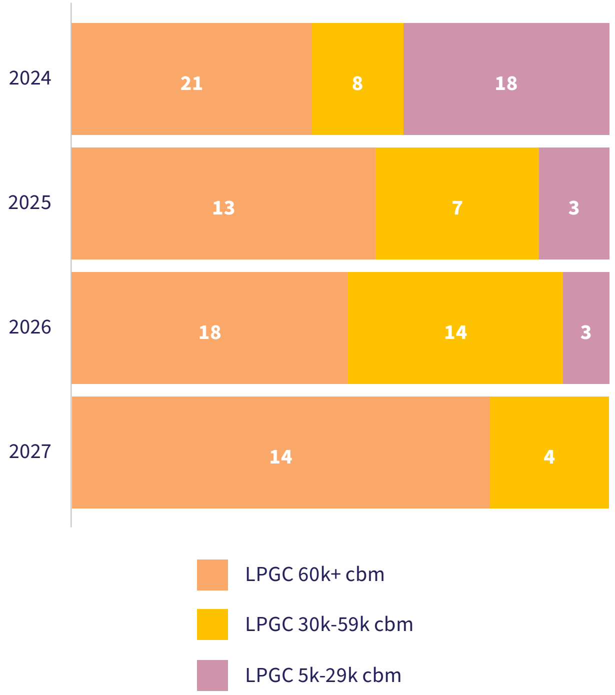


Chart 7: Orderbook and In-service VLGC fleet



Age	Orderbook	0-4	5-9	10-14	15-19	20+
No.	66	48	124	39	50	57

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



The data in the above charts reveals some significant points:

1. There are 64 VLGCs out of a total of 129 LPGCs under construction.
2. There are 364 VLGCs out of a total of 1,614 LPGCs in operation
3. Age liability: 27% (98 out of 364) of the in-service VLGCs are currently over 15 years of age.
4. Out of 80 dual-fuel LPGCs in service, 62 are dual-fuel VLGCs (78%)

The LPGC orderbook divided by shipbuilder and country shows that the East shipbuilding market prevails. It is scheduled that 63 ships above 5,000m^3 will be constructed in Korea, 47 in China, 17 in Japan and one in Brazil until 2026, while most LPGCs are expected to be delivered during 2023 and 2024. The breakdown among the shipyards of each country is shown in the following chart.

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

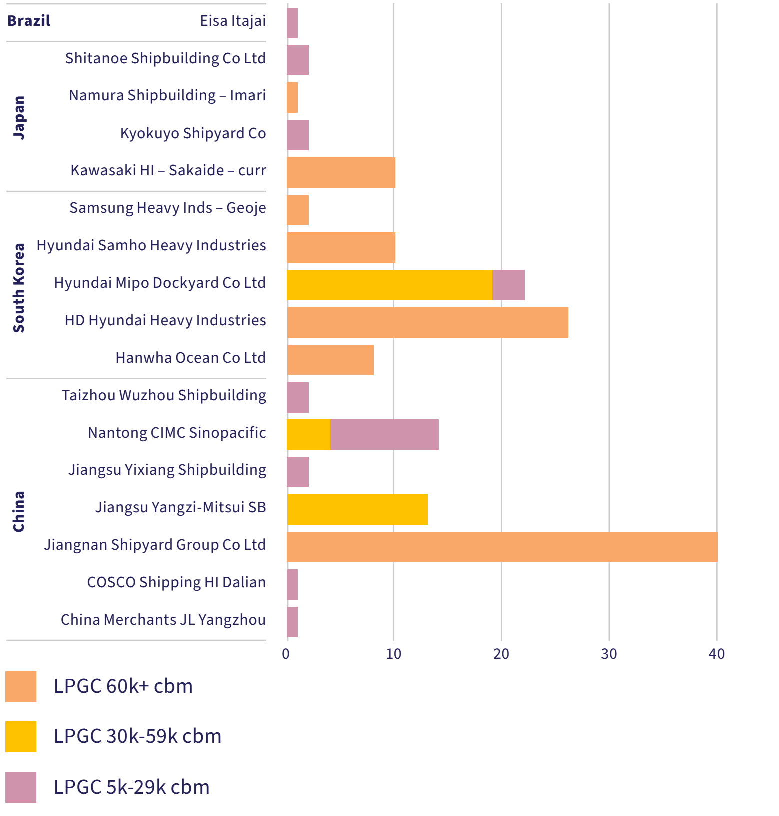


Chart 10: LPGC Dual-Fuel Orderbook by Shipbuilder[13]

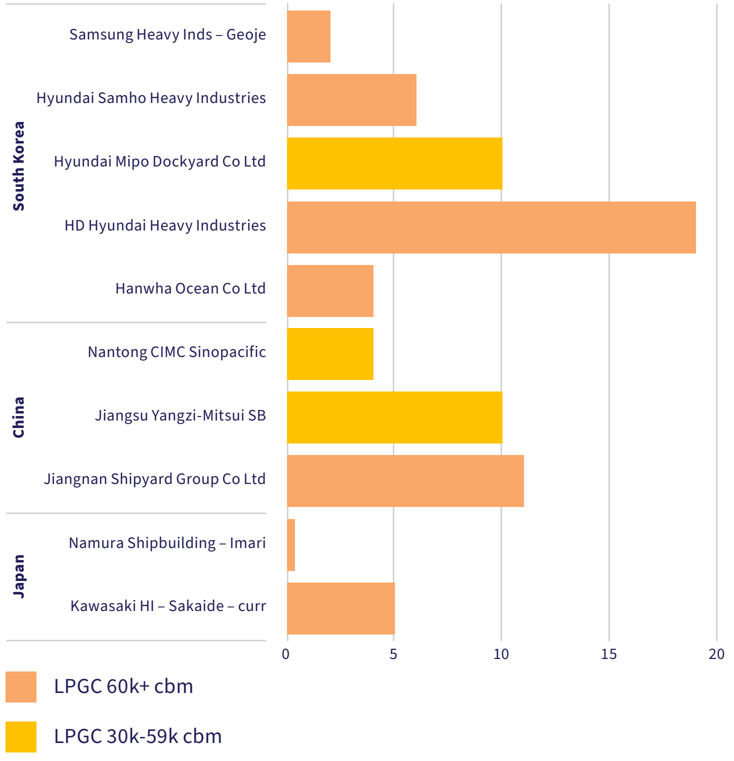
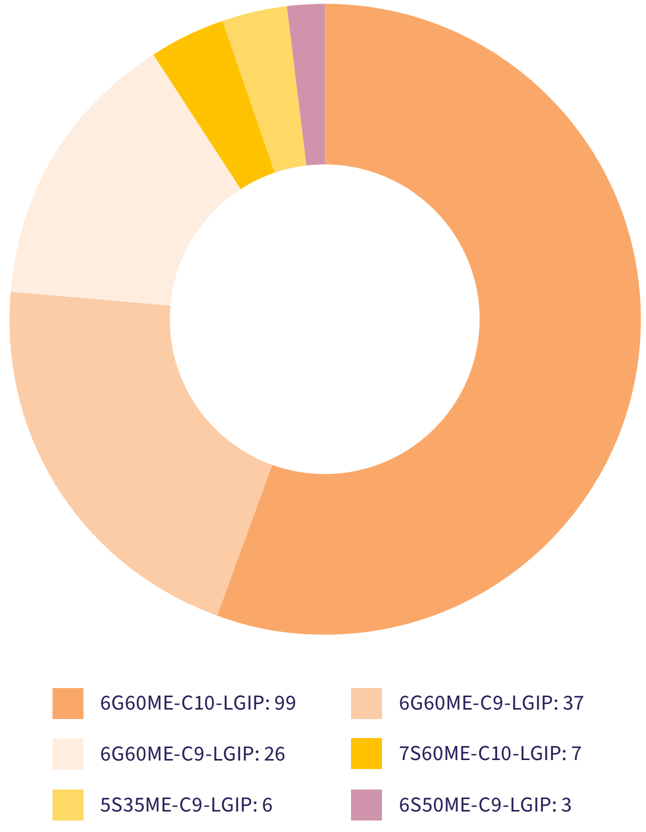


Chart 11: LPGC Dual-Fuel LPGC by M/E type



In addition, the LPGCs dual-fuel orderbook shows that South Korea is the leader with 48 orders, followed by China and Japan with 14 and 8 dual-fuel orders, respectively. Out of 70 dual-fuel LPGCs on the orderbook, 55 are dual-fuel VLGCs (78%).

Considering both in-service and the orderbook, out of 150 dual-fuel LPGCs, 44 are LR classed dual-fuel LPGCs (29%) 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 formulating the following chart. According to the latest data there is 12% rise between 2022 and 2023 capacity while there will be 26% rise in the available LPG fleet capacity between 2022 and 2026.

3.3
Techno-economic drivers

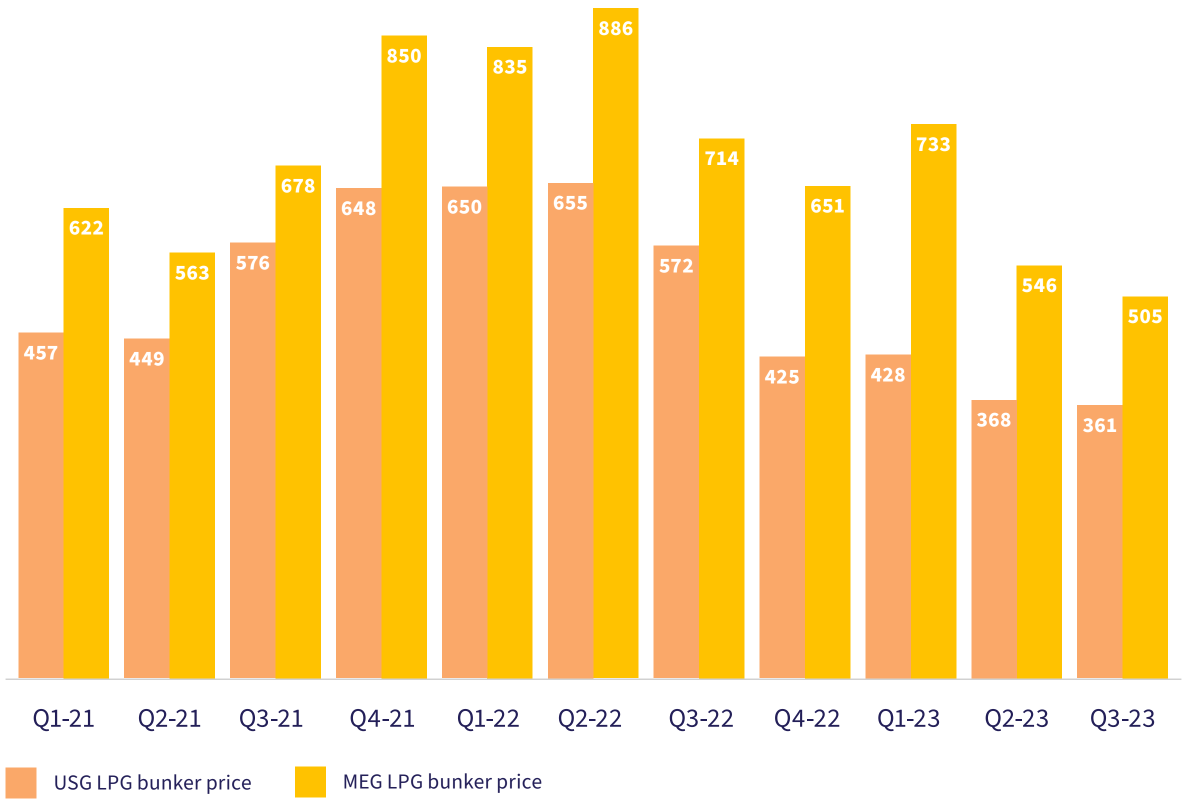
Fuel cost

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

Capital expenditure

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 US$125 million while a similar sized LPG fuelled option for a newbuild would cost around US%100 million, almost 20% less. According to data from MAN Energy Solutions, the retrofit of a conventional diesel oil engine to LNG dual-fuel costs US$12-33 million while the retrofit of the same ship into LPG will cost between US$9.5-27 million depending on the ship type and size.

LPG bunker prices ($/ton)

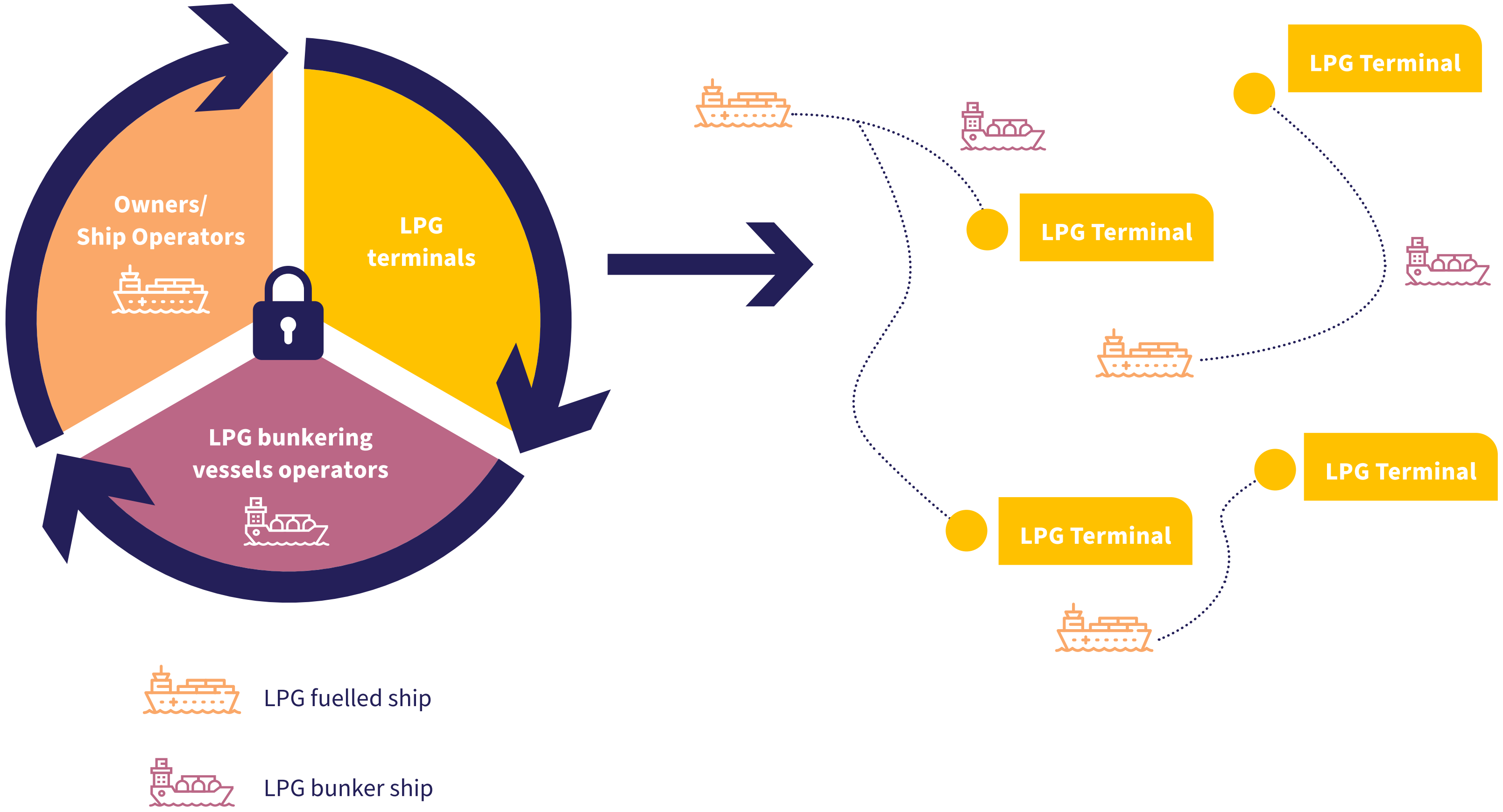


Value chain development

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 marine fuel and the supply points for it across the globe. As mentioned previously, currently there are 607 LPG terminals available worldwide and their trade is projected to be 142 million tonnes by 2027. Further focusing on the supply of LPG, there are 995 LPG carriers up to 15.000 cbm that could be operated as bunkering vessels[14]. 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.

In order 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-and- 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 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.

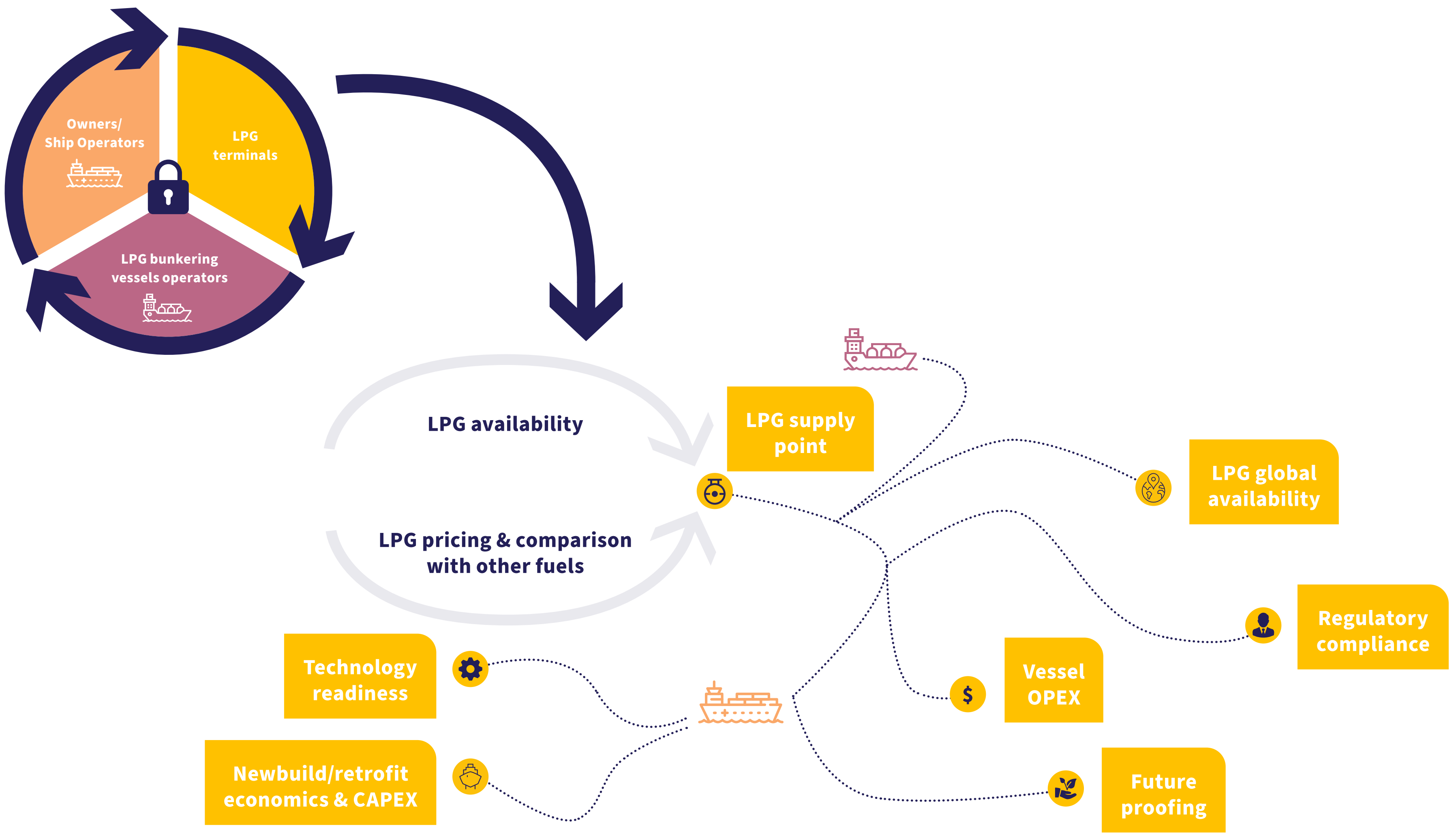
LPG as marine fuel initial steps



Having considered the business model, the technology readiness level should be examined, and currently, as stated above, only MAN provides models of LPG dual-fuel two-stroke engines (ME-LGIP) that can be used for propulsion purposes. 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 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 coming into force and affect ships' operations and economics, something unprecedented for the shipping industry.

LPG as marine fuel developed value chain



4.1

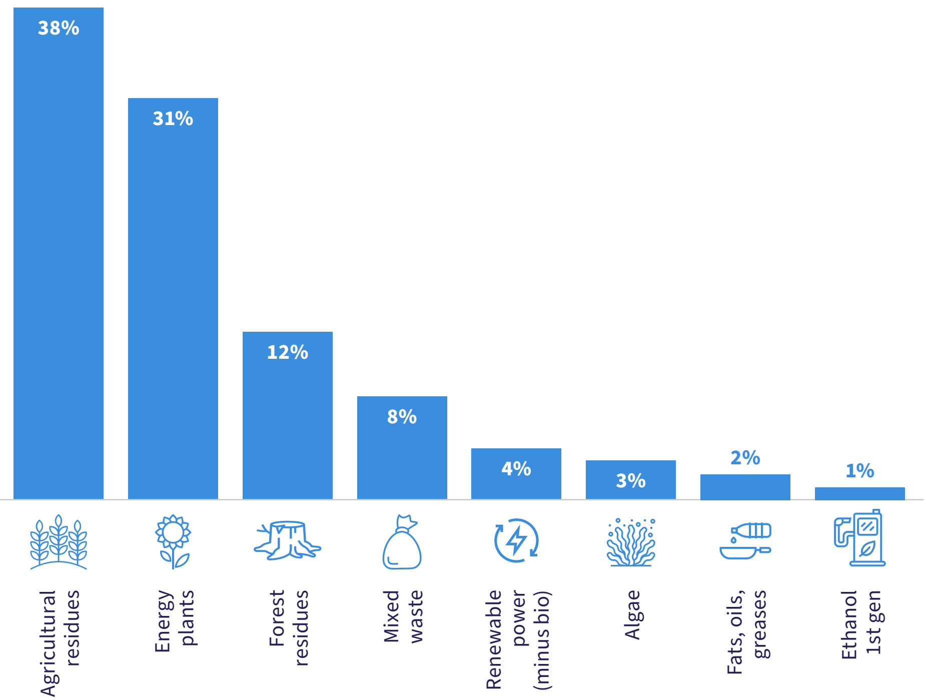
Chapter 4:
Renewable LPG production

Renewable and bio-LPG

As it is chemically and physically identical to conventional LPG, renewable LPG and bio-LPG can substitute LPG without any equipment or machinery upgrades or energy loss during combustion. They can be further blended 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.

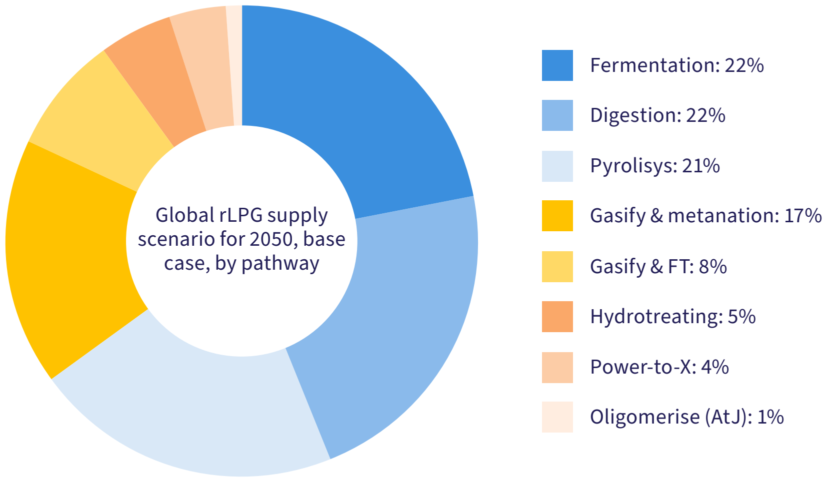
Renewable LPG is produced using renewable electricity, while bio-LPG is produced by anaerobic digestion or gasification of renewable and waste biomass materials after having undergone a series of treatments to purify their energy content. Such materials can be agricultural residues, energy plants, forest residues, mixed waste, algae, fats-oils-greases or first-generation ethanol in percentages as per below[15].

LPG feedstocks



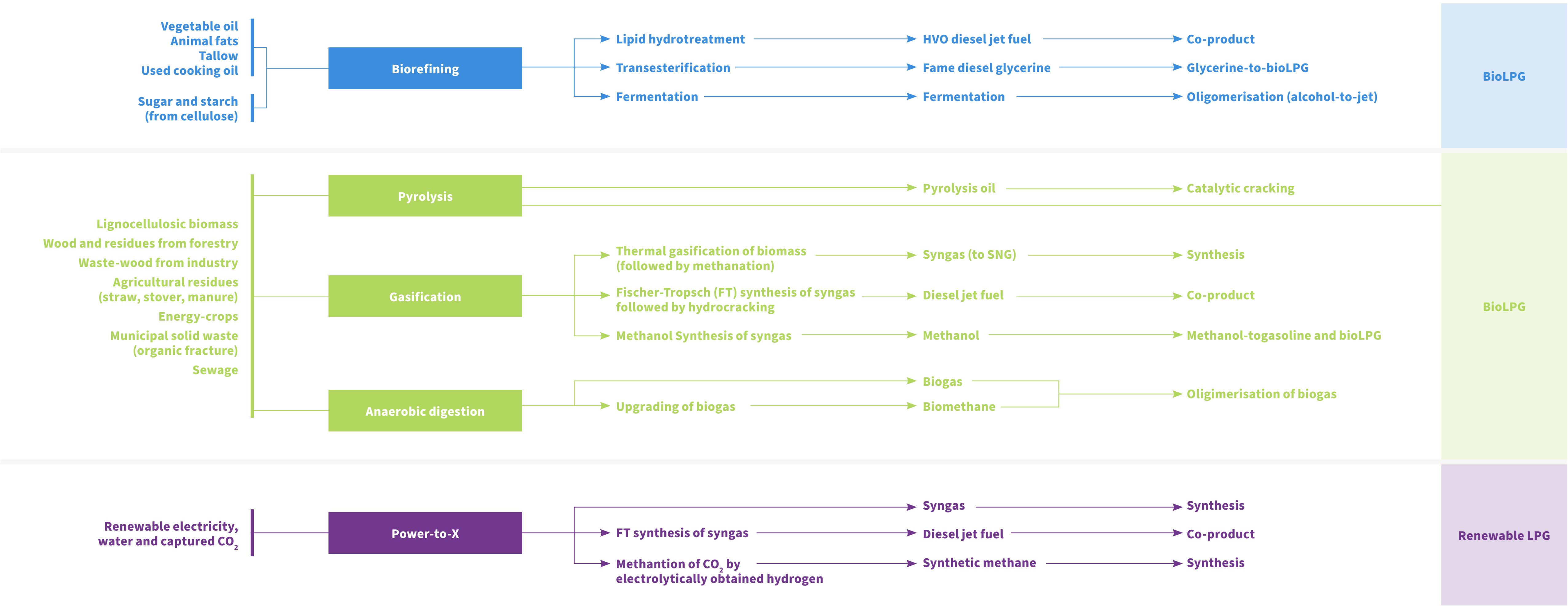
According to WLGA, by 2050 r-LPG supply could potentially satisfy at least 50% of the global non-chemical LPG consumption. The r-LPG supply comes from eight feedstocks, which are processed in eight pathways as depicted below, and depending on feedstock availability, these pathways could globally, by 2050 produce near 220 million tonnes of r-LPG per year.

LPG feedstocks processing pathways



Bio-LPG can also be derived as a byproduct of biodiesel production or after the conversion of biomethane and other biogases. Below, the different production routes of renewable, bio-LPG are presented[16].

Pathways to bio-LPG and renewable LPG



4.2

Renewable Dimethyl Ether (DME)

Dimethyl Ether (DME) is a synthetic fuel and not a natural resource. Renewable DME can be produced from syngas using a wide range of sustainable and renewable feedstocks including sewage sludge, agriculture residues and energy crops, animal waste and forest residues. DME is a clean burning 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 additional technology or cryogenic tanks or pumps. Due to those similarities, DME can be distributed and used via the same supply chain infrastructure as LPG at a blend of up to 20% by weight.

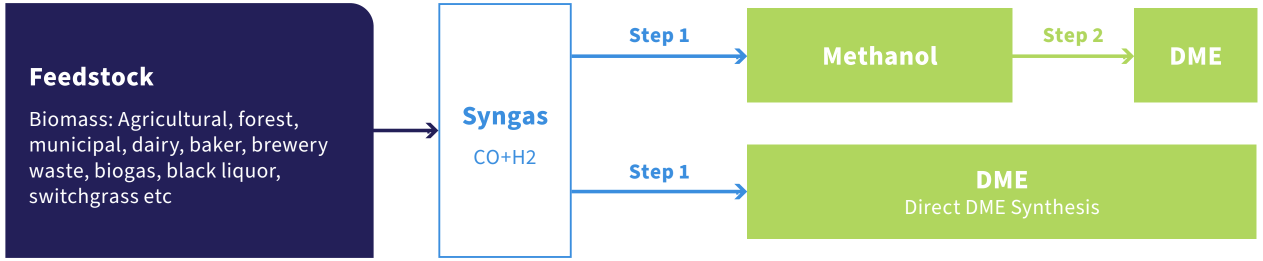
As far as the engines are concerned, MAN Energy Solutions through the ME-LGI engines that they offer, makes the adoption of DME feasible. The ME-LGIP technology used for the burning of LPG as fuel is relative to the LGI technology and the future fuel transition from LPG to DME will not be an obstacle.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

Renewable DME is capable of reaching negative carbon intensity (CI) 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 could reduce CO_2 emissions by up to 30%, considering max blending ratio of 30%/70% (r-DME/LPG)[17,18].

In 2022, EMSA concluded that as far as the Well-to-Tank emissions are concerned, r-DME under certain pathways can offer among the greatest potential for GHG reductions.

The same year, Dimeta was established by SHV Energy and UGI International to advance the production and use of renewable and recycled carbon DME with the target to produce 300,000 tons of renewable and recycled carbon DME per year by 2027. To support the above-mentioned target, Dimeta and KEW technology formed another joint venture, Circular Fuels Ltd which will develop construction-ready r-DME production plants.

Production pathways of DME



The creation of Dimeta came in addition to the other already established renewable DME producer Oberon Fuels in California USA, which had developed world's first commercial renewable and recycled plant which started making renewable and recycled fuel in May 2021. This plant has currently a capacity of 3,900 tonnes per year while the company estimates renewable DME production from its plants of over 500 kT per year by 2027[19].

5.1

Chapter 5: Technology readiness

Marine engines

As far as engine technology readiness is concerned, MAN 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. This engine type employs 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. In service ME-C engines can be retrofitted to dual-fuel ME-LGIP engines capable of burning LPG as fuel[20].

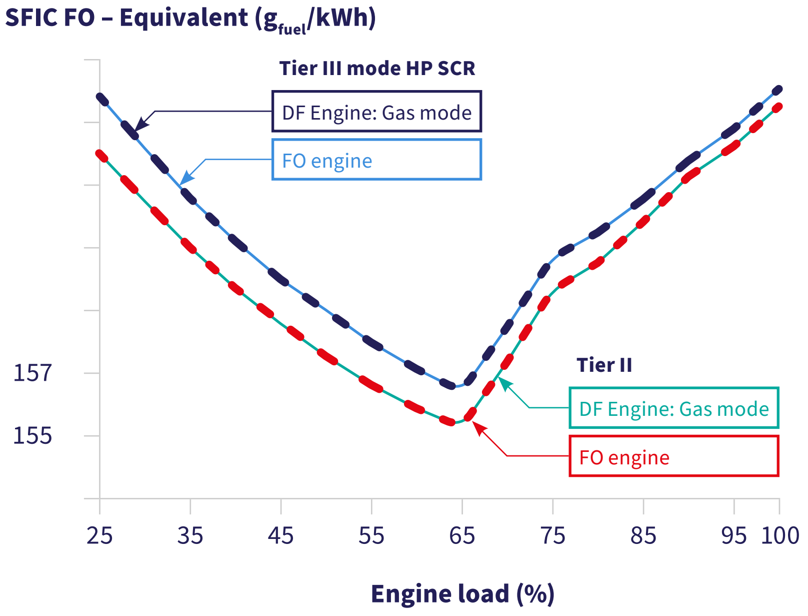
The engine modification process in the case of retrofitting includes:

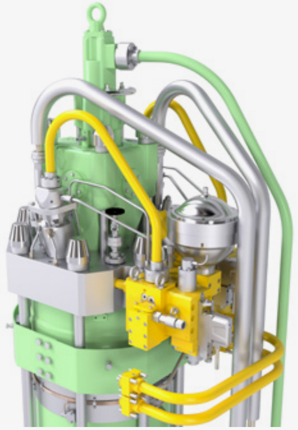
- New cylinder covers
- Additional gas control block
- New LPG injection valves
- Additional gas piping
- New sealing oil pumps
- Control system upgrade

As of March 2023, MAN ES has developed the LPG dual-fuel engine types as 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

Dual-Fuel Engine (DF) vs Fuel Oil (FO) engine TIER III engine HP SCR





MAN S50ME-LGIP LPG unit

MAN S50ME-LGIP

5.2

Fuel tanks and fuel systems

The fuel storage systems used in LPG carriers and in other vessels bunkering LPG will be similar to those deployed in the seaborne transportation of LPG for several decades. The three options are:

- refrigerated, typically at -50°C at close to ambient pressure.
- semi-refrigerated, typically at -10®C and 4-8 bar pressure.
- pressurised, typically at 17 bars, corresponding to the vapour pressure of propane at about 45°C

There are different possible combinations of bunkering ships with pressurised tanks, semi-refrigerated tanks or fully refrigerated tanks and similar arrangements in the ship to be bunkered. WLGA's LPG bunkering[21] guide uses four cases of tank use in LPG bunker vessels and receiving vessels to illustrate some challenges with each tank type:

In the case of pressurised tanks both in the bunkering ship and the ship to be bunkered, the LPG is transferred using a general transfer pump located in the bunkering ship. When filling the LPG tank, pressure will build up because of less gas volume available, and since it takes time to condense LPG, this can increase fuelling time. For practical purposes and to comply with safety regulations, the LPG tank must be equipped with a vapour return system back to the bunkering vessel, i.e. a gas outlet connection in addition to the liquid inlet connection. This case represents the most common and cost-effective LPG bunkering option.

In the case of semi-refrigerated tanks in the bunkering vessel and a pressurised tank in the ship to be bunkered, it is necessary to have a heater and a booster pump in the bunkering ship and a vapour return system in the ship to be bunkered. The heater is needed because the fuel has a lower temperature than the tank design temperature, and this will typically be handled by a heat exchange system using heat from seawater. The LPG filled will have a lower than ambient temperature but needs to be above the tank design temperature. The booster pump is needed to raise the pressure of the LPG before bunkering. Both the heater and booster pump are typically installed on semi refrigerated LPG carriers, that may be used as bunkering ships. The vapour return from the ship to be bunkered may have too high a pressure for the semi-refrigerated tank and must be handled by the re-liquefaction plant in the bunkering vessel, which may require some modifications. An alternative to vapour return in this case is to fill the cold LPG with a spray-line to condense the LPG vapour.

In the uncommon case of pressurised tanks in the bunkering vessel and a semi-refrigerated tank in the ship to be bunkered, the pressure needs to be reduced by lowering the temperature in a liquefaction plant. An LPG carrier with pressurized tanks is typically not equipped with this, thus requiring comprehensive modifications of the equipment and cargo handling system. This case also requires a vapour return system with compressor in the bunkering ship that needs to be set up to increase the pressure of the vapour return. LPG carriers with pressurised tanks are typically equipped with a compressor, but only for the purpose of emptying the cargo tanks.

In the case of semi-refrigerated tanks both in the bunkering vessel and the ship to be bunkered, cooling (and probably not heating) may be necessary. A vapour return system and some modifications of the re-liquefaction plant in the bunkering vessel to ensure a higher capacity may also be necessary.

Based on the cases discussed above, a pressurized LPG fuel tank is the preferred solution when bunkering the ship, because the ship can be bunkered by a bunkering vessel based on an LPG carrier (either with pressurised tanks or semi-refrigerated tanks) without major modifications. Both types of bunkering vessels are possible, depending on the size of the fuel tanks to be bunkered and the number of ships to be served. Semi-refrigerated LPG carriers typically have larger capacity than pressurised LPG carriers and sufficient capacity for all ship types. They are also more flexible, e.g. in terms of filling ships with semi-refrigerated fuel tanks and have a limited cost premium.

5.3

Carbon capture

Onboard carbon capture and storage is among the solutions that will shape the future of maritime decarbonisation as it can play a significant role in the mid to long term. In combination with LPG as a marine fuel, any application of Carbon Capture & Storage (CCS) onboard ships can be optimised.

Combining CCS systems with LPG propulsion systems can not only reduce the environmental footprint but also reduce the required CO_2 storage capacity onboard due to the lower CO_2 emissions from LPG combustion than for other fossil fuels. 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 low 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, and could lead to over US$1 million reduction in annual IMO carbon pricing assuming carbon cost of US$130 per tonne of CO_2[22].

Operators considering CCS should also factor in the downstream greenhouse gas emissions related to the solution - including the production of technologies and consumables related to CCS - as well as the emissions from onboard energy used to power the system.

LR has already issued CCS and CCS Ready notations which allow owners to prepare for a future retrofit at the new building stage, thus saving time and money in the longer term. Owners, yards, and classification societies have already started working on adopting carbon capture systems onboard ships and LR has provided “Approvals in Principle” for CCS technologies.

Dual-Fuel LPG carrier CII compliance

Year of build	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 build	Emissions	2033	2034	2035	2036	2037	2038	2039	2040	2041
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

Chapter 6 Summary and conclusion

LPG as a fossil-derived fuel offers significant air pollution advantages compared to conventional fuel oil, securing compliance with IMO regulations on sulphur oxides. It also delivers a greenhouse gas emissions reduction that could be enhanced by combination with onboard carbon capture to deliver compliance with IMO ambitions into the next decade.

The long-term decarbonisation potential of LPG will depend on the scaling up of renewable fuel production, which is anticipated to be rapid as traditional LPG users seek to reduce their environmental impact. Meanwhile demand and seaborne trade is expected to grow in the coming years, necessitating growth in the global fleet of LPG carriers and providing the opportunity for further uptake of LPG as a fuel in that fleet.

There is potential for LPG to be used as a fuel in other vessel types. The transportation, storage and use as fuel have been established over several decades, while supply and supply infrastructure are widespread. Although long-term projections of fuel prices – especially when considering new renewable fuel types – LPG could also offer attractive operating and capital costs compared to other alternatives.

Increased uptake of LPG in the commercial maritime sector is not without challenges. The range of available engine technologies, though well-established, will need to be expanded to enable full use of the fuel. Currently, for example, there is no four-stroke marine engine capable of using LPG, meaning auxiliary engines on vessels would need to be decarbonised through an additional fuel. The regulatory framework for LPG use, particularly for bunkering, remains patchy, with the first interim guidelines for ship construction and design only just started at IMO level.

Ultimately, the deciding factor in whether LPG will be a significant fuel candidate either as a zero or near-zero emission fuel, or as a transitional fuel, will be the pace and scale of decarbonisation of the fuel production, and how quickly other supportive energy-saving technologies – such as carbon capture – can mature.

7.1

Chapter 7
Other resources and annexes

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