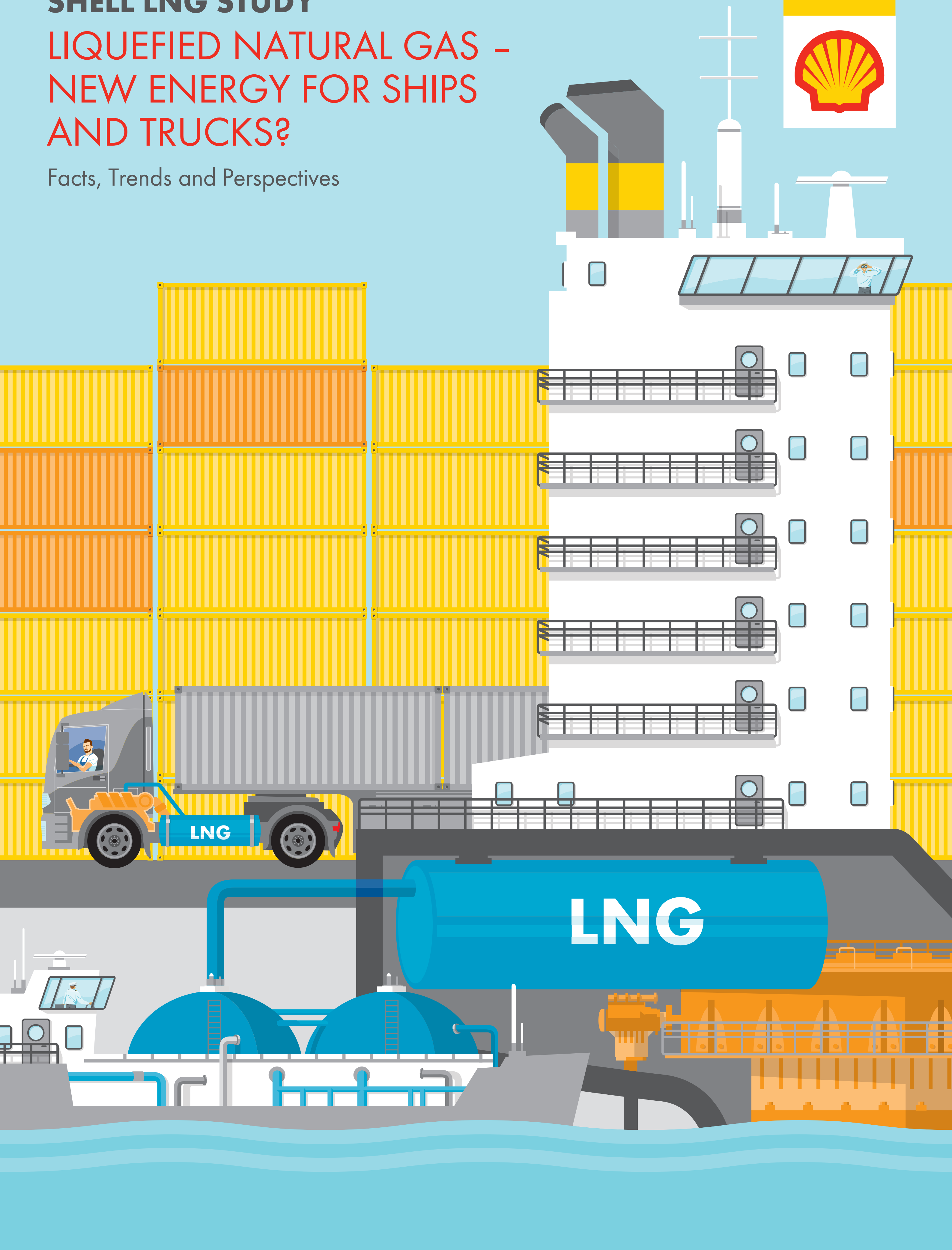
SHELL LNG STUDY

LIQUEFIED NATURAL GAS – NEW ENERGY FOR SHIPS AND TRUCKS?

Facts, Trends and Perspectives



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Facts, Trends and Perspectives

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Since the mid 1960s, natural gas has been transported across the world's oceans in the form of Liquefied Natural Gas (LNG). More recently, interest has been growing in LNG in the transport sector, particularly as a new fuel for shipping and heavy-duty trucks. A key question is what role LNG will be able to play in future as a final energy and fuel in the transport sector, and what impact it has on energy consumption and greenhouse gas emissions as well as local emissions.

Shell has been a leader in the global LNG industry for decades. Working together with the Institute of Transport Research at the German Aerospace Center, and the Department of Marine Engineering at Hamburg University of Technology, Shell has authored a new energy source study that looks at LNG's current status and long-term perspectives, especially as a new energy for shipping and for long-haul road transport with heavy-duty vehicles.

The Shell LNG Study explains the production of LNG from natural gas by means of liquefaction, and describes its technical properties. The sources of natural gas, including alternative gas resources (from renewable energies), supply, demand and trade with natural gas and LNG are analysed as foundation for making LNG available.

The whole LNG supply chain from Well to Wake resp. Wheel is outlined: on the one hand, contemporary large-scale industrial production, transport and regasification of LNG, on the other the new small-scale infrastructure and supply for mobile applications on ships and in heavy-duty vehicles. The potential for utilization of LNG in shipping and long-distance road transport is detailed. To this end, fleets of ships and vehicles are investigated. LNG engine applications as well as their emission advantages compared to diesel powertrains are assessed.

Possible pathways for phasing in LNG are developed with the aid of the scenario technique, as part of an ambitious Pro-LNG scenario for global maritime shipping and EU long-haul road transport. The differential impact of maritime LNG ships and LNG heavy-duty vehicles used in long-haul transport on fuel consumption and greenhouse gas emissions for these modes of transport is estimated.

SHELL LNG STUDY

INTRODUCTION

Shell has published a series of scenario studies on important energy issues. These include, on the one hand, studies for the consumer sectors of transport and domestic heating and, on the other, studies looking at the status and perspectives of individual energy sources and fuels – most recently studies on hydrogen and Power-to-Liquids (PtL), and now Liquefied Natural Gas (LNG). The energy source liquefied natural gas has been used on a major industrial scale for several decades now. In recent years, however, LNG has been attracting increasing interest in the energy industry and beyond, as a new energy for applications at consumer level.

Since the 1960s, Shell has been a leading player in the global LNG industry and operates its own business unit (Shell Integrated Gas) which deals with the production, transport and marketing of LNG. Working together with the Institute of Transport Research at the German Aerospace Center, and the Department of Marine Engineering at Hamburg University of Technology, Shell has produced a new energy source study on the topic of LNG.

The study looks at the current status of LNG production, the role of LNG in the global energy industry and the provision of LNG. In particular, it investigates the long-term perspectives for new end-user applications of LNG in the transport sector, specifically in shipping and long-haul road transport with heavy-duty vehicles.

NEW ENERGY – LNG

Technical processes to turn gases into liquids have been known for over 100 years. They are state of the art when it comes to provision of technical gases. In the last 50 years, the liquefication of natural gas into cryogenic liquefied natural gas and transport and trade with LNG have developed into an important supply channel for the global energy industry, but above all for the gas sector.

Today (2017), approximately 323 billion (bn) m^3 or 230 million (mln) metric tonnes (t) of LNG are traded and transported. Since 2000 (with a converted figure of 136 bn m^3 of LNG), international trade in LNG has more than doubled. Almost all energy scenarios and forecasts are based on the assumption that natural gas and, more particularly, liquefied natural gas will increase in importance within the global energy mix (for example IEA 2018c). In order to satisfy the growing global demand for natural gas in the coming decades, a greater amount of LNG will be available worldwide.

To date, LNG has principally been used as a transport medium for the international trade in natural gas. Once the gas has reached its destination, the LNG is generally regasified and fed into the natural gas grid or used for electricity generation. Due to the ongoing increase in the availability of LNG, and also to its environmental advantages, interest is growing in using it as product respectively fuel for final energy consumption. However, as a small-scale technology in the transport sector, LNG is still a new energy. Although LNG technology is mature and has been tried and tested, possible users do not yet have sufficient experience in handling it.

RESEARCH OBJECTIVES AND KEY QUESTIONS

The current Shell LNG Study ties into the previous Shell studies of energy sources. An important objective of the Shell LNG Study is to provide facts, trends and perspectives for this new energy source, in compact form.

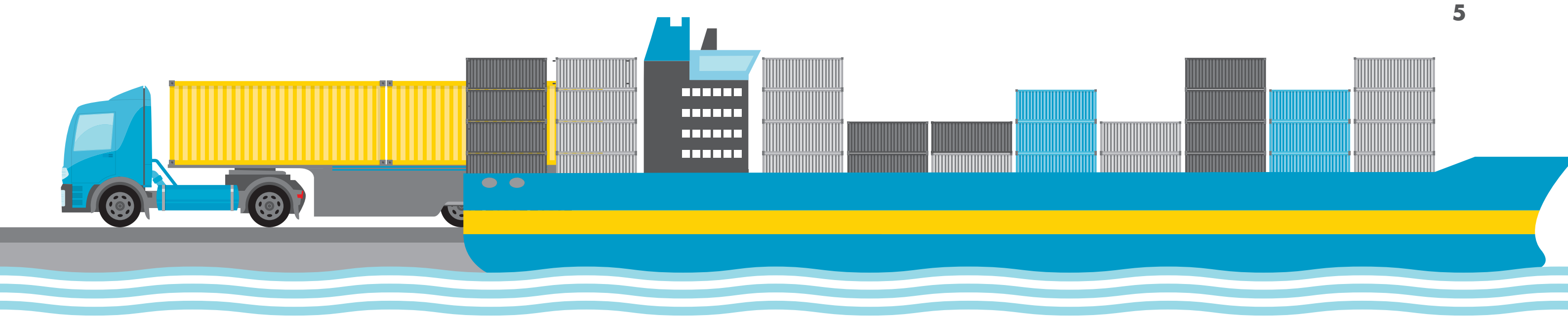
The first priority is to prepare plain information on the production of LNG from natural gas, and on its characteristic technical properties: How is LNG produced, and using which processes? And what are the characteristic properties with regard to its use as an energy source?

The basis for the provision of LNG is formed by sufficient natural gas resources and adequate natural gas supply. But how large is this natural gas supply? And what role will LNG play in the global natural gas industry? In line with a global energy industry with lower and lower emissions, alternative gas resources from renewable sources must also be included in longer-term perspectives.

To date, the LNG supply chain has consisted predominantly of large-scale industrial generation, transport and regasification. However, for direct use among final users, for example for mobile applications on ships and in heavy-duty trucks, a new small-scale infrastructure is required. What does the present LNG supply chain to date look like, and how will the new small-scale infrastructure be built? And what stage has the buildup of the LNG small-scale infrastructure currently reached?

Furthermore, new technologies for direct usage of LNG must be developed and introduced to the relevant user markets. Important potential areas of application for LNG as a final energy are shipping, particularly maritime shipping, and the heavy-duty vehicles that are used in long-distance road freight transport.

Accordingly, the focus of the Shell LNG Study is investigation of the usage potential of LNG in shipping and heavy-duty trucks. In order to estimate the potential for



2018 Shell PtL Study (in English)

2017 Shell Hydrogen Study (in English)

2016 Shell Commercial Vehicle Study (summary in English)

2014 Shell Passenger Car Scenarios (summary in English)

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mobile LNG applications, fleets of ships operating internationally and the European heavy-duty vehicle fleet, respectively, were investigated firstly with regard to their suitability for LNG applications. In addition, the technical level of LNG applications for ship and truck engines was considered, before advantages of the relevant LNG powertrain technology in terms of emissions were investigated.

In order to show the development and impact of new energy technologies, Shell studies make use of scenario technique. As part of quantitative scenario forecasts, possible LNG phase-in pathways are determined for global maritime shipping, on the one hand, and EU long-distance road freight transport, on the other. Finally, the differential effects of LNG ships and LNG trucks on the fuel consumption and greenhouse gas emissions of these two modes of transport are determined in an ambitious Pro-LNG scenario.

Although application technologies have made significant advances recently, LNG is still at the beginning of wider commercial usage. In conclusion, the study therefore considers which accompanying policy measures can be used to develop LNG into an important component in the supply of energy for ships and trucks.

AUTHORS AND SOURCES

When drawing up the Shell LNG Study, Shell worked together closely with the Institute of Transport Research at the German Aerospace Center and the Department of Marine Engineering at Hamburg University of Technology.

The Institute of Transport Research deals with a wide range of questions in the field of transport science; among other things, it has its own in-house truck fleet model to estimate the future development of markets for alternative fuels and powertrain technologies in commercial vehicle fleets. With its research, the Department of Marine Engineering aims to increase the efficiency of ships' propulsion units and of the "ship" as a complete system.

The Shell LNG Study was project-managed and coordinated by Dr. Jörg Adolf, for Shell Germany, and by Andreas Lischke (Dipl.-Ing.) for the German Aerospace Center. The work was created under the scientific leadership of Prof. Dr. Barbara Lenz. Analyses of vehicle statistics and trend projections were established by Gunnar Knitschky (Dipl.-Volkswirt).

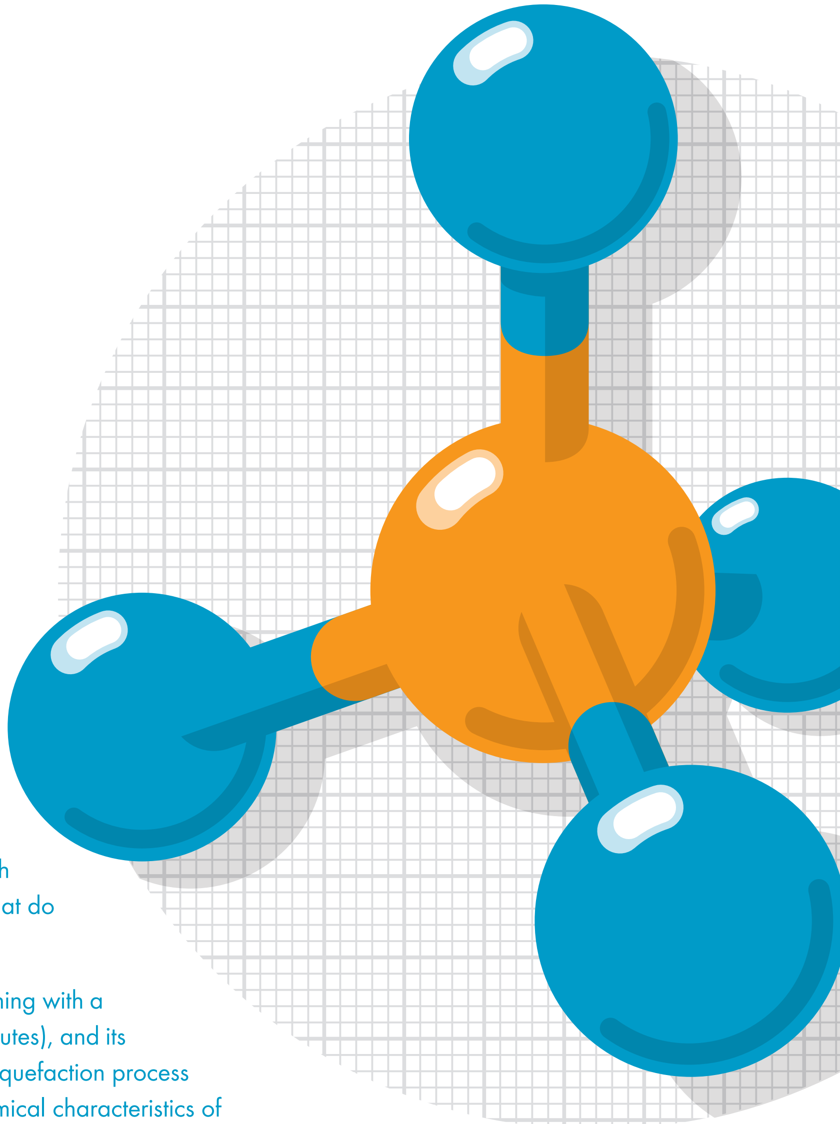
The section on the use of LNG in ships, including the creation of LNG scenarios for shipping, was drawn up by Prof. Dr.-Ing. Friedrich Wirz; he was supported in this work by Märtha-Luise Wendland, B.Sc. The following authors at Shell also contributed to the scientific preparation of the study: Dr. Max Kofod for technical and scientific questions concerning truck powertrains and truck emissions, and Dr. Christoph Balzer for establishing energy source-specific greenhouse gas factors.

The statistical analysis relating to ships is based, in particular, on ships' data from (UNCTAD 2017), (UNCTADstat 2018) and (SEA 2017), while the statistical analysis relating to vehicles is based on vehicle data from (ACEA 2017, 2018) and (Eurostat 2018a-d). Greenhouse gas balances were created with the aid of energy source-specific greenhouse gas factors, which were drawn up on the basis of (JEC 2013, 2014a-d) and updated with further sources.

Finally, a large number of experts, decision makers and stakeholders were consulted in the course of drawing up the Shell LNG Study, and Shell would like to take this opportunity to express its thanks to these contributors once again. A selection of relevant data and sources can be found at the end of the study.

1

TECHNICAL PROPERTIES OF LNG



Liquefied Natural Gas (LNG) is a product of natural gas. LNG is not a natural source of energy, but is produced from natural gas by technical processes. LNG has specific characteristics; it is primarily a cryogenic liquid. However it shares characteristics with its base material natural gas and its main component methane, that do not depend on its physical state.

The technical characteristics of LNG are described below, beginning with a description of the base material, natural gas (and possible substitutes), and its composition. This is followed by an explanation of the technical liquefaction process which converts natural gas into LNG. The main physical and chemical characteristics of LNG that affect combustion are then explained.

Finally, the status with regard to the standardisation of LNG as a fuel for trucks and ships, and the safety of LNG are discussed. A separate account is also given of standardisation and the market development of current standard fuels for trucks and ships.

1.1 NATURAL GAS AND SUBSTITUTES

LNG is produced from natural gas by technical processes. Natural gas is a gaseous substance, since at room temperature (20 °C) and normal atmospheric pressure (1013 hPA) it is neither a solid nor a liquid (Wiegleb 2016).

Natural gas is a fossil energy source – a mixture of substances formed from organic materials long ago. Its composition can vary considerably depending on where it is found (and how it is treated). The composition of natural gas formed as a by-product of oil production, for example, is quite different from the gas from a natural gas field. The main component (> 85 %) of natural gas is the saturated hydrocarbon methane (CH_4). It also contains higher hydrocarbons such as ethane, propane and butane, other non-combustible components such as nitrogen, carbon dioxide, oxygen, water, traces of noble gases and some sulphur (DVGW 2013).

Variations in the composition can also produce technically relevant differences in the natural gas transported in the gas network, which has already been processed. There are two types of natural gas in Europe: **High Calorific Gas (H-gas)** and **Low Calorific Gas (L-gas)**. H-gas has a higher methane content and a higher calorific value than L-gas. H-gas from Russia, for example, has a very high methane content, while L-gas from Germany contains more nitrogen.

Biomethane, synthetic natural gas from biomass (Bio-SNG) or synthetic Power-to-Gas (PtG) are renewable alternatives to fossil natural gas. Biomethane is produced by fermenting biomass to create biogas. The composition of biogas varies considerably depending on the type of biomass used (the substrate). The methane content varies between 50 and 75 %.

Biogas has a high CO_2 content (25 to 45 %) and a relatively high water content (2 to 7 %) and contains hydrogen sulphide, oxygen, nitrogen and other components and impurities such as siloxanes. Biogas is cleaned and treated to obtain network quality gas with a high methane content so that it can be fed into the natural gas network or used by consumers, hence its other name, **biomethane** (FNR 2010).

Bio-SNG (Synthetic Natural Gas), based on biomass, is produced by the gasification of biomass and, like biogas, is cleaned and treated so that it is the same quality as fossil natural gas.

Another method of producing natural gas fuel substitutes is **Power-to-Gas (PtG)**. In the first stage of this process hydrogen (H_2) is produced from water (H_2O) with electricity (power) by electrolysis. The hydrogen can be combined with carbon dioxide or carbon monoxide and converted to a synthetic natural gas with a catalyst.

Gaseous substances such as natural gas and its substitutes have a far lower density than those of liquids. This is impractical for some applications, particularly in the mobility sector. One way of increasing the density, and therefore also the energy density, of natural gas is to compress it. Mechanical compression is used to produce Compressed Natural Gas (CNG) for CNG vehicles. Another option for "compressing" the gas is liquefaction by cooling.

Methane from any source – fossil natural gas, biogas/biomethane, Bio-SNG or Power-to-Gas – can be liquefied. Biomethane is then called Bio-LNG, Bio-SNG is called synthetic LNG and PtG is called PtG-LNG. Unlike fossil LNG, the other alternatives can have a higher methane content (EU-COM / DGM 2014, 2018).

1.2 NATURAL GAS LIQUEFACTION

Liquefaction is the process of cooling natural gas to very low temperatures, i.e. below the boiling point of natural gas. This results in a phase transition which changes the physical state of the gaseous natural gas from gas to liquid. An important objective of natural gas treatment and liquefaction is to provide a product (LNG) with consistent technical characteristics and to make it easier to transport. This requires multi-stage treatment processes.

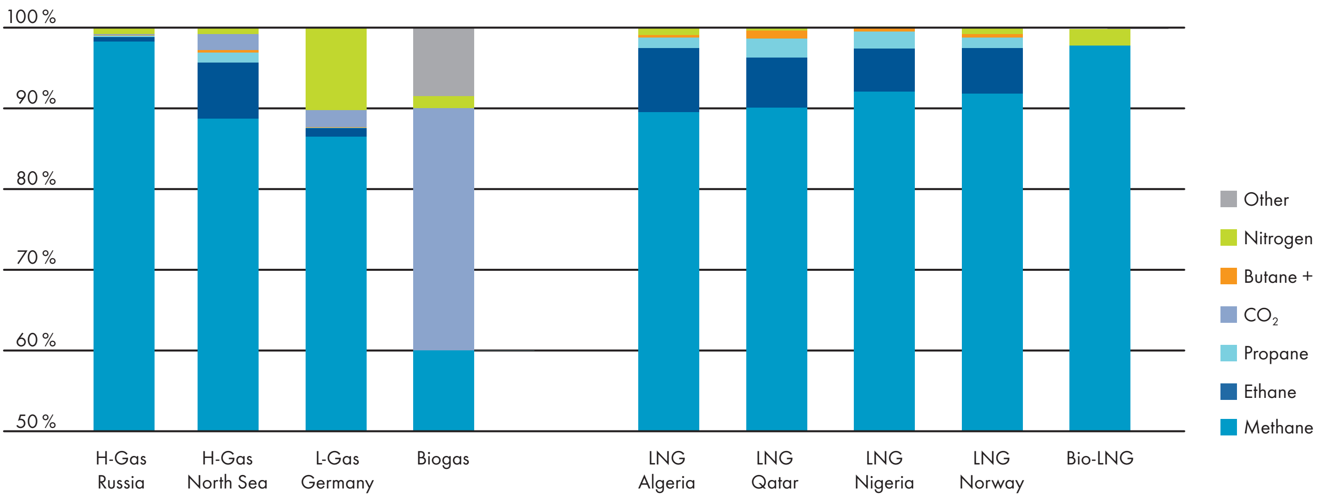
Before it is sent to a liquefaction plant the feed gas is cleaned and treated in technical facilities. Here, it passes a measuring point where its pressure is checked and adjusted. The first stage of gas cleaning and treatment is to remove water, dirt and particulates, and gas condensates.

Gas condensates are long-chain hydrocarbons which are undesirable in LNG. The acid and corrosive gases hydrogen sulphide (H_2S) and carbon dioxide (CO_2) along with water (H_2O), nitrogen (N) and other impurities are then removed by various processes.

Hydrocarbons with five or more carbon atoms, also known as "pentanes plus" (C_{5+}), are stripped out during the next stage (pre-cooling). While high nitrogen and CO_2 contents reduce the energy content of the gas, the fuel gases ethane, propane and butane have scarcely any effect on the energy content of LNG, as their calorific value is almost the same as that of methane (EIA 2006; GIIGNL 2009; Camron 2018).

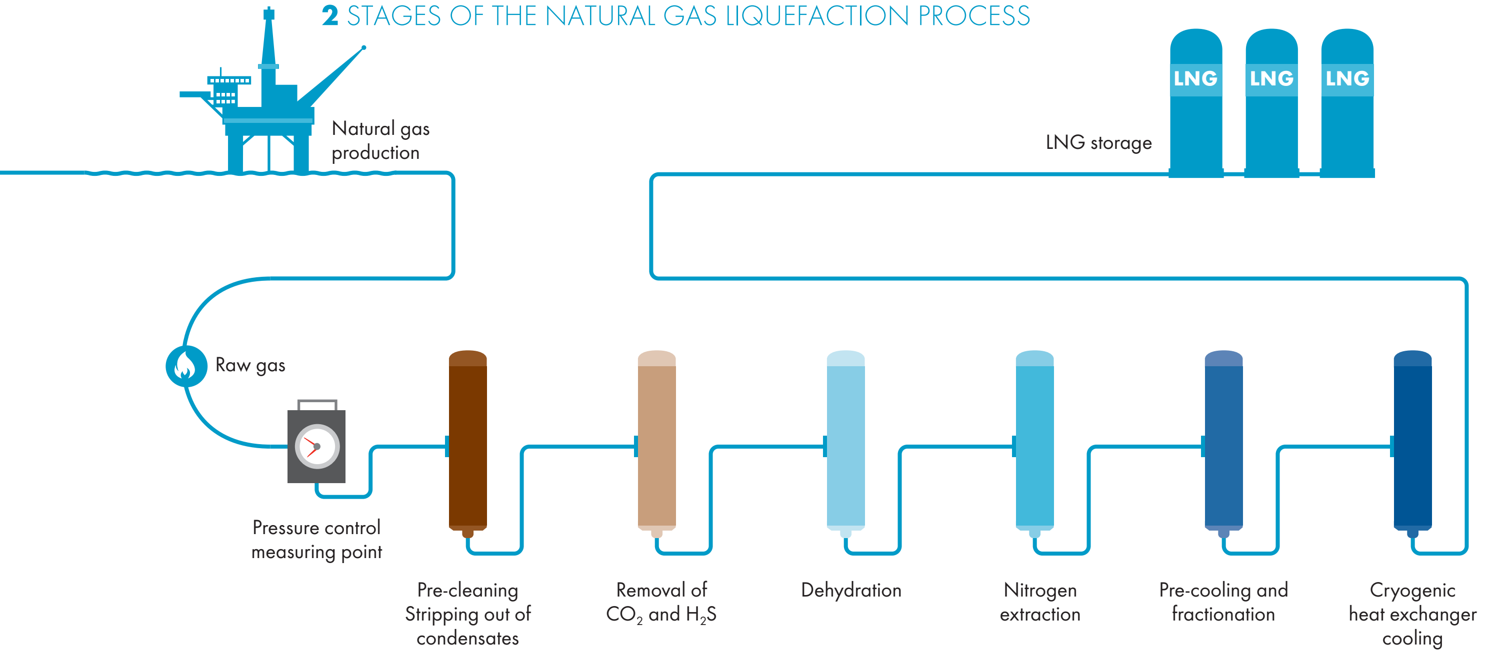
Following the natural gas treatment, the gas consists mainly of methane. **Methane** is a saturated hydrocarbon (alkane) containing one carbon atom and four hydrogen atoms (CH_4). The four hydrogen atoms are arranged as a

1 COMPOSITION OF NATURAL GAS AND LNG



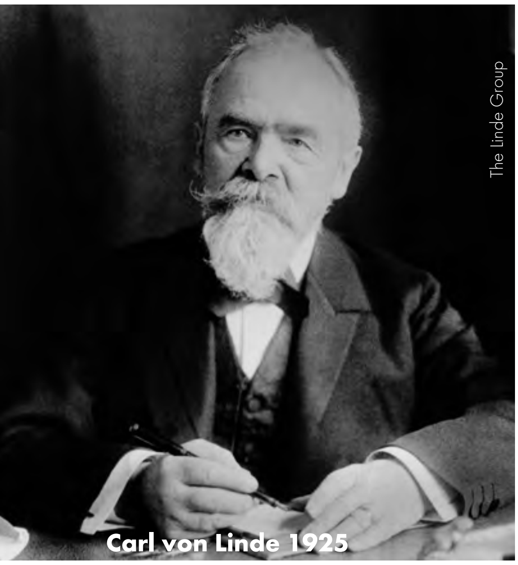
FNR 2010, IGU 2012, DVGW 2013, EU-COM/DGM 2014

2 STAGES OF THE NATURAL GAS LIQUEFACTION PROCESS



tetrahedron, so that the pairs of bonding electrons are as far apart as possible. The angle of the tetrahedron is the angle (109.5°) of the bond between the carbon atom and two hydrogen atoms.

The treated natural gas also contains small quantities of hydrocarbons with 2, 3 and 4 carbon atoms. The LNG from the countries that mainly supply Europe (Qatar, Algeria, Nigeria and Norway) has a consistent methane content of 90%. LNG is usually purer than pipeline gas and has a more consistent composition.



Carl von Linde 1925

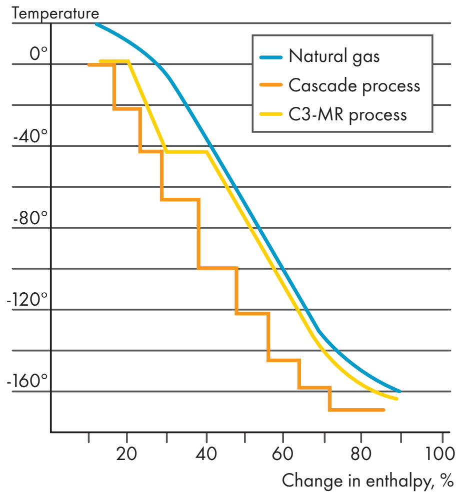
Cleaning and treatment is followed by liquefaction by transferring heat from the treated natural gas to a refrigerant. Pre-cooling with propane (to -35 °C) is followed by subcooling in the main cryogenic heat exchanger.

The gas liquefaction process was developed over a century ago by Carl von Linde (**Linde process**) who devised a process for liquefying air in 1895, followed by an air separation process in 1902. Liquefaction processes utilise the **Joule-Thomson effect** of real gases. When a compressed gas expands, its temperature changes. The Joule-Thomson coefficient expresses the direction of the temperature change, depending on the initial temperature.

A positive Joule-Thomson coefficient leads to cooling of the gas on expansion. For cooling to take place, the initial temperature must be lower than the inversion temperature, which is around 6.75 times higher than the critical temperature of a gas (in Kelvin).

As the temperature of a gas increases when it is compressed, the compressed gas must be pre-cooled by the cooled gas. If the pre-cooled compressed gas

3 COOLING CURVES OF DIFFERENT LIQUEFACTION PROCESSES



is expanded again, its temperature can be reduced still further. By applying this process in several stages, very low temperatures can be reached (Wiegleb 2016).

Natural gas liquefaction processes can be characterised by the number of process stages and the refrigerant used (Uhlig/Wohlgemuth 2012). The process uses either simple (single-component) or mixed refrigerants. The refrigerants must be cold enough to liquefy the natural gas at the end of the process. Propane (for pre-cooling), ethylene, methane itself and nitrogen are the main refrigerants. Mixed refrigerants do not have a boiling point but a boiling curve.

Simple, less complex cooling processes, such as the nitrogen expander process, have the advantage that they are inexpensive and easy to use. However, with single-component coolants, the boiling temperatures at each pressure produce stepped cooling curves.

Figure 3 shows the cooling curves for treated natural gas, a cascaded cooling process with single-component coolants and the multi-stage C3-MR process (Uhlig/Wohlgemuth 2012). Cooling processes with mixed refrigerants are able to adapt to the natural gas cooling curve more effectively by continuously transferring heat (changing the enthalpy). The principle here is that the smaller the area between the cooling curves of the refrigerant and the methane, the more efficient the cooling process. Natural gas liquefaction plants predominantly use multi-stage cooling processes because of the efficiency benefits they provide.

Natural gas liquefaction is an energy-intensive process, but, unlike pipeline gas, very little energy is required to transport LNG over long distances. LNG is more energy-efficient than pipeline transport, particularly on longer supply routes of over 7000 km (JEC 2014a). Nevertheless, work continues on components and processes to improve the efficiency of natural gas liquefaction.

Liquefaction requires electricity, particularly, and this is often produced from the available natural gas itself in special power plants. The energy actually required for liquefaction depends, among other things, on the composition of the feed gas, the liquefaction process and the ambient temperatures. Around 0.08 megajoule (MJ) of energy is required to liquefy 1 MJ of natural gas, in other words about 8 % of the LNG produced (JEC 2014a; IEA 2018c).

1.3 PHYSICAL CHARACTERISTICS

Mass density is an important parameter when considering energy sources. It describes the mass per unit volume, for example kilograms per cubic metre (kg/m^3). The density of a gas depends on the pressure and temperature conditions.

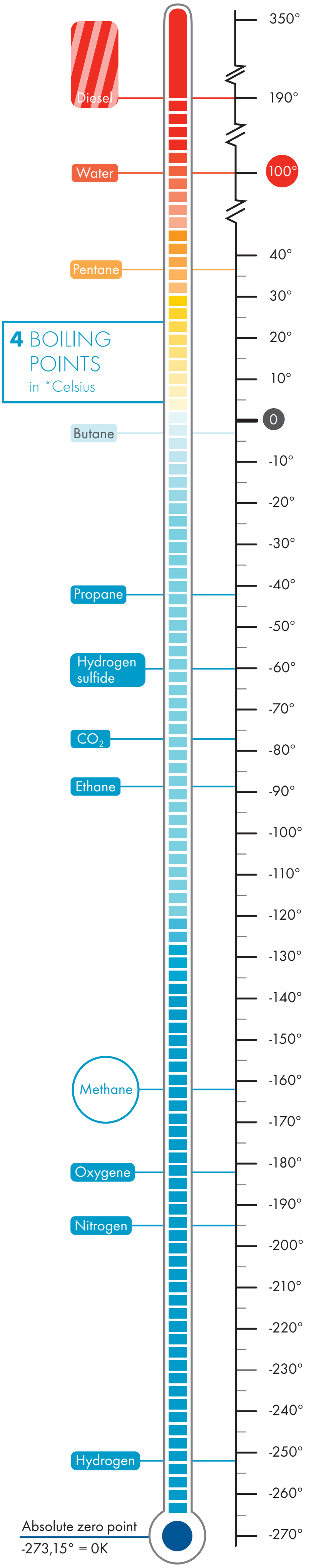
Methane, the main constituent of LNG, is 0.7 kg/m^3 under standard conditions, making it lighter than air (approx. 1 kg/m^3) and rapidly evaporates in the open air. Depending on its composition, LNG has a density of 430 to 470 kg/m^3 and an average density of 450 kg/m^3. LNG is therefore less than half as heavy as heavy fuel oil (970 kg/m^3) and slightly less than half as heavy as diesel (832 kg/m^3) or synthetic Fischer-Tropsch diesel produced from natural gas, also called Gas-to-Liquids resp. GTL (780 kg/m^3).

Cold LNG vapour can remain on the ground or in enclosed spaces for some time. However, it quickly evaporates when heated or under ambient conditions, cooling the surrounding air so that the moisture in the air condenses into water vapour. When LNG is spilled in or on the water, it floats upwards until it has evaporated. This behaviour also prevents LNG from contaminating soil.

The transition from the liquid to the gas phase is determined by the boiling point of a substance. Methane has a very low boiling point: if it is cooled to below -161 °C under atmospheric conditions (1 bar pressure), it condenses and passes from the gas to the liquid phase. Very few gases have a lower boiling point than methane, but those that do include hydrogen and nitrogen. These low-temperature gas condensates are also called **cryogenic liquids** because they can be used for special cooling purposes.

The behaviour described above applies at normal pressure, but the picture gets more complex if pressure changes are factored in. The behaviour of the substances then is illustrated with pressure-temperature phase diagrams (Mortimer/Müller 2010).

4 BOILING POINTS in °Celsius



A transition from the gas to the liquid phase, or the reverse, occurs at the boiling point and is characterised by a sudden change in density. The normal boiling point of methane is -161.5 °C and 1.013 bar. For each gas there is a temperature at which the gas can no longer be liquefied by increasing the pressure, or there is no longer a transition from the gas to the liquid phase (supercritical state). This temperature is called the **critical temperature**; the critical temperature of methane is -82.6 °C.

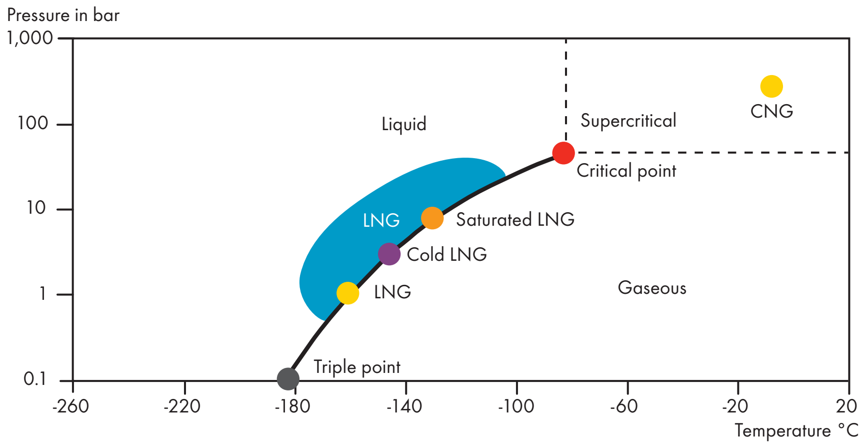
Similarly, once it reaches a sufficiently high pressure, a gas can no longer be liquefied by lowering the temperature. This pressure is known as the **critical pressure**, and for methane it is 46 bar. The critical temperature and critical pressure characterise the **critical point** (CP) of a substance, which is -82.6 °C and 46 bar for methane.

The **melting point** (the transition from solid to liquid) is only slightly dependent on the pressure; for methane it is -182.5 °C. Under **triple point** (TP) conditions (-182.5 °C; 0.43 bar) all three phases – solid, liquid and gas – are in equilibrium.

Figure 5 shows methane in the pressure-temperature phase diagram. However, the gas and liquid phases and the supercritical (fluid) state of methane immediately above the critical point (CP) are of particular interest here. The **vapour pressure curve** runs from TP to CP and represents all of the pressure-temperature conditions under which the liquid and gas phases of methane are in equilibrium.

When methane is cooled to below -161.5 °C under atmospheric pressure (1.035 bar), it condenses and passes from the gas to the liquid phase. This phase transition leads to a sudden reduction in volume from around 550 l/kg at -160°C to 2.4 l/kg, equivalent to a factor of 230. Methane at 1 bar pressure and ambient temperatures (20°C) has a volume of approximately 1,500 l/kg; thus the volume of liquid methane is actually **600 times** smaller than that of gaseous methane.

5 METHANE PHASE DIAGRAM



In industry, LNG is used at different pressures. At a slightly higher pressure, the LNG storage temperature can be raised as shown in the vapour pressure curve. Different types of LNG are used here:

Cold LNG, at approx. 3 bar and -150 °C, is close to the normal boiling point of methane. Its liquid phase is colder than the gas phase and it has a higher energy density. With **saturated LNG** the gas and liquid phases are at the same temperature; although a higher temperature of approx. -130 °C at a pressure of 8 to 10 bar is possible, this requires a more expensive, pressure-resistant tank design. The distinction between cold and saturated LNG is relevant for its use in truck engines respectively for engine control systems.

Compressing methane at normal pressure and temperature conditions, instead of liquefying it, produces a supercritical fluid (top right). When compressed at 200 bar, the volume of methane at ambient temperature and pressure decreases from 1563 l/kg to approx. 6.25 l/kg. Hence, the volume of Compressed Natural Gas (CNG) is reduced by a factor of 250. If the pressure of gaseous methane is increased to 350 bar, it has a volume of approx. 4.4 l/kg, i.e. a reduction factor of approximately 350. The characteristics of ideal gases no longer apply here, since the volume of the gas cannot be reduced to the same extent by increasing the pressure.

1.4 LNG STORAGE

The physical characteristics of natural gas also determine the behaviour of liquefied natural gas during storage. LNG is stored as a boiling cryogenic liquid, which means that the liquid is stored at the boiling temperature applicable to the storage pressure used. A moderate pressure increase, for example to 10 bar in a vehicle tank, allows it to be stored at a slightly higher temperature.

To minimise pressure increases, cryogenic liquefied gases must be stored in well-insulated tanks. When heat from outside penetrates the storage tank, some of the liquid evaporates. If this vaporised liquid is released from the tank, it is called **boil-off gas** (BOG). The boil-off rate for large tanks is generally 0.1 % per day; for smaller, poorly insulated LNG tanks it will be 1 % per day (EU-COM/DGM 2017b).

Evaporation causes evaporative cooling, so the boil-off gas is used to cool the rest of the liquid. The tank insulation is so effective that only relatively small amounts of boil-off gas are needed to maintain the temperature. As LNG is a mixture of substances, the composition of the liquid phase varies depending on the boiling point of its individual components. Components with a low boiling point, like nitrogen and methane, evaporate first; heavier hydrocarbons like ethane, propane and butane evaporate later.

The composition of the LNG liquid phase can change during long periods of storage. This phenomenon is also known as **weathering** or **ageing**. The boil-off reduces the methane content and heavy components accumulate in the liquid phase. This mainly affects smaller tanks like those used in trucks. LNG ageing can impair the fuel quality. The pressure in large tanks can increase as a result of boil-off or of refilling with LNG and the stratification of LNG components (rollover) (EU-COM/DGM 2017b).

To avoid LNG ageing, LNG evaporation and evaporation losses must be minimised by insulating tanks effectively and making intensive use of LNG vehicles. Programs that calculate the methane number of LNG in advance on the basis of the LNG specification, the boil-off rate and the boil-off composition, can also be obtained from various suppliers.

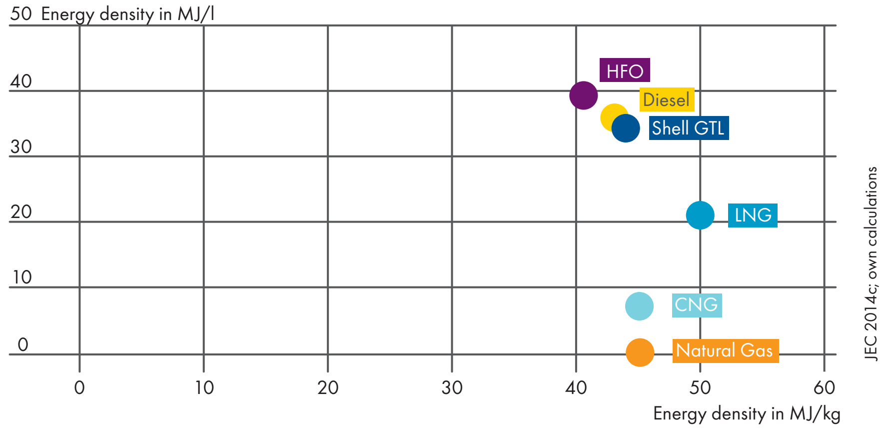
Other options include refilling the LNG tanks with cold LNG or reliquefying the boil-off gas. Another renewable alternative is biogenic LNG (LBG), which does not age because, besides methane, it contains only small amounts of nitrogen and oxygen and none of the heavier hydrocarbons.

1.5 CHEMICAL CHARACTERISTICS

The ignition temperature is the temperature to which a substance must be heated before it auto-ignites in the presence of oxygen. The ignition temperature of methane is relatively high, at around 550 °C, and thus around twice as high as that of diesel fuel, for example. However, when the share of higher alkanes in the LNG fuel rises (due to evaporation, for example), the ignition temperature falls.

Below the ignition temperature, a gas/air mixture can only be ignited by an ignition source such as a naked flame, spark plug, sparks or an electrostatic charge. LNG cannot be ignited as long as it is kept in closed, oxygen-tight containers. The explosion limits of methane/air mixtures (4.4 to 17 %) are slightly wider than those

6 ENERGY DENSITY OF HDV AND MARINE FUELS



of liquefied petroleum gas (autogas) and far higher than those of diesel (0.6 to 6.5 %). Natural gas and LNG have a high flame temperature; they burn faster and generate more heat than liquid fuels (GIIGNL 2015b).

The Wobbe index (WI) is an important parameter for the technical design of heating boilers and engines. It is calculated from the volumetric heating value H and the square root of the relative density of the fuel to that of air: $W=H\sqrt{(\text{fuel density})/(\text{air density})}$. There is no unit of relative density, which is also called specific gravity, so the Wobbe index uses the same unit as the volumetric heating value H (GJ/m^3).

The Wobbe index is in inverse proportion to the air-to-fuel ratio. In engines with the same mass ratio of air to fuel, gaseous fuels with the same Wobbe index can be burned and produce the same output. If the composition of the gas changes because of a higher propane/butane content in the natural gas, for example, the Wobbe index, and hence the air-to-fuel ratio, will also change. As the density of the mixture would then be different, a different amount of gas would flow through the engine and the power output would also be different (Richards 2014).

While gas suppliers favour an upper Wobbe index of 49 to 57 MJ/m^3 for LNG, the engine manufacturers are aiming for the narrowest possible WI range of +/-2 % (EUROMOT 2011). The EU LNG Blue Corridors Project recommended a lower Wobbe Index of 44.7 to 49 MJ/m^3 (EU-COM/DGM 2014, 2017a). However, the air-to-fuel ratio can also be adjusted by the engine control system.

Another important factor for the energy and economic value of an energy source is its usable **energy content**; for internal combustion engines, this is called the lower heating value.

Based on its gravimetric heating value (megajoules per kilogram), natural gas, and hence also LNG, has a higher energy content than diesel. The energy content of pure methane is 50 MJ/kg and that of natural gas (in the EU mix) is around 45 MJ/kg, while diesel has an energy content of only 43 MJ/kg. The marine fuels marine gasoil and distillates are close to diesel; heavy fuel oil with a density of around one kilogram per litre is heavier with an energy content of only 40.5 MJ/kg (JEC 2014c). Paraffinic EN 15940 diesel produced from natural gas (Gas-to-Liquids) is slightly lighter than standard diesel and therefore has a slightly higher energy density of 44 MJ/kg.

The situation for the volumetric energy density (megajoules per litre) is slightly different: The energy content per unit volume of standard commercial CNG (200 bar, normal conditions) is around a quarter of that of diesel (approx. 7 MJ/l compared to just under 36 MJ/l). It should nevertheless be borne in mind that the energy content of CNG per sales unit (kilogram) is about a third higher than that of a sales unit of diesel (litre). However, because of the tank size required, the volumetric energy density of compressed natural gas is still too low for it to be used in ships and heavy-duty trucks.

LNG has around 60 % of the volumetric energy content of a litre of diesel, i.e. around 21 MJ/l LNG as compared with around 36 MJ/l for diesel. The energy content per sales unit of LNG (in kilograms) is almost 40 % more than that of diesel (in litres). The volumetric energy density of LNG is only just over half (53 %) that of heavy fuel oil (39.7 MJ/l), while for synthetic GTL fuel it is 34.3 MJ/l.

Overall, the volumetric energy density of LNG is therefore much closer to that of liquid fuels than compressed natural gas (CNG). However, here too, the advantages in terms of gravimetric energy density are counterbalanced by the heavier fuel tanks required for cryogenic liquids.

High knock-resistance is ultimately very important for engine combustion. Knocking occurs when the unburned gas/air mixture auto-ignites; it produces high-frequency gas oscillations and causes high thermal stress of components. This can adversely affect engine performance, increase engine emissions or even damage the engine (ASUE 1992; EUROMOT 2011, 2017; DNV GL O&G 2017).

Natural gas/methane has better knock-resistance than petrol and can reach octane numbers of up to 130. Very knock-resistant petrol has an octane number of around 100. LNG internal combustion engines are optimised to utilise the high knock-resistance of methane. This is reflected in the engine efficiency, which is unusually high for petrol engines.

A new parameter, the methane number (MN), was introduced to describe the LNG grade. This is an index similar to the octane number, which provides information about the knock-resistance of different grades of LNG. Pure methane has, by definition, a methane number of 100; hydrogen has a methane number of 0. If the content of higher alkanes, such as ethane, propane, butane and pentane, in the natural gas increases, the methane number falls significantly. The addition of hydrogen also produces lower methane numbers. The following relationship holds: The heavier the gas and the higher the Wobbe index, the lower the methane number.

Almost all LNG supplied to Europe has a methane number (MN) of at least 65, but only 12 % of the LNG manages an MN of over 80 (GIIGNL 2015a). This must be taken into consideration for engine development. The alternative sources of methane referred to above (biomethane, Bio-SNG and PtG methane) have high methane numbers of 100.

Engine manufacturers state the admissible methane number for their engines (often MN 80 or at least MN 70) (EUROMOT 2017). However the amount of natural gas/LNG used in engines is still small. Further obstacles are the higher cost of secondary LNG treatment (to remove more of the higher hydrocarbons) and relatively moderate engine efficiency gains (GIE 2012).

Methane number calculators or software packages which calculate the methane number of different LNG grades are now available online. However, these work by different methods and consequently produce different results. Intelligent gas engine control systems (feed-forward fuel-adaptive engine control systems) are being developed to avoid unnecessary engine performance losses and increased gas treatment costs (DNV GL O&G 2017).

An important combustion-related specification for engine applications is the sulphur content of fuels and thus also of fuel gases. To protect components and reduce combustion-related sulphur oxide emissions, the sulphur content of fuel must be reduced to the absolute minimum (EUROMOT 2017).

In the EU, road transport and inland navigation fuels have been sulphur-free (sulphur content of less than 10 ppm) for a long time. Natural gas has a very low sulphur content compared to sulphur-containing marine fuels. In the interests of gas safety, odorants, most of which contain sulphur (up to 30 ppm), are added to pipeline natural gas for detection purposes (Wiegleb 2016). Liquefied natural gas generally has a very low sulphur content of 2 ppm.

1.6 LNG FUEL STANDARDS

A whole raft of standards have been introduced for handling LNG as a substance, but there are not yet any specific LNG fuel standards. In the EU, LNG used as a road transport fuel is covered by the fuel standard EN 16723-2 for natural gas and biogas, adopted in 2017. This sets limits for a whole range of fuel components such as amines (from the amine wash, a possible stage in the Bio-LNG production process), hydrogen, water (dew point) and sulphur, and requires a minimum methane number of 65. It also contains other restrictions relevant to biogases, such as a maximum silicon content.

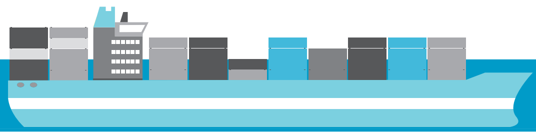
In addition to this, natural gas for fuel use must not contain any other impurities which would preclude its use in motor vehicles. LNG fuel must also comply with a maximum particulate concentration of 10 mg/l to protect the LNG engine from wear.

Annex D to EN 16723-2 states that stricter voluntary specifications may be agreed beyond those contained in the standard. This applies particularly to the sulphur content of LNG, since odorants containing sulphur are not added to LNG, as they are to pipeline natural gas for safety reasons. However, the catalysts of exhaust gas cleaning systems are very sensitive to sulphur. Therefore, using LNG as a fuel offers a significant advantage. A higher methane content of 70 and a lower heating value of 44 MJ/kg is also specified.

Working groups of the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) are also working on LNG-specific fuel quality standards for road transport and shipping.

7 EU SPECIFICATION FOR NATURAL GAS FUELS IN ACCORDANCE WITH EN 16723-2

Constituent	EN 16732-2	Annex D
Hydrogen (H_2)	≤ 2 % mol/mol	≤ 2 % mol/mol
Dew point (water)	≤ -2 °C	≤ -2 °C
Oxygen (O_2)	≤ 1 % mol/mol	≤ 1 % mol/mol
H_2S + COS	≤ 5 % mol/mol	≤ 5 % mol/mol
Sulphur (S)	≤ 30 mg/m³	≤ 10 mg/m³
Methane number (MN)	≥ 65	≥ 70
Net calorific value	-	≥ 44 MJ/kg
Wobbe Index inferior	-	41,9 – 49,0 MJ/Sm³
Silicon Si (for biogas)	≤ 0,3 mg/m³	≤ 0,3 mg/m³



MARINE FUELS

The fuels used in international shipping are called bunker fuels. The consumption data for shipping vary depending on whether the top-down (IEA 2018c) or bottom-up method (IMO 2015, 2016) is used to record them. However, the annual global consumption of marine bunker fuels is currently estimated at around 300 mln t.

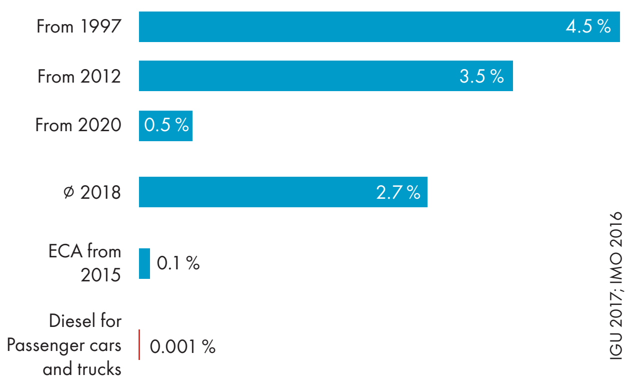
Marine fuels normally have to comply with particular requirements for viscosity, specific gravity, sulphur content, ignition point etc. The main international standard for marine fuels is ISO 8217, which divides marine fuels into two categories, distillate and residual fuels, which are subdivided into six or seven further fuel categories.

Marine gasoil (MGO), like diesel, is a product of crude distillation. MGO has similar product characteristics to heating oil, except for the ignition temperature. Heavy fuel oil (HFO) is a residual fuel from crude processing. Unlike MGO, heavy fuel oil must be heated before it can be used. Another category is marine diesel oil (MDO), a blend of HFO and MGO. Seagoing ships can use both heavy fuel oil and marine gasoils; since 2011, only diesel has been permitted for inland waterway vessels in the EU.

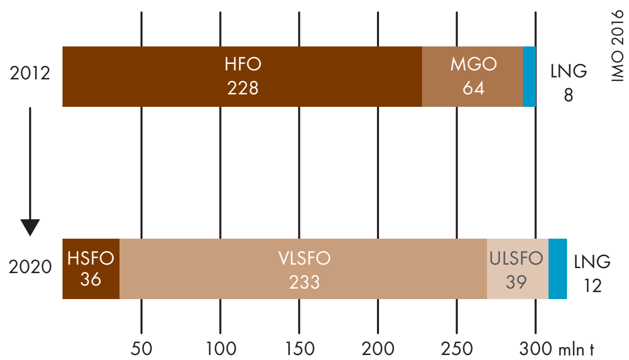
More than three quarters of the bunker fuels are heavy fuel oils; nearly half (46 %) of the global heavy fuel oil demand comes from shipping. Just under a quarter of bunker fuels are marine gasoil (MGO). The largest consumers of bunker fuels are coming from Asia and Europe.

To reduce sulphur oxide emissions, the permitted sulphur content of bunker fuels was repeatedly reduced under MARPOL Annex VI. The sulphur content of bunker fuels was limited to 4.5 % from

8 SULPHUR LIMITS



9 BASIC PROJECTION FOR BUNKER FUELS



1997 and to 3.5 % from 2012. After a review of the global availability of heavy fuel oil (IMO 2016), the IMO decided to reduce the sulphur content of marine fuels to 0.5 % worldwide from 2020.

This fuel quality requirement can be met either by marine gasoil, very low sulphur fuel oil (VLSFO) or suitable blends of gasoil and heavy fuel oil. Alternatively, exhaust gas cleaning systems (EGCS), also called scrubbers, can be installed. However, at the moment they can only be installed in a small proportion of the shipping fleet, so only a few thousand ships will be able to continue using heavy fuel oil with a sulphur content above 0.5 % from 2020; most will have to use VLSFO (IMO 2016).

Thus, sulphur emissions from shipping will have to be capped. LNG is therefore an interesting and relevant alternative marine fuel, because it contains, so to speak, only "homoeopathic" amounts of sulphur. In 2012, 8 mln t of the global bunker fuel demand was consumed in the form of LNG, primarily by LNG carriers (LNGC); this could change if more and more ships are equipped to use LNG as a fuel. The IMO is expecting maritime LNG consumption to increase to around 12 mln t in the short term (IMO 2016).

However, there are other regulatory developments which encourage the use of LNG as a marine fuel. Since 2015, only marine fuels with an ultra low sulphur content of 0.1 % (ultra low sulphur fuel oil, ULSFO), heavy fuel oil combined with scrubbers, or low-emission LNG have been permitted in Emission Control Areas (ECA) such as the North Sea and the Baltic. LNG would be an even better low-emission marine fuel for ECAs.

SAFETY

LNG has been transported safely across the world's oceans for around 50 years, but it has not been used widely as a fuel, except in LNG carriers. Consequently, neither potential users nor the wider public know very much about its hazardous characteristics or how to handle it safely. Questions that frequently arise are how safe is LNG, and what factors have to be taken into account to handle it safely?

To protect human beings and the environment from harm when handling chemical substances, all chemicals must comply with classification and labelling requirements before they are put onto the market. The EU Classification, Labelling and Packaging (CLP) Regulation EC/1272/2008 distinguishes between physical hazards, hazards to human health and hazards to the environment.

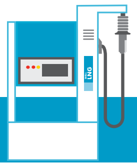
The type of hazard is described by hazard classes. To visualise hazards standard pictograms are specified by the Globally Harmonised System of classification and labelling (GHS). Safety-relevant information about substances and mixtures, including prevention, reaction, storage and disposal measures, are summarised in Safety Data Sheets (UBA 2013; Shell 2018).

LNG itself is an odourless, colourless, non-corrosive, non-flammable and non-toxic liquid. So, on the face of it, it appears to be less hazardous than petrol and diesel.

However, LNG is a cryogenic liquefied gas. Therefore GHS statement H281 applies, which means that it may cause cryogenic burns upon contact with unprotected skin. It may also cause embrittlement of materials that are not resistant to cold. To prevent this, suitable protective clothing should be worn when handling LNG. Systems and components that come into contact with LNG should be designed for very low temperatures.

LNG also consists of natural gas, and mainly of methane. Although methane only auto-ignites at high temperatures, it still forms a highly flammable and explosive gas on evaporation. As a consequence, natural gas is sorted into hazard category 1.

A second feature of LNG vapour that is relevant to safety is its extreme flammability, for which LNG gets physical H-statement H220 according to the CLP-Regulation.



TRUCK FUELS

Until now, natural gas, and particularly LNG, have played only a minor role in the European fuel market. 257 bn litres, or 72 % of the fuel consumed in the EU is diesel. Germany is by far the largest market for diesel sales in Europe, followed by France. Diesel sales have continued to increase in most countries in recent years. Overall diesel sales in the EU are currently more than 10 bn litres higher than they were in 2010 (EEA 2018c).

The proportion of the diesel consumption accounted for by road freight transport varies from country to country, depending on the size and mileage of the truck fleet. Road freight transport is estimated to consume around half of the diesel in Germany (BMVI 2018). Around 80 % of the diesel demand of all commercial vehicles operating in Germany is accounted for by heavy-duty vehicles (Shell 2016).

Standard European fuel requirements are specified by the EU fuel quality directive 98/70/EC, which was last amended by Directive 1513/2015/EU (EP/Council 2015a). Other minimum requirements, such as the cetane number, density, polyaromatics and sulphur content, flash point etc. are defined by the EU diesel standard EN 590.

The diesel specification has become significantly stricter over the years. For example, the diesel fuels marketed in the EU today are almost exclusively sulphur-free. However the most recent revisions of the EU fuel quality directive in 2009 and 2015 focus less on the constituents of fuels than they did in the past. Instead, they target the fuel manufacturing process and particularly its sustainability.

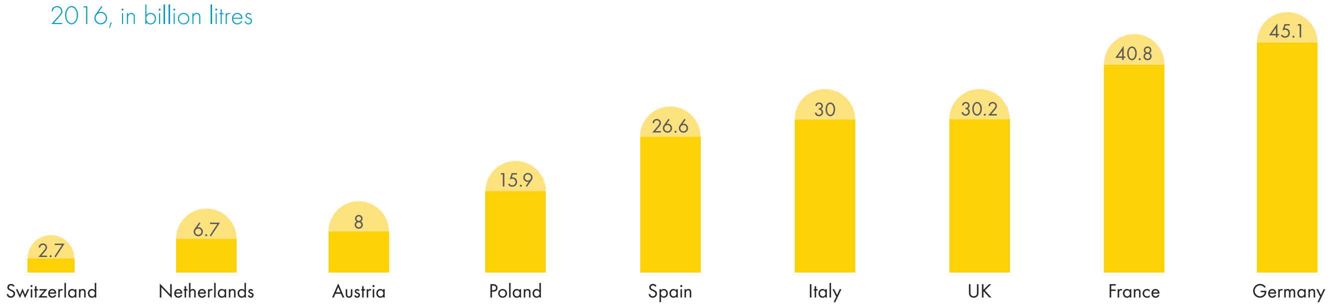
Under the existing fuel quality directive, by 2020, anyone bringing fuels onto the market will have to make a 6 % greenhouse gas saving on the fuels sold. While requirements for fuel-specific greenhouse gas savings will continue to apply, the greenhouse gas quota will in principle be replaced by a renewable energies quota for the transport sector of 14 % of final energy consumption up to 2030 (EP/Council 2018a).

The paraffinic fuels specified in EN standard 15940, which include a natural gas-based synthetic Fischer-Tropsch fuel called Gas-to-Liquids (GTL), are one type of replacement or supplementary liquid fuel; the other is biofuels. A blended fuel composed of 93 % fossil diesel and 7 % biodiesel (B7) is now established as standard fuel across almost the entire EU diesel sector.

In addition to diesel, modern Euro VI diesel trucks require an Aqueous Urea Solution (AUS, sold under the brand name AdBlue®) for exhaust aftertreatment by selective catalytic reduction (SCR); this is not a fuel additive but an exhaust treatment fluid.

10 EUROPEAN DIESEL MARKETS
2016, in billion litres

EV 2017; EEA 2018. Latest available figures for Netherlands from 2014



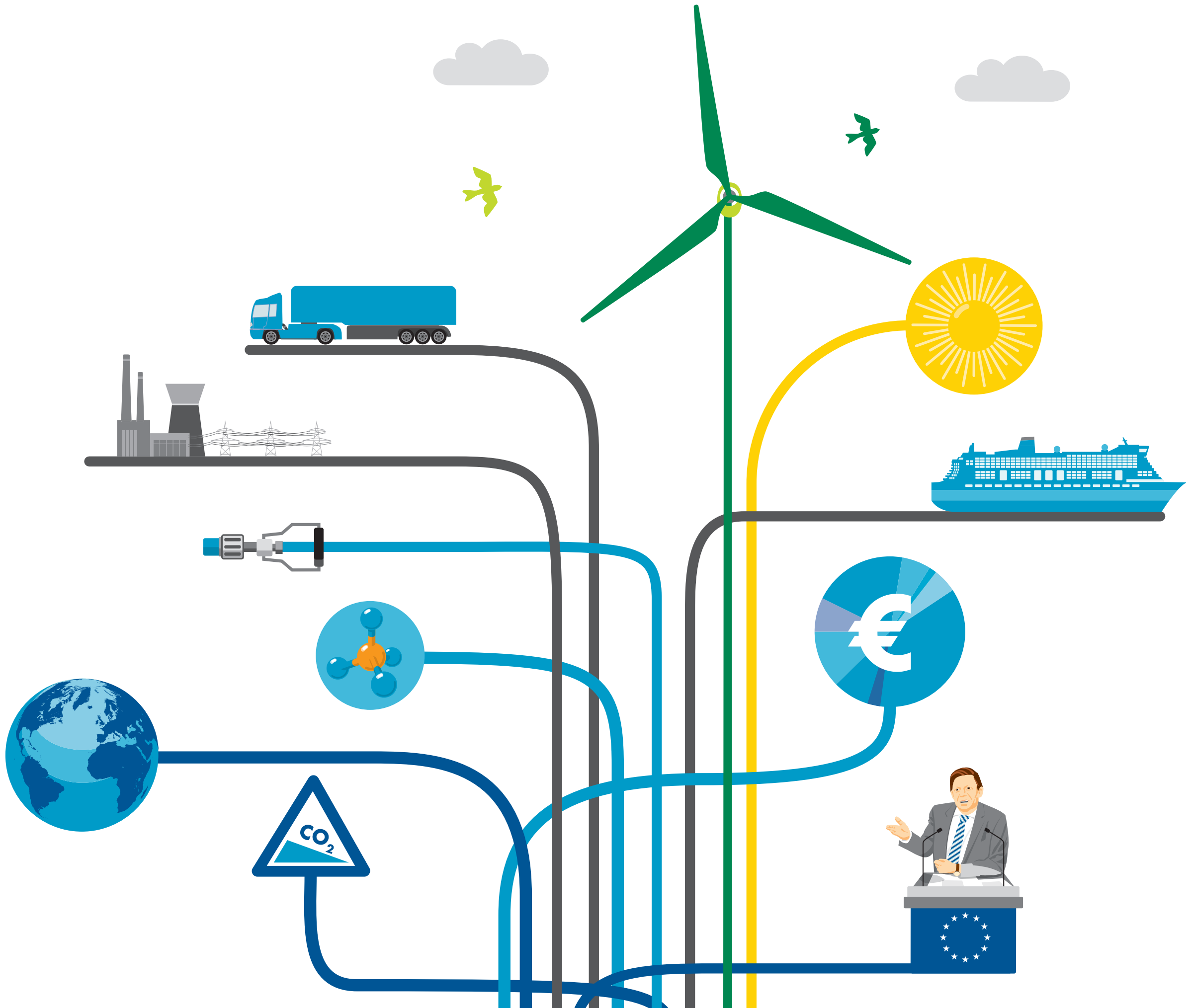
The flammable range of methane-air mixtures (4.4 – 16.5 %) is almost twice that of petrol (7.4 – 1.6 %) and diesel (0.6 – 7.5 %). However, methane only ignites at higher concentrations in a blend.

An oxidant (air/oxygen) and an ignition source are needed to burn methane. For safe handling of LNG vapours, this means that LNG must be stored and transported in closed (i.e. sealed) air- and oxygen-tight systems and tanks. Cryogenic pressure tanks should have high safety margins and be fitted with relief valves. Ignition sources must be avoided.

As methane is lighter than air, it rapidly escapes upwards. Methane, like all other gases, should therefore either be stored in the open air or in enclosed spaces with good aeration and ventilation. Safety can also be increased by using gas sensors.

There are many international codes and standards, particularly ISO standards, for the safe handling and storage of LNG in LNG plants and on LNG carriers. ISO 16903:2015 (Petroleum and natural gas industries – Characteristics of LNG, influencing the design, and material selection) deals with fundamental health and safety matters in the LNG industry. Standards for LNG infrastructure and LNG applications in the retail sector are often more recent or are still being developed. The comprehensive ISO 16924:2016 (Natural gas fuelling stations – LNG stations for fuelling vehicles), for example, deals with safe fuelling station design (GIIGNL 2015b).

2



THE NATURAL GAS SECTOR

The global energy demand could almost double in the first half of the century. More energy, and particularly more clean energy, is needed to mitigate the effects of this increasing energy consumption. What role could natural gas, the cleanest fossil energy source with the lowest carbon content, and its liquefied derivative LNG, play in the future global energy mix?

The development of the global natural gas demand, the situation with regard to global natural gas resources and possible alternative gas resources and the current supply of natural gas as a basis for LNG are examined below.

This overview is followed by an account of major trends in the global natural gas and LNG trade and a general discussion of natural gas and LNG pricing and price development.

2.1 GLOBAL ENERGY DEMAND, NATURAL GAS AND LNG

According to almost all long-term global energy scenarios, natural gas is the fossil fuel whose share of the global energy mix will increase the most. The International Energy Agency's (IEA) central energy scenario, the New Policies Scenario (IEA 2018c), puts the average growth in the gas demand at 1.6% a year; the annual growth in the global primary energy demand is around 1% a year.

The global gas demand has risen from around 2,500 bn m^3 in 2000 to 3,752 bn m^3 today (2017). The USA, followed by the EU, Russia, China and Japan, are by far the largest natural gas-consuming nations. The global gas demand is expected to rise by around 45%, or 1,647 bn m^3 to around 5,400 bn m^3 by 2040.

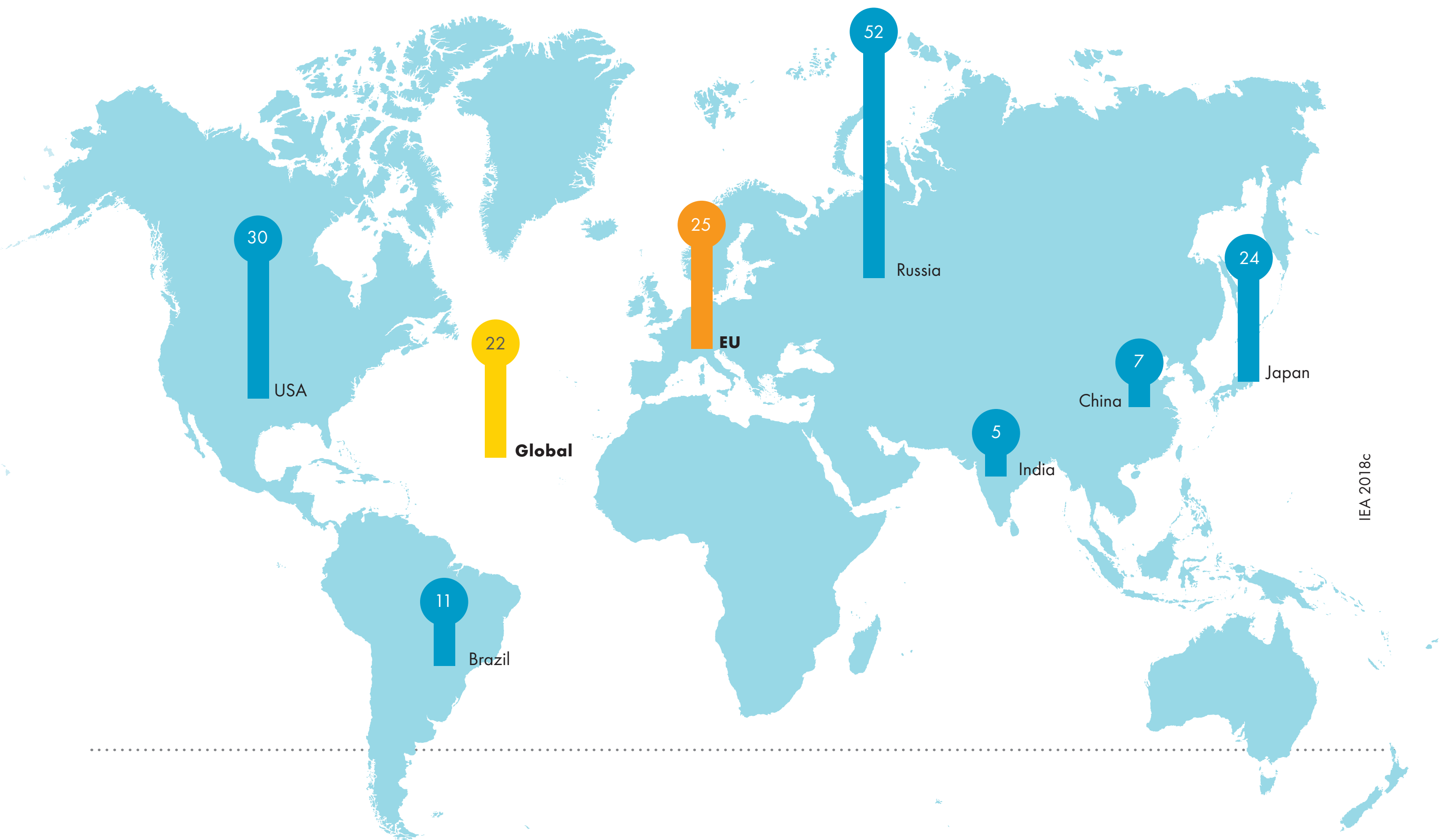
The natural gas share of the global energy mix currently (2017) stands at just under 22% (figure 11). Russia has the highest share, with over 50%, followed by the USA with around 30%. In the EU, the natural gas share is 25%, but it is by far the largest natural gas importer, with imports of around 350 bn m^3 (2017). On the other hand the natural gas share in many emerging and developing countries is still relatively small: just 7% in China, for example, and 5% in India.

In its New Policies Scenario, the International Energy Agency expects the natural gas share of the global energy mix to rise to 25% by 2040; the IEA Current Policies Scenario (5,847 bn m^3) and the ambitious IEA Sustainable Development Scenario (4,184 bn m^3) predict the same increase, although at different absolute levels. It should be borne in mind that none of these scenarios is a "high gas scenario" like the earlier "Golden Age of Gas" scenario (IEA 2011).

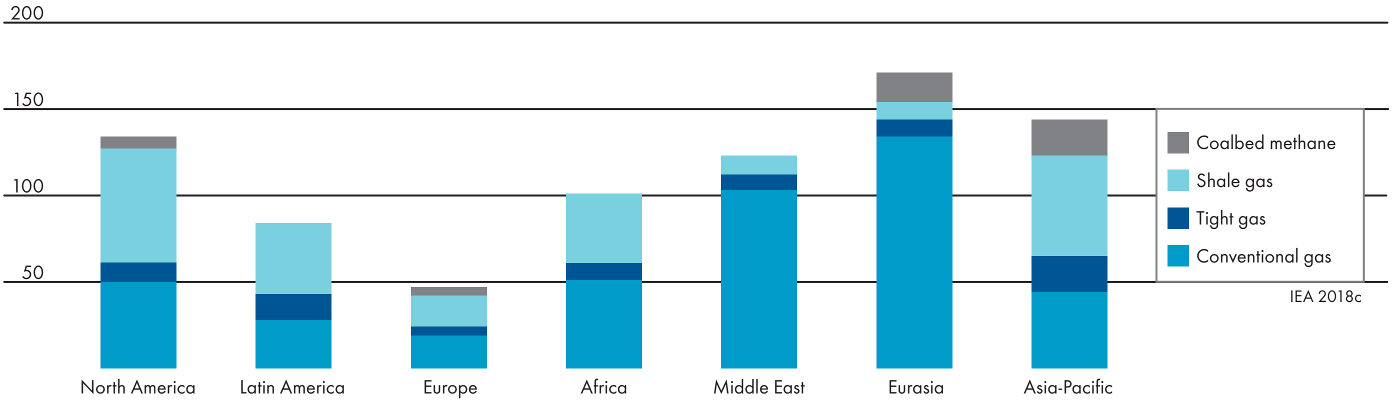
The main driver of gas consumption is electricity generation, where natural gas is increasingly used as a replacement for coal, and occasionally for nuclear energy. The use of natural gas for electricity production worldwide has risen by about two thirds since 2000. A second driver of natural gas consumption is industry, which uses natural gas to generate process heat or, in the case of the chemical industry, as a feedstock. The dynamic of natural gas consumption in the building sector is slower, and consumption in the transport sector is still relatively low. Electricity production and industry are seen as growth areas for natural gas in the coming years also, as is the transport sector, particularly shipping and road freight transport.

With over 100 mln t of oil equivalent (toe) worldwide and a share of about 5%, natural gas is in fact the main alternative energy source in the transport sector, ahead of biofuels. Although it is used predominantly for pipeline transport (around 60 mln t of oil equivalent is used to operate pipeline compressor stations) around 42 mln t of oil equivalent is still consumed by road transport, primarily as compressed natural gas (CNG). Relatively little natural gas is used as an alternative fuel in shipping – currently (2016) around 150,000 t of oil equivalent (IEA 2018b).

11 NATURAL GAS SHARE OF PRIMARY ENERGY CONSUMPTION IN 2017
in percent



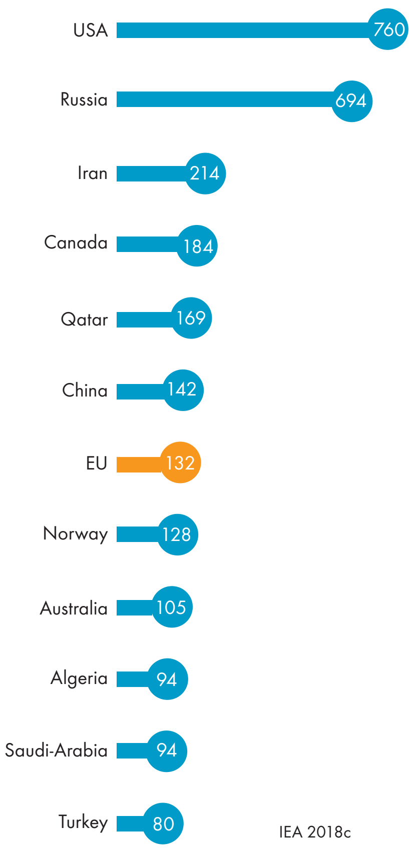
12 GLOBAL NATURAL GAS RESOURCES IN 2017
in thousand billion m³



2.2 GLOBAL GAS RESOURCES AND GAS SUPPLY

World natural gas resources are plentiful, and have the potential to cover the rising demand for many decades to come. At current global consumption levels, the recoverable conventional natural gas reserves will last for just under 60 years.

13 THE LARGEST NATURAL GAS PRODUCERS
2017, in billion m³



Global natural gas resources, currently estimated at around 800,000 bn m³, are a better indicator of future natural gas production. At the current production level, the technically available gas resources will therefore be sufficient to meet gas demand for over **210 years** (IEA 2018c).

Advances in exploration and production technologies have increased our ability to develop gas resources, particularly from unconventional reserves. Unconventional gas resources currently account for approximately 46 % of global natural gas reserves (IEA 2018c). These include shale gas, tight gas (from rock formations with low permeability) and coalbed methane (CBM); shale gas accounts for around 70 % of the unconventional gas reserves.

Natural gas resources are distributed geographically across large parts of the world, and much more widely than oil reserves. The largest conventional gas resources are in Russia and the Middle East. The largest unconventional gas reserves are in major gas-consuming regions such as North America and Asia-Pacific (particularly China).

The main gas producing regions are North America, particularly the USA with around 760 bn m³, the Middle East and the area of the former Soviet Union, including Russia (just under 700 bn m³). The largest conventional gas producers are Russia, Iran and Qatar, while the USA is the largest unconventional gas producer.

World gas production is dominated by conventional gas, with a share of just under 80 % of total production (IEA 2018c).

2.3 ALTERNATIVE GAS RESOURCES

Other potential alternative sources of natural gas, and therefore LNG, besides fossil sources include **renewable gases**. These are natural gas substitutes from renewable energies which are treated to bring them to the same quality as natural gas; they include biomethane produced from biogas, synthetic natural gas (SNG) and Power-to-Gas fuels (PTG). These gaseous substitutes can also be liquefied into Bio-LNG or PTG-LNG. The production and supply costs, which are still considerably higher than those of fossil gases and fuels, are still a challenge for all renewable natural gas substitutes, such as biomethane, Bio-LNG and PTG (DLR et al. 2015).

Supported by state subsidies, renewable gases in the form of biogas and biomethane have gained their first shares of the electricity and gas market. According to the most recent figures (2016) for the EU 28, a total of around 16.7 mln t of oil equivalent of primary energy was generated in the form of biogases; that is more than the current EU biofuel consumption of 14.2 mln t of oil equivalent (EurObserv'ER 2018).

The equivalent amount of natural gas of biogenic origin (just under 20 bn m³) corresponds to about 4 % of the current

EU natural gas consumption of 482 bn m^3 (2017). However, the 17,700 or so EU biogas plants have mainly been used for electricity production; only 1.5 bn m^3 of **biomethane**, or 0.3% of natural gas consumption, was fed into the EU gas network (EBA 2018). There are also very few pilot projects for direct production of liquefied biomethane (EU-COM 2015).

In the medium term, European biogas and biomethane resources could increase to 50 bn m^3, equivalent to around 10% of total EU gas consumption, although only a part of this will be available as a substitute for natural gas in the natural gas network. However, if the consumption sector is small (a part of the LNG-fuelled truck fleet, for example) a significant proportion of LNG consumption could be endowed with certified renewable gas (EU-COM 2015).

Until now the use of **Power-to-Gas fuels** has been investigated mainly in concept studies, analyses of technical potentials and a few pilot projects (dena/LBST 2017; Agora/FE 2018). When considering the supply of LNG for electricity production, it should be borne in mind that there are still many financial and technological challenges to be overcome. The renewable electricity must be supplied cheaply. More efficient electrolysers must be developed and used on a large scale. The carbon required can initially be obtained from concentrated industrial sources of CO_2, but for a genuinely renewable solution, it will have to be obtained from the air in future (direct air capture, DAC).

Electricity-based LNG pathways are ultimately still competing with direct hydrogen applications, as PTLNG requires one more chemical reaction than hydrogen for use in vehicles with a fuel cell or internal combustion engine. The **methanation** or **Sabatier** process is described by the following reaction: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$. In practice, another 20% of the initial energy is lost during this exothermic (heat-releasing) reaction. Finally, the Power-to-Gas fuel obtained, which is similar to natural gas, must also be liquefied.

2.4 NATURAL GAS TRADE AND LNG

Although the global gas resources are more evenly distributed between the regions than the oil reserves, at present the large gas-consuming regions generally use far more natural gas than they can produce. If the production and consumption of natural gas deviate from each other, the gas must either be imported or exported. Around 770 bn m^3 of natural gas are traded internationally at present (2017), which is about one fifth of global consumption.

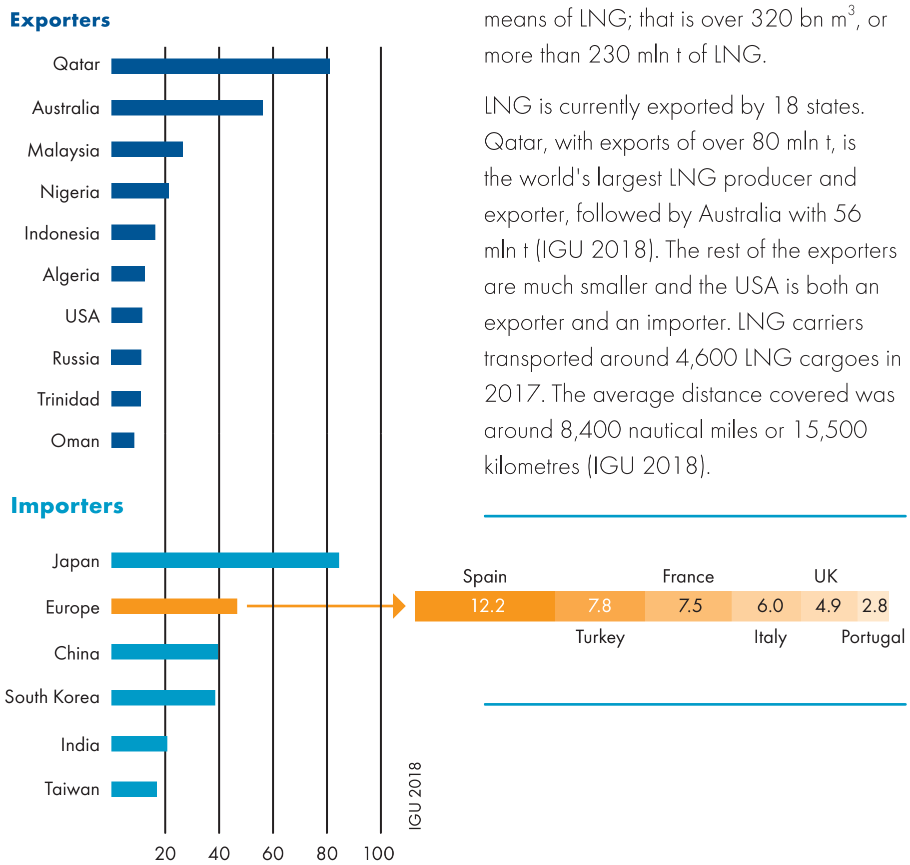
With imports of around 350 bn m^3, the EU is now the world's largest gas importer, followed by China, Japan and Korea. Russia, the Middle East, the Caspian region and Australia, on the other hand, are major gas exporters. The EU will remain the world's largest gas importer in the future, not least because its own natural gas production continues to decline. Within the next decade, China will become the second largest gas importer. The USA, in particular, is expected to become a major gas exporter in the future because of the shale boom (IEA 2018c).

If natural gas is traded, it must also be physically transported. The majority of the natural gas destined for the international gas market is now transported via large international pipelines, most of which pass through several countries. Nearly 60% of the interregional gas trade is conducted by pipeline.

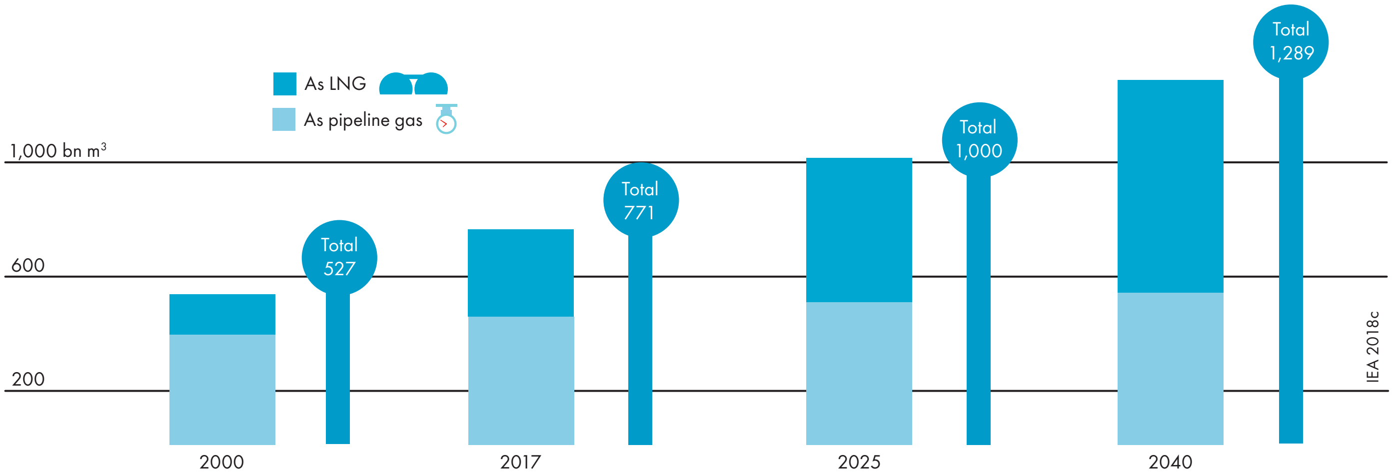
However it is sometimes impossible, or too expensive, or the production and consumption locations are too far apart to transport the gas by pipeline. This is often the case when the production location and the centre of consumption are separated by long sea routes. In such cases, the natural gas can be liquefied and traded as liquefied natural gas (LNG) allowing these gas resources to be developed. At present (2017) more than 40% of the international gas trade is physically conducted by means of LNG; that is over 320 bn m^3, or more than 230 mln t of LNG.

LNG is currently exported by 18 states. Qatar, with exports of over 80 mln t, is the world's largest LNG producer and exporter, followed by Australia with 56 mln t (IGU 2018). The rest of the exporters are much smaller and the USA is both an exporter and an importer. LNG carriers transported around 4,600 LNG cargoes in 2017. The average distance covered was around 8,400 nautical miles or 15,500 kilometres (IGU 2018).

14 THE LARGEST LNG EXPORTERS AND IMPORTERS
2017, in million tonnes



15 OUTLOOK FOR THE GLOBAL NATURAL GAS TRADE



The number of countries that import LNG has now increased to 36. The largest LNG importer is Japan with 85 mln t – about the same as Qatar's exports. Overall, LNG imports are dominated by Asian countries: Japan, followed by China and South Korea. By 2040, emerging countries in Asia will have absorbed over 80 % of the growth in the international LNG trade (IEA 2018c).

But Europe as a whole (including Turkey) is now also importing substantial LNG volumes – around 47 mln t in total. Spain is the major LNG importer in Europe, followed by Turkey and France. The LNG share of the EU's natural gas imports is currently 15 % and is expected to increase further by 2040 (IEA 2018c). The majority of Europe's LNG comes from Qatar, Algeria and Nigeria (IGU 2018).

The trend indicates that demand for liquefied natural gas is growing much faster than that for natural gas overall. In its New Policies scenario, the IEA predicts the global natural gas trade will grow by around two-thirds by 2040, and LNG will account for over 80 % of growth (IEA 2018c).

The trade in LNG, and hence its availability, would therefore increase by a factor of two-and-a-half in less than 25 years. In 2040, LNG would account for 60 % of the natural gas traded globally, and around 14 % of the natural gas consumed worldwide, as compared with 8 to 9 % today.

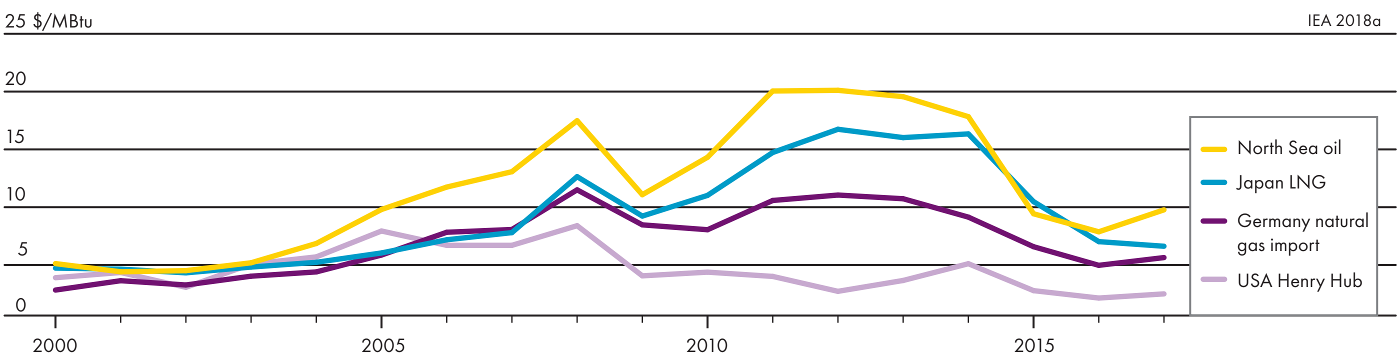
2.5 NATURAL GAS & LNG PRICES

The deciding factor for competitive pricing, and hence ultimately for the actual consumption of a final energy source, is the cost of the primary energy source. For LNG that means the cost of buying natural gas on the international gas market.

The gas markets are not yet as fully integrated and liquid as the markets for crude and oil products. That is partly because more crude is traded internationally and freely, and partly because it has been traded for many years.

There are still considerable differences in the gas price in the major consumer regions Europe, North America and Asia. The gas prices are highest in Asia and lowest in the USA, with Europe in the middle. From 2015 to 2017, wholesale gas prices in the USA were below $3 per mln British thermal units (MBtu; 1 million British thermal units is equivalent to 1,055 MJ or 0.29 megawatt hours). In continental Europe (in this case

16 INTERNATIONAL WHOLESALE NATURAL GAS PRICES



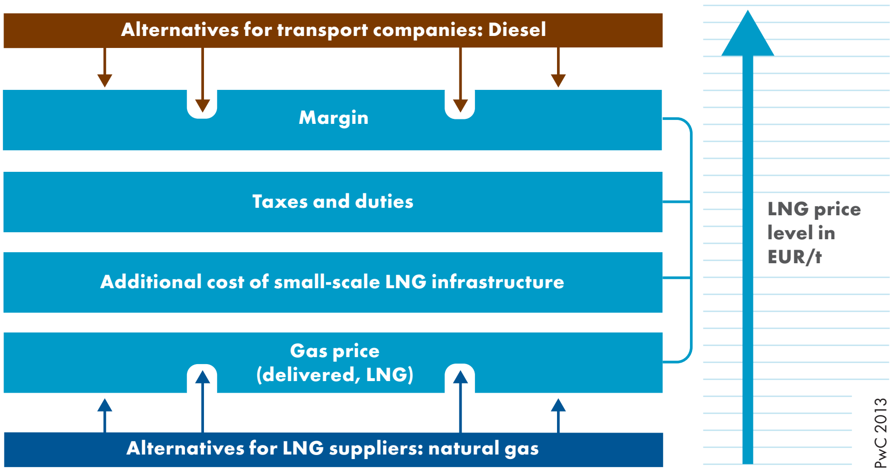
Germany) the natural gas import prices have been two to three times higher than in the USA in recent years, and they have been even higher in Asia (Japan).

The price differences can be attributed primarily to availability and access to gas resources. Germany can obtain gas from a variety of different sources via pipeline, while Japan can only import LNG by sea. The boom in North American shale gas is having a considerable impact on the gas markets. As a result of the abundance of natural gas in North America, the US reference price (Henry Hub) has been well below the price in Europe or Asia for over ten years.

Another relevant factor affecting the gas price is the way it is set: whether by long-term or short-term contracts, with free or limited product disposal, by gas-to-gas competition pricing or linkage to the oil price. The Anglo-Saxon markets are the most flexible and liquid. In continental Europe, but particularly in Asia, some energy prices are still linked to oil prices.

Generally, natural gas is slightly cheaper on the international market than North Sea oil. Only LNG imports to Japan have sometimes been slightly more expensive than crude oil. For (marine) fuels that can be replaced by LNG the following price structure can be observed: the price of heavy fuel oils is generally lower than the crude price and the price of gasoils and marine diesel is generally slightly higher.

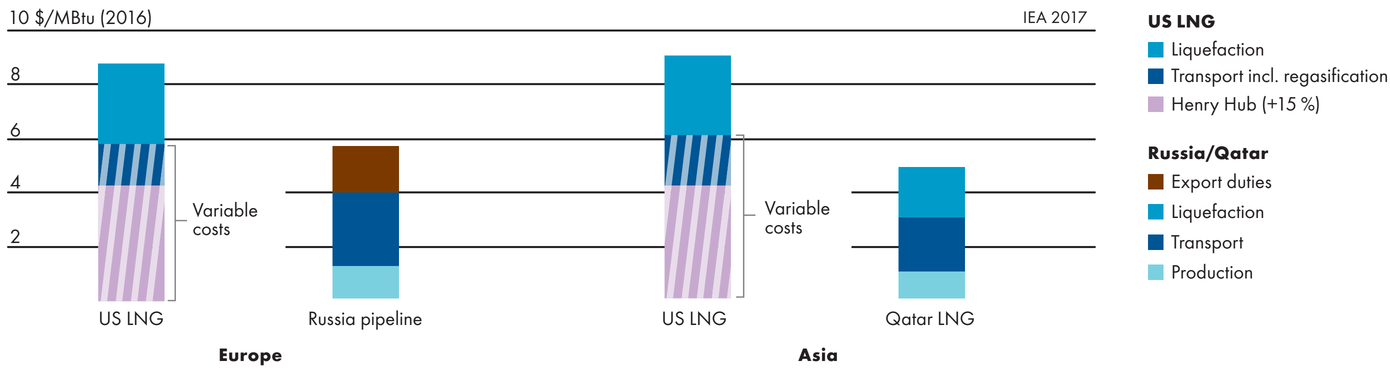
17 PRICING IN THE SMALL-SCALE LNG MARKET



The international gas market is becoming increasingly competitive, less dependent on the oil markets, more liquid and more flexible. The gas markets are expected to converge gradually, but not as far as the global oil market (IEA 2017). The increasing global market share of LNG is making an important contribution to the integration of the global natural gas market, although the logistical costs of large-scale LNG are higher than those of pipeline natural gas because of liquefaction (IEA 2017).

The **delivered cost** of LNG comprises the cost of buying or producing and processing the natural gas, the cost of liquefaction, the cost of transport by LNG carrier and (for small-scale LNG) the cost of regasification. The **retail price** of small-scale LNG in the transport sector differs from the international market prices referred to above. The cost of transport to receiving terminals and of bunker solutions and fuelling stations must also be taken into account. In addition to this, energy and turnover (or sales) taxes are levied on fuels for national transport, but not for international shipping. Finally, a profit margin for the seller must be factored in. In the end, when it comes to pricing, the LNG demand of the transport sector will orientate itself towards the retail prices of the alternative products (diesel, marine gasoil, heavy fuel oil) and the LNG sellers towards the demand from industry and electricity and heat supply (PwC 2013).

18 COST OF SUPPLYING NATURAL GAS TO EUROPE AND ASIA

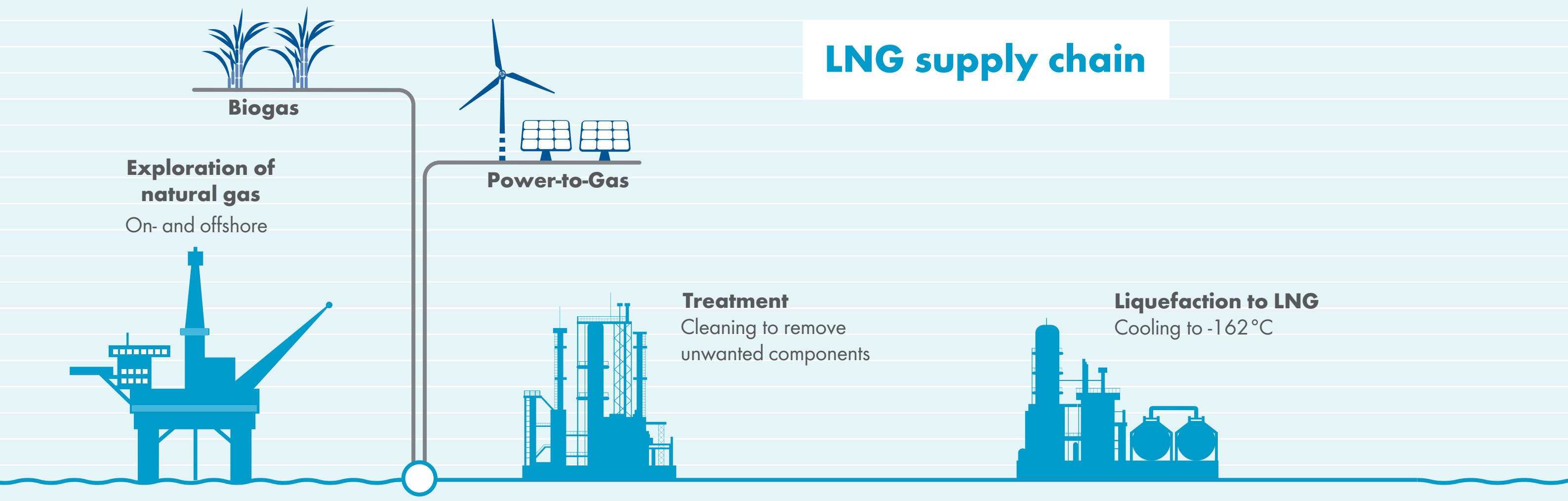


3 SUPPLY CHAIN, LOGISTICS AND RETAIL INFRASTRUCTURE

There are many stages in the LNG supply chain from production to use by the consumer. The first processing stages of LNG, gas production and gas treatment, are almost identical to those for gaseous natural gas and the last stages of the supply chain, when the LNG is regasified and then distributed via pipeline and used in gaseous form, are similar to those for pipeline natural gas.

However the LNG process chain is distinguished from pipeline gas by liquefaction, transport in liquid form, and re-gasification. Consumers also increasingly use LNG as an end product in liquid form; this new stage in the value chain is also called retail or small-scale LNG.

The stages in the LNG supply chain will be described in general below. This will be followed by a description of the elements of the supply and value chain for liquefied natural gas, from liquefaction to possible special uses of LNG as final energy. The stages are: natural gas liquefaction, LNG transport including temporary storage, regasification and distribution, taking account of the end user infrastructure specific to small-scale LNG.



3.1 LNG-SUPPLY CHAIN

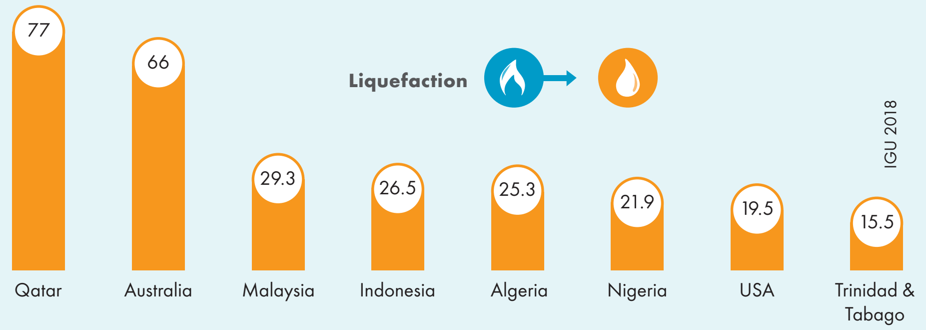
If LNG is of fossil origin, the natural gas is first produced from natural gas resources; some of it is also associated gas from oil resources. In principle, the renewable LNG substitutes Bio-LNG or PTLNG can also be obtained from biomass or electricity. In the medium term this could be used to supplement or replace some of the fossil LNG, but so far almost all LNG comes from fossil natural gas reserves.

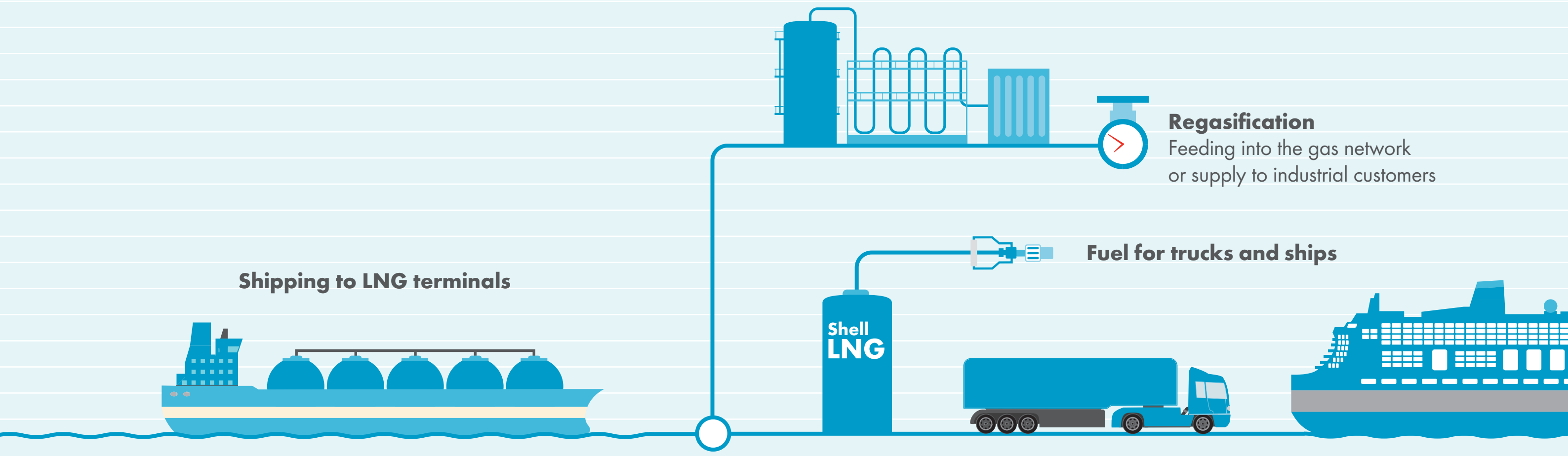
As a naturally occurring gas, the composition of natural gas can vary, so it is treated in special facilities to bring it up to the required quality. It can then be liquefied in special liquefaction plants to produce cryogenic liquefied natural gas at -162 °C. This is where the LNG-specific supply chain begins, which has become established worldwide since the 1960s.

Large quantities of natural gas in liquid form are transported to their destination over great distances in special ships called LNG carriers. The LNG is then usually returned to its gaseous state in large regasification plants, before being supplied directly to consumers or fed into the public gas network. Until now the large-scale LNG-specific supply chain has ended with transport to the destination and its regasification.

However, more recently, LNG has been used increasingly as an **end product**, instead of being transported as a wholesale technical intermediate. For this application, LNG is not regasified, but is stored in liquid form in cryotanks. From there, it is then used as a fuel for shipping (not only in special LNG carriers), short sea shipping and inland navigation, for heavy-duty trucks for road freight transport or for buses and coaches.

19 THE LARGEST LNG LIQUEFACTION CAPACITIES BY COUNTRY
2018, in mln t





This requires the large volumes of the international LNG trade to be broken down into smaller quantities for consumers, which is done in **breakbulk terminals**. Other infrastructure facilities such as bunker stations and refuelling stations must be provided to supply short sea shipping, inland navigation and heavy-duty trucks.

3.2 LIQUEFACTION

Natural gas is liquefied because this reduces its volume significantly, in fact by a factor of 600; that is far more than the reduction achieved by compression. Only via "compression" natural gas becomes a product that can be traded worldwide and filled into vessel or vehicle tanks and used as fuel.

Liquefaction plants vary in size depending on whether they are centralised plants liquefying gas on a large-scale at the place of production, or decentralised plants liquefying gas from the natural gas network close to the point of consumption or from smaller-scale local natural gas resources. At present the dominant LNG supply model is the **hub-and-spoke model**, which involves centralised liquefaction in large industrial facilities, transport and onward distribution (GIIGNL 2015b).

These large industrial natural gas liquefaction facilities are called **LNG trains**. Two, or even more, LNG trains are often built alongside each other to ensure continuous and safe operation. The LNG trains are either large-scale base load plants with a liquefaction capacity of 3 to 8 mln t of LNG a year, medium-sized plants with a capacity of 0.5 to 2.5 mln t a year or small plants with a capacity of 0.3 to 0.5 mln t a year. The latter are often used as peak shaving plants to even out

FLOATING LNG PRELUDE

The Floating LNG project "Prelude" started operations in 2018. It is one of the world's first offshore LNG plants, and currently the largest. Prelude produces and liquefies natural gas around 300 miles off the coast of Western Australia. The floating platform operates at a sea depth of 250 metres and is 488 metres long by 74 metres wide, making it the size of four football pitches. The Prelude FLNG facility can produce 5.3 mln t of liquids a year and also store some of it; 3.6 mln t of its annual production is LNG, 1.3 mln t is condensate and 0.4 mln t is liquefied petroleum gas.

fluctuations in consumption in the natural gas network. More than 100 peak shaving plants were built in the USA in the 1960s and 1970s (DOE/NETL 2005).

An even newer category is mini or micro liquefaction plants, which are used for local liquefaction of biogas or biomethane (Bio-LNG) or to supply LNG in isolated areas to which it cannot be transported (Wartsilä 2016).

Large-scale plants in particular use complex, efficient liquefaction processes; simpler processes can also be used in small plants, but they rely on electricity from the grid (AP 2009; GIIGNL 2015b) Liquefaction terminals can be installed permanently as onshore facilities. However, **floating LNG facilities (FLNG)** are a more flexible and cost-effective option.

There are FLNG facilities both for natural gas production sites and for LNG receiving terminals. Floating units which can take natural gas from current production, liquefy it to produce LNG and store it, are called **floating production storage and offloading units (FPSOU)**. They have been used in oil production since the1980s and 1990s. In gas production this is still new technology, which allows smaller, more remote natural gas resources to be developed more cost-effectively. The first FPSOU began to export LNG in 2017 (IEA 2017; IGU 2018).

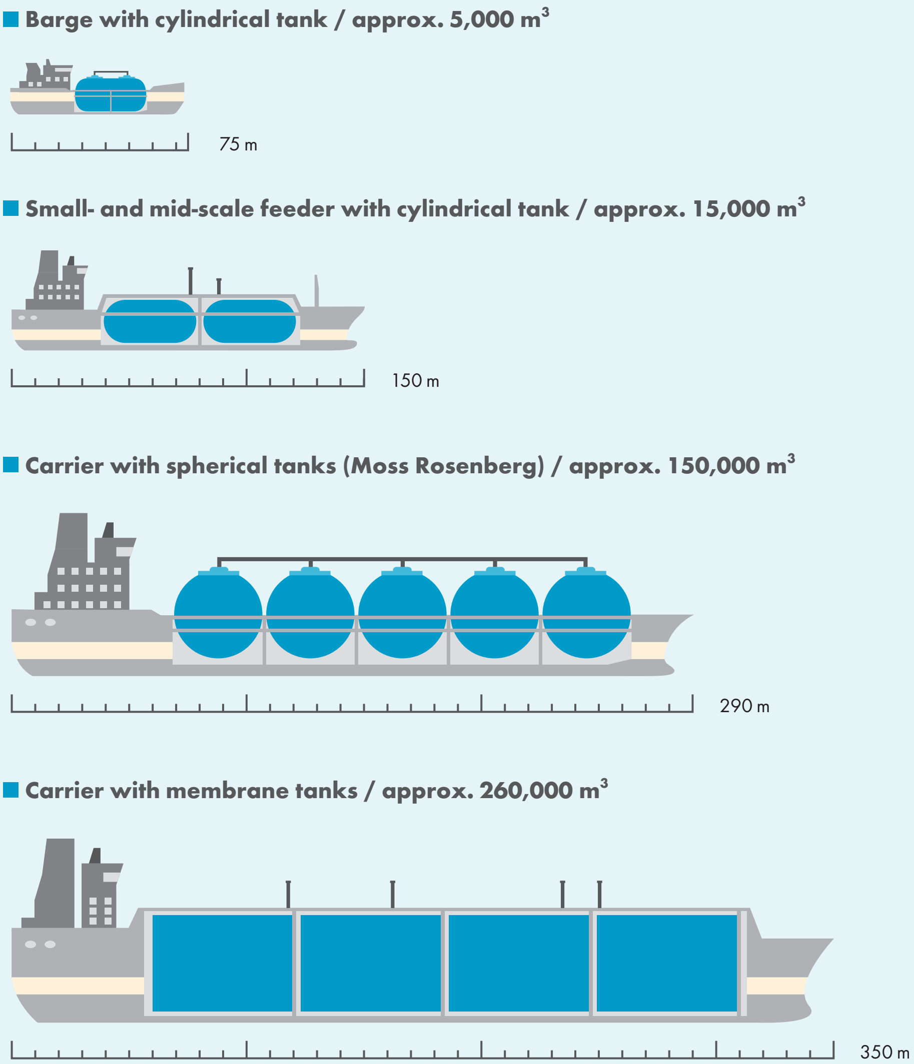
The nominal global capacity of LNG liquefaction plants is around 370 mln t of LNG. With global LNG exports of 293 mln t, LNG liquefaction plants were therefore operating at 84 % capacity in 2017.

The order of the major LNG exporters correlates with their natural gas liquefaction capacities, depending on how much of that capacity is utilised. Qatar and Australia have by far the largest liquefaction capacities. In Europe, only Norway has a gas liquefaction terminal at the moment, with an annual capacity of 4.3 mln t (GIE 2018a).

3.3 LNG-CARRIER (LNGC)

LNG is transported from the gas liquefaction terminal to a receiving terminal in special ships, called LNG carriers (LNGC). LNG was first transported across the Atlantic by ship in 1959. Transport of LNG by ship has grown rapidly since the 1960s, not least because of the technological development of the LNG carriers.

20 LNG TRANSPORT VESSELS



LNG carriers are classified in category 3 of the International Maritime Organisation's (IMO) International Gas Carrier Code (IGC), called refrigerated gas carriers. These are carriers which transport cryogenic gases at atmospheric pressure (Wartsilä 2015). There are currently around 230 LNG carriers worldwide (UNCTAD 2017).

The LNG in these carriers must be kept at a very low temperature during transport. As LNG carriers have no active refrigeration, the tank systems have external insulation, which protects the ship's hull from cryogenic temperatures and keeps LNG boil-off low. Most LNG tank systems are designed for a boil-off rate of 0.15 % per transport day; this can be controlled by the material and the thickness of the insulation. The best LNGCs have boil-off rates of 0.08 % of transported gas per transport day. So if a transoceanic LNG transport lasts 10 days, only around 1 % of the LNG cargo will boil off. The boil-off gas is generally used to power the ship; if it does not provide sufficient fuel, boil-off can also be forced.

The first transatlantic LNG transport, from the US Gulf Coast to the UK, took place in 1959. The LNG prototype, the Methane Pioneer, was a converted World War II cargo ship with a capacity of only 7,000 m^3 of LNG.

The first purpose-built commercial LNG transport ship, the Methane Princess, was launched in 1964 to ply the route between Algeria and the UK. It had a LNG transport capacity of 27,400 m^3. The Methane Princess had a sister ship, the Methane Progress. The Methane Princess was about half the length and width (189 m by 25 m) of a modern large LNG carrier and had around a tenth of the capacity of the largest LNG carriers today. It was scrapped in 1997 (MarEx 2014).

If the LNG carrier does not need all of the boil-off gas, because it is powered by a slow-speed diesel engine or a dual/ tri fuel engine, the boil-off gas can also be reliquefied and fed back into the LNG tanks. Ultimately, the boil-off gas can also be burned in a gas combustion unit (GCU) (Wartsilä 2015; IGU 2018).

There are two main types of LNG carrier, depending on the type of storage system used: the Moss Rosenberg design and carriers with membrane tank systems. **Moss Rosenberg tank systems** are composed of several spherical tanks. They are made of aluminium alloys with additional insulation and have an internal diameter of 40 m or more. They are positioned in a line in the ship's hull and are separate from each other.

Moss Rosenberg Systems are relatively safe and can be installed without a double hull. Another advantage is that they can transport partial cargoes. For many years they represented the leading technology for tanks on board LNG carriers, but they do have disadvantages: the spheres are heavy and do not fill the ship's hull adequately and they require high superstructures, which have an adverse effect on aerodynamics.

A better use of space can be achieved with **membrane tank systems** arranged in a row, although they still take up significantly more space than liquid tanks. Membrane tanks differ according to the number of membrane layers and the type of membrane and insulation materials. Unlike the spherical tanks, the membrane tank systems are not separate from the ship's hull, but are usually permanently fixed to it (Uhlig/ Wohlgemuth 2012; Wartsilä 2015)

Besides spherical and rectangular LNG tank systems, there are also prismatic or cylindrical systems. Important characteristics for the materials used to construct LNG tank systems include low thermal conductivity, and low-temperature ductility.

Most modern LNG carriers have storage capacities of 150,000 to 180,000 m^3, and the largest are equipped with membrane tanks which reduce the amount of dead space. They can now transport over 260,000 m^3 of LNG. However, because of their size, the largest LNG carriers are unable to enter some seaways; these include canal systems like the Panama Canal (IGU 2018). The global LNG carrier fleet has a total transport capacity of 76.6 mln m^3 (LNG WS 2018).

There are also smaller LNG carriers, called small-scale or mid-scale carriers, which have capacities of a few thousand to several tens of thousands of cubic metres of LNG. These LNG carriers are used to supply LNG to regional storage facilities (bunkering stations) or for direct fuelling of ships.

3.4 LNG REGASIFICATION

On arrival at the destination, LNG can be converted back into its gaseous state in special regasification units and supplied to local consumers.

Regasification units can also be installed permanently onshore. These are large units which can be used in a variety of ways. They generally take longer and cost more to build, but they also operate for longer on site. **Floating storage and regasification units (FSRU)** are an alternative.

FSRUs have been developed since the beginning of this century and are significantly cheaper and quicker to build. The first FSRUs were converted LNG carriers but there are now purpose-built carriers, which can be modified in different ways. There are also floating storage units (FSUs), most of which are old LNG tankers not equipped for regasification, or smaller floating storage regasification barges. Some FSRUs are also combined with a power generation unit (OE 2017; Norrgård 2018).

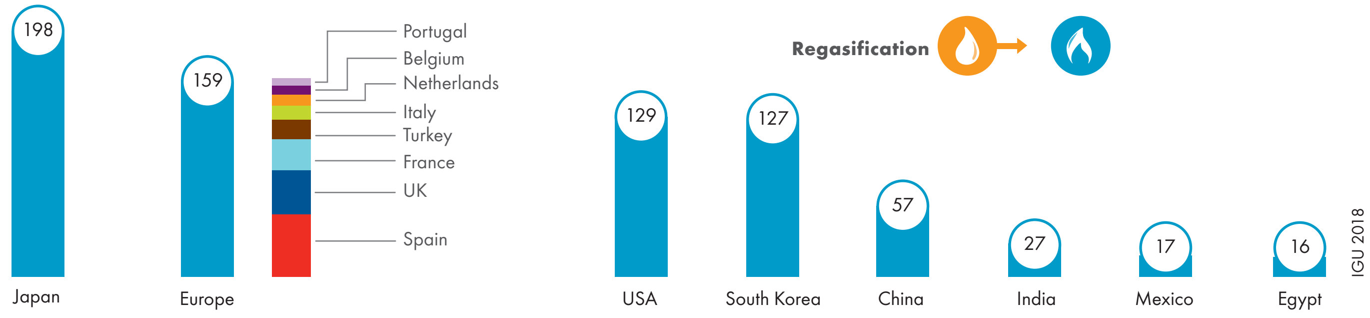
FSRUs allow simpler and more flexible access to the global LNG market without the need to construct extensive pipeline networks in the consuming region. The floating LNG option is nevertheless restricted to regions with access to the sea. There are already 30 FSRU terminals worldwide and more under construction (IEA 2017; IGU 2018).

The global LNG regasification capacity of the 120 or so receiving terminals is 850 mln t. Which is more than twice the gas liquefaction capacity. Cost-effectiveness is not always the main criterion; independence from the supplier is also an important consideration. Regasification units can be built to secure or maintain the gas supply, or to cover seasonal peaks. The average utilisation of capacity is low, at only 35 %, and generally lower for the permanent onshore facilities than for the smaller, more flexible FSRU terminals (IGU 2018).

Japan, the USA and South Korea have very large LNG reception capacities. South Korea and Japan have the largest LNG terminals, with reception capacities of 30 to 40 mln t for single terminals. The capacities in the USA are historical import capacities from the period before the shale gas boom, which are now little used. There are around 30 regasification terminals in Europe with a capacity of 160 mln t, equivalent to about 20 % of the global regasification capacity (IGU 2018). Theoretically, the European regasification terminals alone could receive over half of the global LNG supply and convert it back to natural gas. However the capacity utilisation of European terminals is actually below the global average.

Besides liquefaction and regasification terminals, more and more LNG storage capacities are also being built, although at present they only have a capacity of 30 mln t (IGU 2018). They increase the supply security, serve as a platform for LNG distribution or provide a basis for loading trucks.

21 THE LARGEST LNG REGASIFICATION CAPACITIES BY COUNTRY
2018, in mln t



The **Gas Access to Europe Terminal (GATE terminal)** is a large LNG import terminal in Rotterdam, which opened in 2011. GATE has three double-hull storage tanks each with a storage capacity of 180,000 m^3 and is also able to receive LNG from the largest, Q-Max class of LNG carrier. The LNG, which generally comes from the Middle East, Africa or Norway, is regasified and fed into the European natural gas distribution network. With an average throughput of 12 bn m^3 of natural gas a year, GATE could cover about a third of the energy consumption of the Netherlands.

LNG retail infrastructure has recently been added to GATE, with Shell as the first customer. This means that LNG can now be loaded onto LNG bunker ships, ISO containers or LNG tank trucks, which in turn supply other LNG-fuelled vessels and LNG vehicles (GIIGNL 2015b, GATE 2019).

22 LNG SIZE CLASSIFICATION

GIIGNL 2015b; EMSA 2018

	Large Scale LNG	Medium Scale LNG	Small Scale LNG
Liquefaction	> 1.0 mln t per year	0.4 – 1.0 mln t per year	< 0.4 mln t per year
Ships	100,000 – 267,000 m^3 LNG carrier	7,500 – 30,000 m^3 LNG feeder ship	<10,000 m^3
Receiving terminals	>100,000 m^3	10,000 – 100,000 m^3	
Bunkering stations			Bunkering terminals 270 – 2,000 m^3/day; Bunkering stations 35 –135 m^3/day
Trucks			35 – 56 m^3 Truck 21– 45 m^3 Containers

3.5 RETAIL INFRASTRUCTURE

LNG is produced, transported and stored almost exclusively in large-scale industrial units. Until now, LNG activities have been described as **large-scale LNG** in terms of their production, transport and storage capacities. However new LNG activities, such as its use as final product in the mobility sector, are on a far smaller scale.

Therefore, these new LNG usage require much smaller LNG distribution and supply units, in other words smaller temporary storage facilities, smaller supply stations with suitable access, smaller transport ships and tank trucks for distribution to the consumer ship or truck. The miniaturisation of the previously large-scale LNG activities is therefore called **small-scale LNG** or **retail LNG**; for mobile applications it is called mobile LNG (GIIGNL 2015b; EMSA 2018). The size classification of stages in the LNG supply chain is summarised in Table 22; however the table does not show the new **micro scale** (<0.1 MTPA) category of LNG liquefaction plants separately.

For LNG to be used as a transport fuel, an extensive supply infrastructure must be developed in ports and onshore. With the Alternative fuels infrastructure directive (2014/94/EU) for LNG in maritime and inland navigation ports and along the highways of the Trans-European Network for Transport (TEN-T), the EU has established the basis for the construction of an EU-wide LNG supply network for shipping and heavy-duty road freight transport (EP/Council 2014).

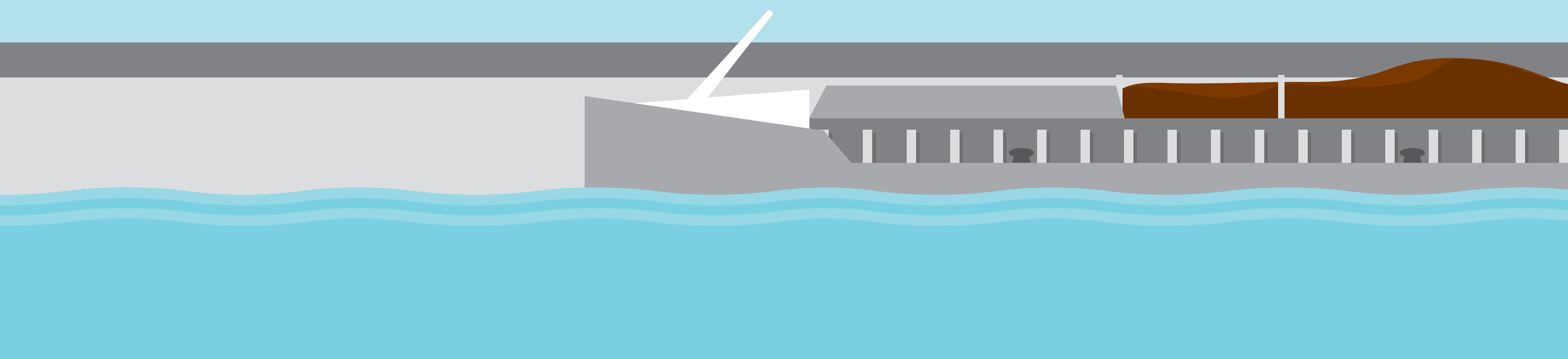
The directive, also called the **AFID**, specifies as a guide that by 2025 LNG bunkering stations should be built at major ports of the TEN-T core network, and LNG refuelling stations at 400-km intervals along the TEN-T road network. The construction of these national networks should be coordinated between neighbouring EU states. Each EU Member State must produce a national strategy framework for this, which must be updated continuously (BMVI 2016).

23 BUNKERING SIZE CLASSIFICATION

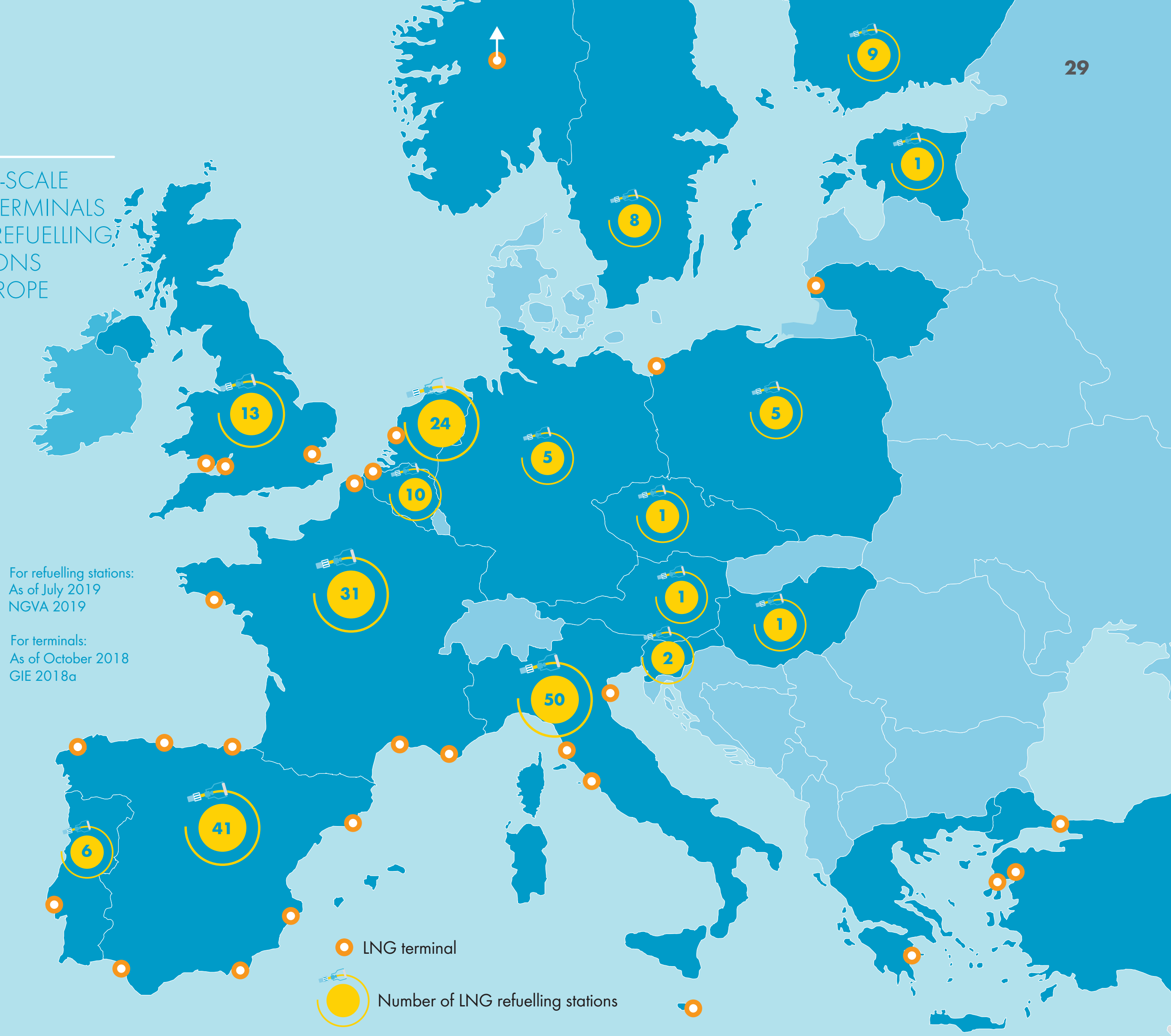
LNG BUNKERING VOLUMES BY TYPE OF SHIP

Boats	50 m^3
RoRo & RoPax	400 – 800 m^3
Small freighters	2,000 – 4,000 m^3
Tankers, bulkers & containers	10,000 – 20,000 m^3

EMSA 2018



24 LARGE-SCALE LNG TERMINALS AND REFUELLING STATIONS IN EUROPE

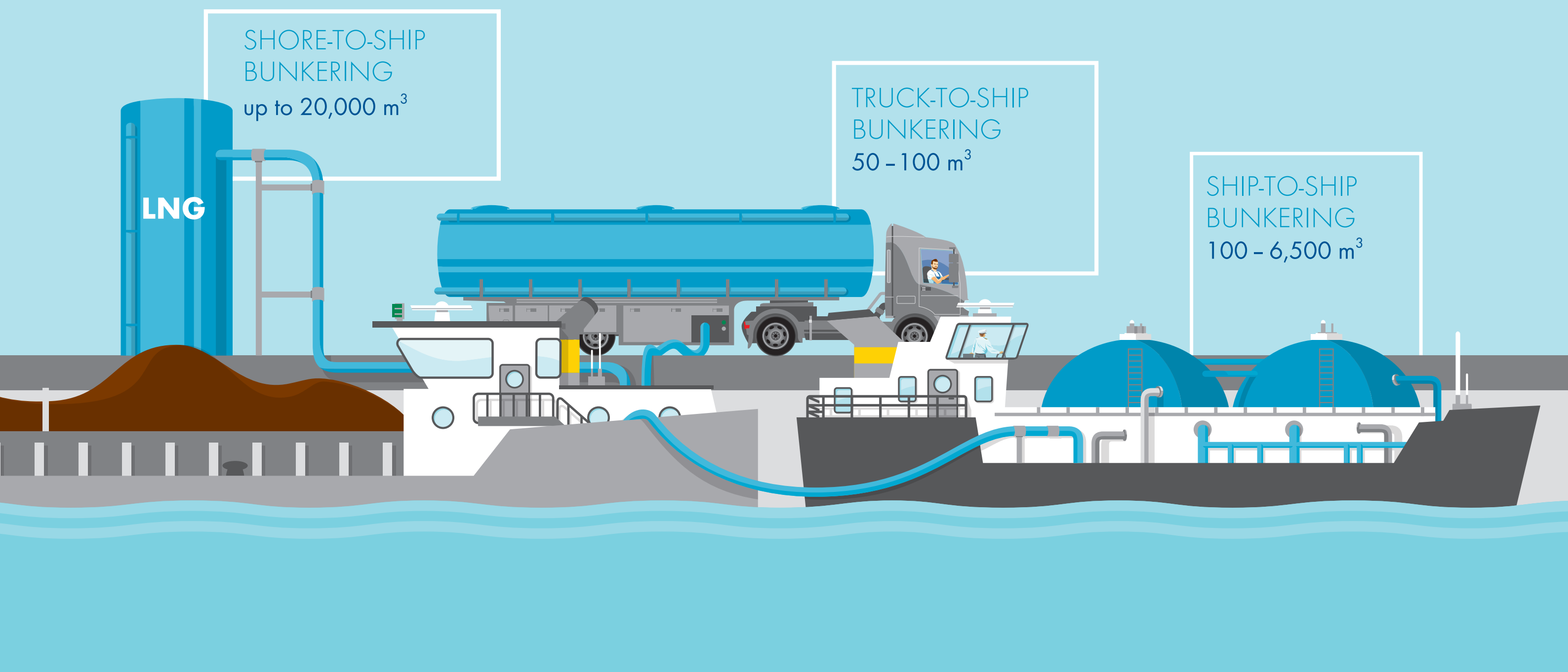


For refuelling stations:
As of July 2019
NGVA 2019

For terminals:
As of October 2018
GIE 2018a

The EU states currently have around 200 LNG refuelling stations. Most of these are located in Italy (50) and Spain (41), followed by France (31), the Netherlands (24) and the UK (13). The network is being developed under the EU AFID Directive and within EU- or government-supported projects such as Blue Corridors and the BioLNG EuroNet.

There are also around 30 large-scale LNG import terminals in Europe, the country with the highest number of LNG terminals being Spain. LNG import terminals generally have the capacity to store several hundreds of thousands cubic metres of LNG. The largest import terminal, with a storage capacity of 1,000,000 m^3, is on the Isle of Grain in the UK. There are more LNG import terminals at the planning or construction stage. There is also a large-scale export terminal with a capacity of 4.3 mln t in Hammerfest in the far north of Norway, and a growing number of unrecorded, small-scale LNG import, export and liquefaction facilities and bunkering stations and over 1,000 small storage facilities (GIE 2018a, b).



Bunkering stations for ships

During LNG bunkering, ships take on LNG which is used as fuel and for the on-board energy supply. There are basically three different bunkering concepts for seagoing and inland navigation ships that can be used to develop the LNG bunkering infrastructure. These are truck-to-ship, ship-to-ship and shore-to-ship. Each of the bunkering concepts has a different capacity regarding bunkering volume or bunkering speed (EMSA 2018).

With **truck-to-ship**, the LNG is supplied to the ship directly by truck. This option can be used as a temporary solution or for small bunkering volumes of 50 to 100 m^3. It lends itself to situations where it is impossible to operate an alternative bunkering infrastructure cost-effectively and is a kind of entry-level option.

Bunkering of a ship from an LNG bunker ship is called **ship-to-ship**. The bunkering volumes here are higher, at 100 to 6,500 m^3. LNG bunker ships offer a certain degree of flexibility with regard to the bunkering location, as they can reach other sea or domestic ports and supply ships lying there with LNG.

The **shore-to-ship** bunkering concept requires the construction of port infrastructure. It makes direct fuelling possible by providing seagoing or inland navigation ships with direct access to a stationary LNG tank or an LNG pipeline connected to an LNG terminal. The ships are fuelled by a loading arm instead of a hose connection, allowing much higher bunkering rates. The LNG bunkering volumes range from tank volumes of a few hundred m^3 for RoRo/RoPax ships to very large container ships or very large crude carriers with a tank volume of up to 20,000 m^3.

Besides supplying energy for ships, LNG delivered in ISO containers, by bunker ship or tank truck can also be used to fuel power generators at the port.

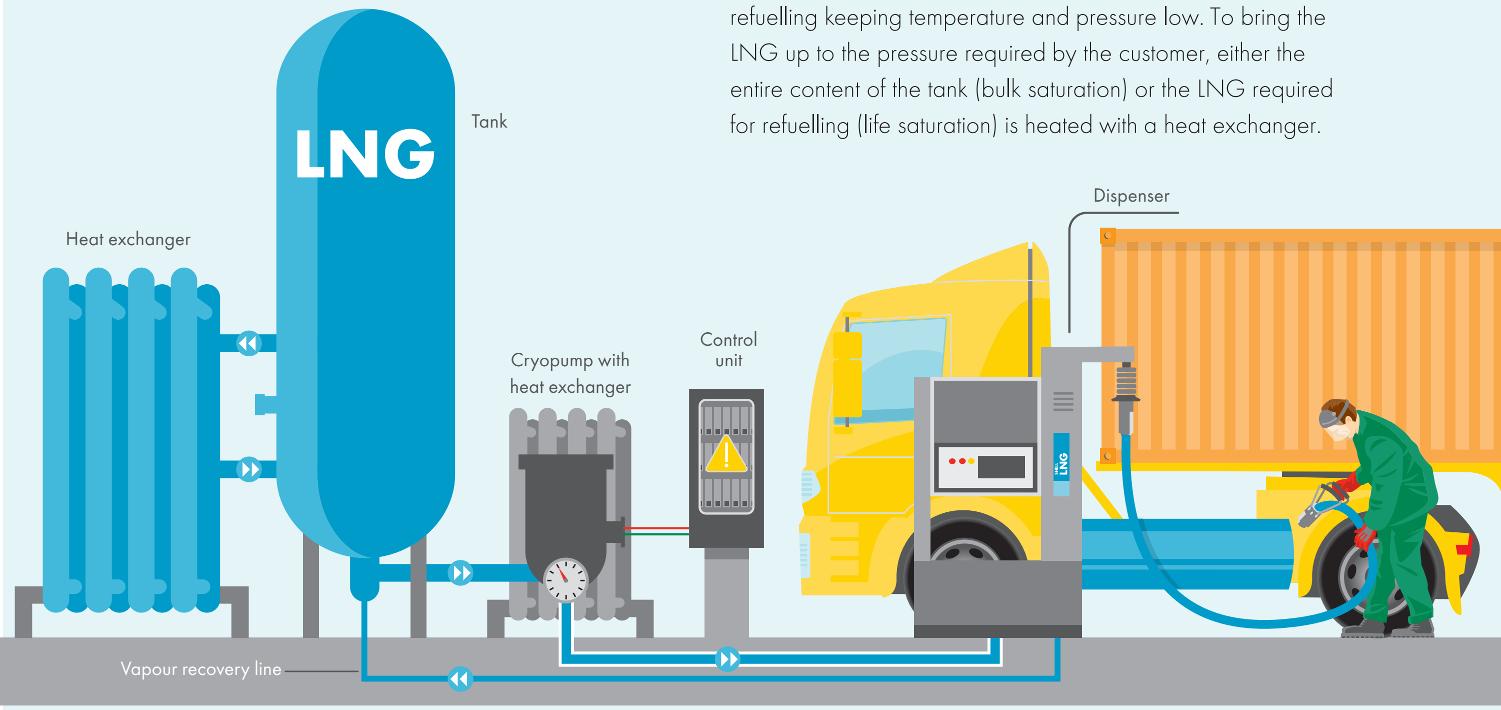
In all, there are currently around 40 to 50 LNG bunker stations for ships in Europe, some of which are located at LNG terminals. The majority of European bunker

25 ARCHITECTURE OF AN LNG REFUELLING STATION

Certain technical components are required for the construction of an LNG refuelling station. For all refuelling stations these include LNG storage facilities of adequate size, heat exchangers to bring the LNG to the required pressure for fuelling, cryopumps, control systems and dispensers.

An LNG storage tank consists of a double-wall, insulated gas tank, which protects the cryogenic LNG from heat. These tanks generally have a storage capacity of 20 to 80 m^3 of LNG and a maximum fill level of around 90 %. The pressurised tank is usually designed for a pressure of 8 to 18 bar. The minimum design temperature is -195 °C, although the operating temperature should be -160 °C to -120 °C (DVGW 2017).

In normal operation, cryogenic LNG is added during regular refuelling keeping temperature and pressure low. To bring the LNG up to the pressure required by the customer, either the entire content of the tank (bulk saturation) or the LNG required for refuelling (life saturation) is heated with a heat exchanger.



stations are in Norway, but some are also in the Netherlands, Spain and France. There are more LNG bunker stations at the planning or construction stage. The global hotspots for LNG bunkering are in South-East Asia, the Middle East and the Gulf of Mexico (DNV GL 2018; GIE 2018b).

LNG refuelling stations

A requirement for the use of LNG in heavy-duty vehicles is the provision of LNG refuelling stations. These are usually the starting point for truck journeys and the point to which the trucks have to return to refuel after driving the distance allowed by one tank of fuel. To ensure the widespread availability of LNG, an LNG fuelling station infrastructure must be established along the Trans-European Transport Network (TEN-T) (EP/Council 2014).

The fuelling station infrastructure for road freight transport can be developed in line with the demand for LNG. Mobile fuelling facilities can be used to provide the fuel for the first operators while demand is still low. These could be either 40- or 45-foot tanks or special trailers with a volume of 35 to 56 m^3 of LNG, which could be used for direct fuelling (EMSA 2018).

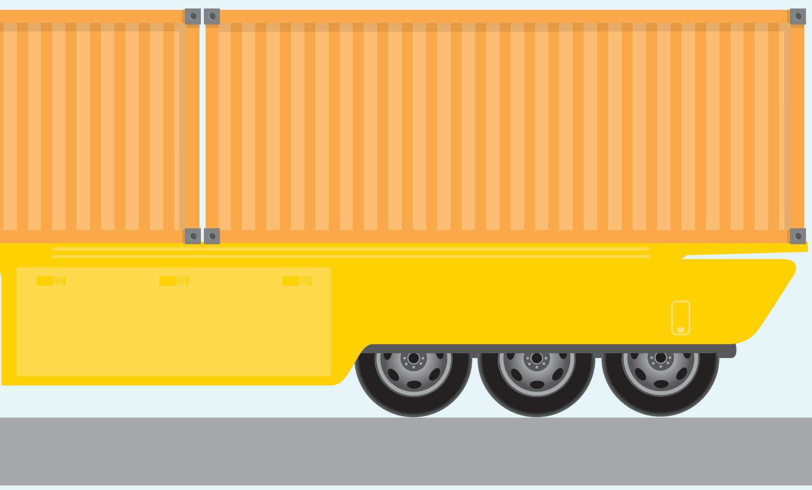
As demand grows, permanent LNG refuelling stations, offering frequent refuelling opportunities for heavy-duty vehicles along the TEN-T road network or at logistics depots, for example, will become economically viable. These stations will consist of an LNG storage tank with a volume of 20 to 80 m^3 (DVGW 2017).

An LNG refuelling facility can be integrated into an existing refuelling station as an additional fuel offering. The main precondition for this is that there is sufficient space for these facilities at the existing site and that LNG can be delivered, stored and dispensed alongside other liquid or gaseous fuels, both from a technical and a regulatory perspective. Alternatively, new LNG refuelling stations can also be built as stand-alone facilities.

Despite being stored in insulated tanks, LNG slowly increases in temperature and produces boil-off gas, continuously increasing the pressure inside the tank. Precautions are taken to prevent the build up of internal pressures that are critical for the tank. These include removing the boil-off gases for use as compressed natural gas, feeding them into the natural gas pipeline network (if available) or reliquefying them, which requires a compressor. A final option would be to release the LNG in a controlled way through a safety valve, but is limited to safety-critical situations.

The LNG is pumped from the LNG tank to the dispenser through low-temperature resistant, insulated pipes with a cryopump. From the dispenser, LNG is pumped into the vehicle tank through a hose designed for cryogenic liquids and a safety coupling, which is connected to the vehicle. An additional connection returns any vapour in the vehicle tank to the LNG storage tank.

As fuelling can only be carried out by trained staff, truck drivers must attend a short training course. Protective clothing must be worn during fuelling, specifically protective goggles, protective gloves and clothing that covers the body, arms and legs, because cryogenic liquids cause burns on contact with the skin.



4

LNG IN SHIPPING

Shipping is one of the main sectors in which LNG will potentially be used as a fuel. In the past only the long distance LNG carriers were fuelled by natural gas. Simply because this product was on board already. The use of natural gas as shipping fuel changes now. In the face of increasingly strict air pollutant emission regulations, the shipping industry is looking for alternative fuels. LNG is currently the only serious alternative to oil-based marine fuels for shipping (IMO 2016).

This chapter will begin with a qualitative and quantitative analysis of the merchant shipping fleet and an examination of current and future LNG applications in shipping and inland navigation as well as in retrofitted ships. This will be followed by a general description of engine designs and LNG gas engines for ships. To conclude, trends for powertrain-related emissions from ship engines, particularly gas engines, and the relevant regulations will be discussed.

4.1. FLEET

Ships are classified as inland navigation vessels or seagoing ships, depending on where they are used, and divided into various categories according to the type of transport they provide. This section begins by describing the main criteria for assessing ships and the most relevant types of ship for maritime transport. This will be followed by a statistical survey of the global merchant fleet. The section concludes with a review of LNG applications.

Types of ship

Although there is no clear convention, ships are generally classified as general cargo ships, container ships, bulk carriers or bulkers, oil tankers or "other ships".

General cargo ships include multi-purpose vessels for combined and non-bulk cargo, special transporters and roll-on roll-off (RoRo) cargo ships. The other types of ship include tankers for liquefied gases, special chemicals and oil products, refrigerated ships, ships for the construction and supply of offshore facilities, tugs, dredgers, coastguard and military vessels and passenger ships, which includes cruise liners, ferries and yachts.

Nowadays, ships are generally measured officially in gross tonnage, which is a measure of the interior volume of a ship calculated in accordance with specific rules. However, in practice, ships are described by the size required for their purpose.

Container ships, for example, are described by the maximum number of twenty-foot containers they can accommodate (twenty-foot equivalent unit or TEU), ferries by the number of passengers they can carry (PAX), tugs by their bollard pull (tons bollard pull or tbp) and bulkers and tankers by their maximum deadweight tonnage (DWT). Another important factor for ships is whether their load capacity is limited by space (volume carriers like ferries or car transporters) or by mass (weight carriers like bulkers or tankers).

Some types of ship will be discussed in more detail below. They will be selected on the basis of their significance in numerical terms, global fleet size and other aspects which are particularly relevant to the use of LNG. The descriptions all relate to seagoing ships but can also be applied to inland navigation vessels. Anything that relates particularly to inland navigation vessels will be mentioned separately.

Multi-purpose vessels

Conventional multi-purpose vessels (also called general cargo ships) are able to transport a variety of packaged goods at the same time. Efficient on-board loading gear allows them to unload packaged goods, bulk goods and ISO containers no matter what the local circumstances. Because of the increasing specialisation of ships, multi-purpose vessels are gradually being replaced by container ships and bulk carriers, but they are still in use all over the world because of their long service life.

Container ships

Container ships specialise in the transport of internationally standardised containers. The size of these ships is given in TEU (twenty-foot equivalent units). Most of the containers shipped today are double-length (or forty-foot equivalent unit, FEU) containers.

The capacity of container ships ranges from small feeder ships of 1,000 TEU to large ocean-going ships of 8,000 to 10,000 TEU (very large container ships or VLCS) or even 22,000 TEU (ultra large container vessels or ULCV). Container ships ply fixed routes according to a strict timetable.

Punctual transport requires these ships to be capable of high speeds of 17 to 20 knots (kn), which is why they are usually designed with slim hulls. Low fuel costs contributed to even higher speeds of up to 30 kn, and this was a substantial factor in enabling ships' engines to reach top installed power outputs of up to 80,000 kW. However, in recent years, the significant fuel price rises and an ongoing shipping crisis have led to a considerable reduction in the speed of container shipping (slow steaming) and hence also a return to low installed power outputs.

Germany plays an important part in container shipping, as the biggest share of the world's container ship owners and operators is registered there.

Bulk carriers

About a third of worldwide sea transport is undertaken by bulk carriers. The unpackaged goods such as ore, coal or grain are called bulk goods. As this form of transport involves a continuous flow of goods (individual pieces of ore do not have to arrive at their destination promptly), high transport capacities and many ships are required, but high speeds are not. Bulk carriers therefore reach average speeds of 13 to 15 knots.

Bulk carriers are designed with the maximum possible displacement for the given dimensions, which results in very broad hulls. However, because of the low speeds, the required power outputs are relatively low. Bulk carriers are classified by load capacity. Common categories are: Handysize bulkers up to 40,000 DWT, Supramax bulkers up to 60,000 DWT, Panamax bulkers up to 100,000 DWT and Capesize bulkers from 100,000 DWT.

Oil tankers

The basic conditions for oil tankers are the same as for bulkers: The cargo is not a fixed-deadline commodity, but a continuous flow of goods to be maintained, which requires only low speeds and a high deadweight tonnage.

However, there are special structural requirements for ships carrying liquids. The movement of liquids in partially filled tanks can have a very destabilising effect, even at slight angle of list. Environmental and safety requirements must also be taken into account. This is manifested in the arrangement, design and filling of the tanks, in double hulls and in adequate transverse strength and an enclosed upper deck.

The tanker size classifications are similar to those for bulk carriers: Coastal tankers from 10,000 DWT, Aframax tankers up to 119,000 DWT, Suez-Max tankers at approximately 240,000 DWT, very large crude carriers from 200,000 DWT and ultra large crude carriers from 320,000 DWT.

Passenger ships

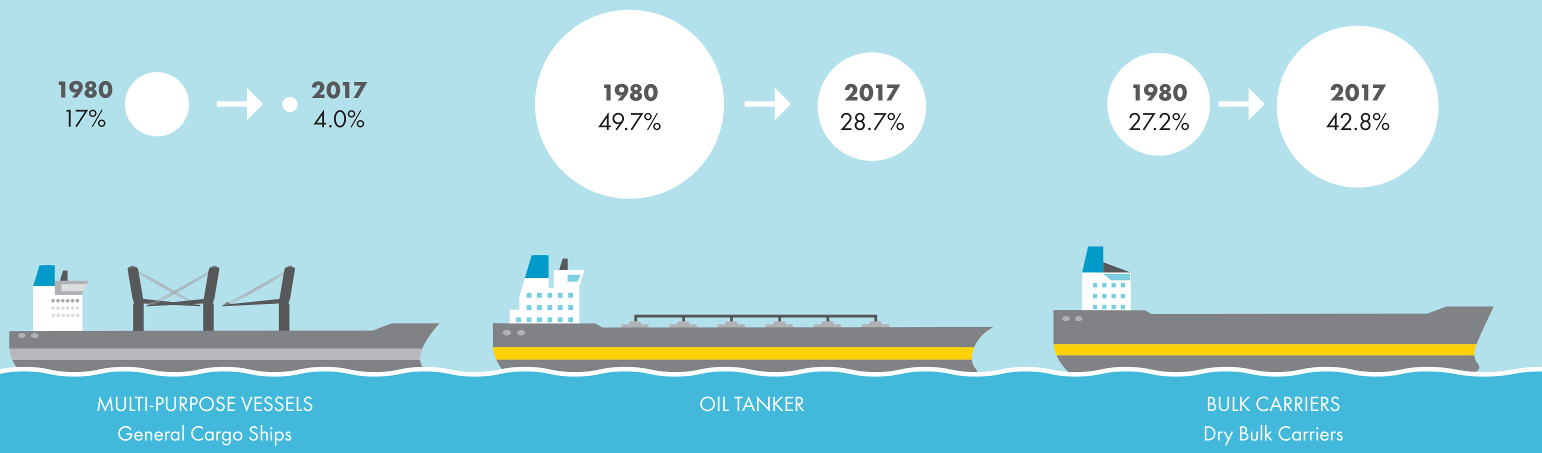
Cruise liners and ferries are used for passenger transport. However, there is a significant difference between the two types of ship. While ferries, some of which carry only passengers and some both passengers and vehicles (RoPax), are means of transport, a cruise liner caters for the leisure requirements of its passengers.

Ferries are therefore designed to transport their cargo quickly and efficiently, while cruise liners operate energy-intensively to provide a range of gastronomic options and leisure activities, whereas locomotion can be of secondary importance.

However, something common to both types of ship is that they are directly associated with the transport services they deliver to their customers. Therefore, they are under pressure to make progress on environmental and health-related issues. A very important, even pioneering, role in the use of alternative means of propulsion and fuels such as LNG is therefore assigned to this type of ship, even though the absolute number of these ships in the total shipping fleet is rather small.

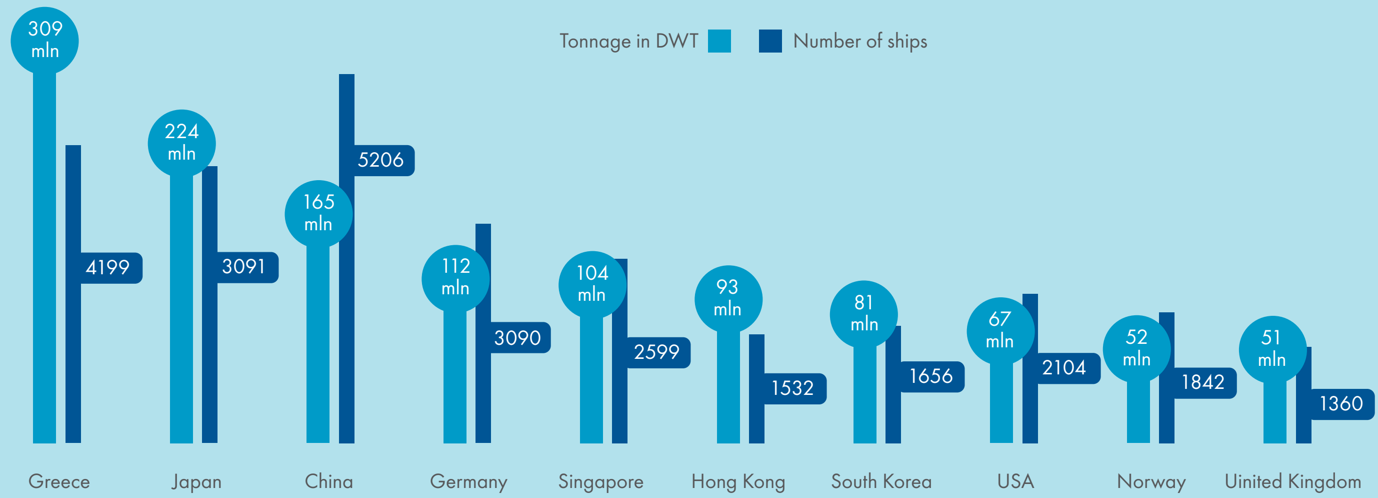
26 TYPES OF SHIP AND THEIR SHARE OF TOTAL GLOBAL DEADWEIGHT TONNAGE (DWT), 1980 TO 2017

UNCTAD 2017; own diagram



27 TONNAGE AND NUMBER OF SHIPS BY COUNTRY, 2017

UNCTAD 2017; own diagram

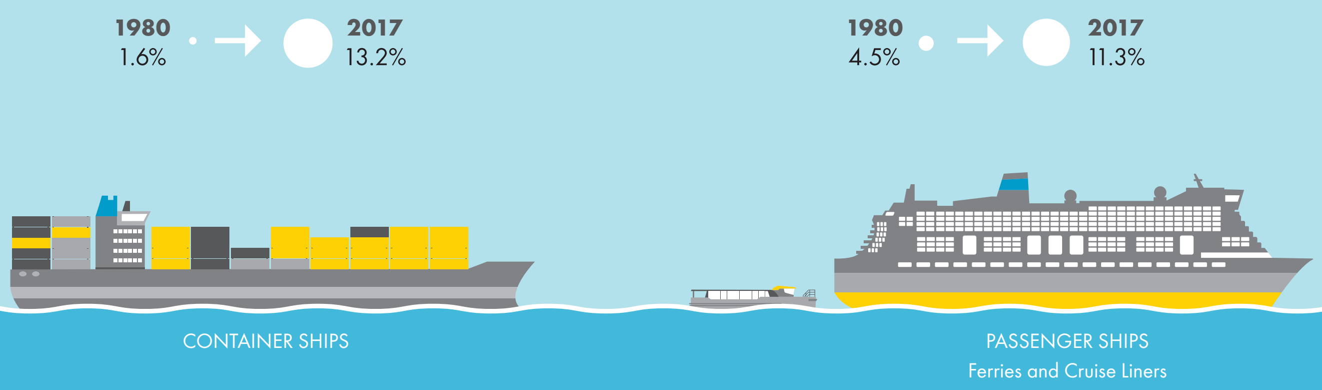


Global merchant fleet

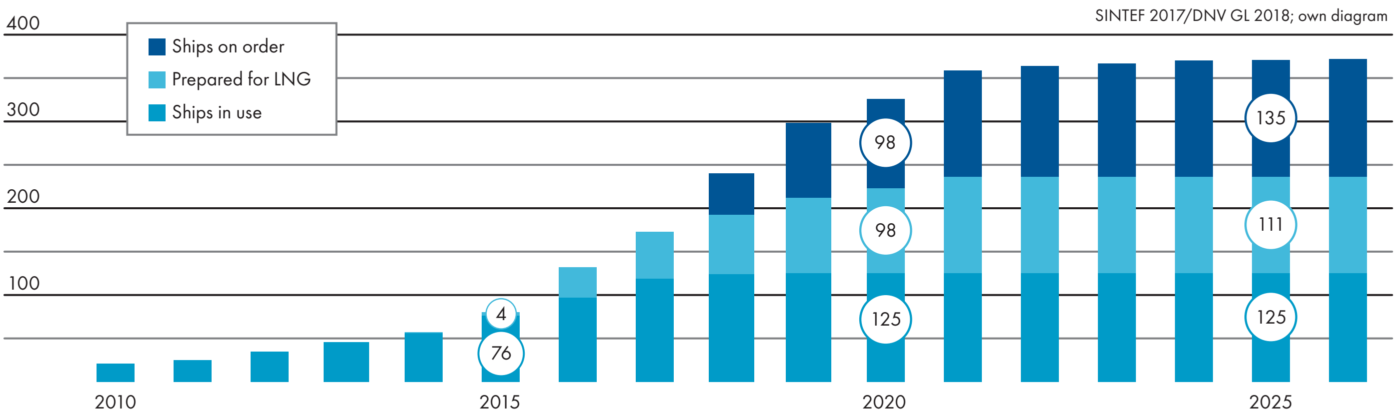
The global merchant fleet currently (2017) has a total deadweight tonnage (DWT) of over 1.9 bn t distributed over around 93,000 ships. Bulkers and tankers combined account for about 23 % of the fleet and 71 % of the total deadweight tonnage (figure 26). Container ships make up only 5 % of the merchant fleet, although they account for around 13 % of its deadweight tonnage (UNCTADstat 2018). Around half of the fleet falls into the category "others", which includes 4,428 passenger ships and ferries and 458 cruise liners (DM 2017).

The number of ships has grown significantly in recent years. In the past 15 years the deadweight tonnage has more than doubled (UNCTADstat 2018). The fact that the gross tonnage is rising faster than the number of new ships indicates that there is a trend towards larger ships.

The average age of the global merchant fleet is around 20 years. Taking into account that a large share of the total fleet is newly built, a lifetime of 30 years is therefore entirely possible for individual ships. Around 5,000 new ships are added to the fleet every year and fewer than 2,000 are scrapped.



28 DEVELOPMENT OF THE LNG SHIPPING FLEET



The main ship-building nations are South Korea, China and Japan, while scrapping is concentrated in India, Bangladesh, Pakistan and China. Since more ships are registered than scrapped, the worldwide merchant fleet is growing, albeit with considerable fluctuations (UNCTAD 2017).

The major ship-owning nations by number of ships are Greece, Japan and China followed by Germany and Singapore (figure 27). China has the largest merchant fleet with 5,200 ships. The five largest shipping nations control more than half of the worldwide cargo ship capacity (in DWT).

LNG ships

Compared to the size of the global merchant fleet, the number of LNG ships is still small (figure 28). What does the LNG fleet look like today, and what are the developments in the registration of new LNG ships?

LNG ship fleet

125 LNG-fuelled ships, i.e. ships not transporting LNG but only using it as a fuel, were operating worldwide at the end of 2018. Another 230 or so LNG tankers or LNG carriers (LNGCs) are generally fuelled by boil-off gas, which forms during the transport of LNG (UNCTAD 2017; DNV GL 2018).

LNG is becoming increasingly attractive for shipping because of its low-emission characteristics, particularly when used in Otto combustion engines. This is especially true for ships that operate primarily in emission control areas (ECAs) and hence in coastal waters.

Taking tank construction (pressure-resistant tank for cryogenic liquids) into consideration, the energy density per unit volume of LNG is about a quarter that of a comparable diesel fuel. This poses a major challenge for the use of LNG as a fuel for ships, as it significantly reduces a ship's usable volume.

The tank volume required is determined essentially by the power of the engine and the range of the ship. Passenger ferries, which travel short distances and thus only need small bunker capacities or tank volumes, are therefore a particular focus for LNG.

Around a quarter (33 ships) of the existing LNG-powered fleet are passenger ferries operating primarily in Northern Europe. Tugs, which only operate within small areas, are already represented on the market with ten ships. In addition to these, there are also ten tankers and three multi-purpose vessels fuelled by liquefied natural gas worldwide (DNV GL 2018).

The remaining LNG-powered ships are other types of ship operating over short distances and are usually pilot projects. These will help the customers, shipyards, engine manufacturers and suppliers to gain experience with LNG. They include the first LNG-fuelled patrol boats, the first icebreaker with a hybrid propulsion system (both Finland), small container ships (feeders), smaller bulk carriers, special-purpose ships and RoRo ferries (DNV GL 2018).

The world leader for the use of LNG-fuelled ships is Norway, with 61 ships in operation, which is around half of the existing global fleet. Norway is not only the largest gas producer in Western Europe, but also already has the infrastructure for bunkering LNG and, more importantly, statutory regulations and financial incentives for the use of LNG, which have been put in place by the government.

In addition to the Norwegian LNG fleet, the EU-wide fleet of around 23 LNG ships accounts for about 18 % of existing LNG-fuelled seagoing ships worldwide. The number of LNG-powered ships in the US maritime transport fleet has also risen to 17 since 2012. By contrast, there are only seven LNG-powered ships operating in Asian waters.

Construction of new LNG ships

136 orders have already been confirmed for the construction of new ships with an LNG propulsion system by 2026. Although the existing fleet is dominated by ferries operating regionally, the shipyards' order books demonstrate a growing specialisation and a trend towards larger ships such as oil and chemical tankers, container ships and cruise liners. 12 of the 136 new orders already verified are conversion projects, primarily ferries.

According to the order figures, the increase in the ferry sector will come to a halt for the time being with the delivery of the latest 14 ferries at the end of 2018, when the global ferry fleet will include 47 ships with an LNG propulsion system (DNV GL 2018). The growth in the tanker sector accounts for 25% of new ships (33 LNG ships) and container ships of 15% of new ships (21 LNG ships) up until 2021. Given that there are over 5,300 container ships operating worldwide, LNG-powered ships only account for a small proportion of the container fleet (DM 2017).

Another market which opened up to LNG as an alternative fuel in 2018 is the cruise liner sector. By 2024, 23 of the 270 or so cruise liners operating globally (CLIA 2017) will be powered by LNG; that is a significant share of new ships.

Furthermore, interest in using LNG as a fuel is growing, particularly in the short-sea and special-purpose shipping sector. In addition to 14 special-purpose ships, such as dredgers, fishing boats, offshore installation vessels and coastguard and research vessels, the shipyards will deliver another five LNG-powered tugs by 2020.

The outlook for new ships in the future is influenced by the distribution or position of the Emission Control Areas (ECAs). The waters of Northern Europe are an ECA and hence subject to strict emission regulations. This explains why a total of 73 additional newbuild orders have been placed for these shipping areas (including Norway). In US coastal waters, the number of LNG-powered ships in the fleet will double to 28 by 2024 (DNV GL 2018).

The total number of ships operating worldwide, both new and converted, that can be powered by LNG has risen to 94 as a result of increased orders for container ships, tankers and cruise liners.

If the number of existing LNG ships is combined with the number of currently known LNG newbuilds and LNG ready vessels (ships that can be converted to LNG), around 400 ships will be powered by LNG by the middle of the 2020s (DNV GL 2018).

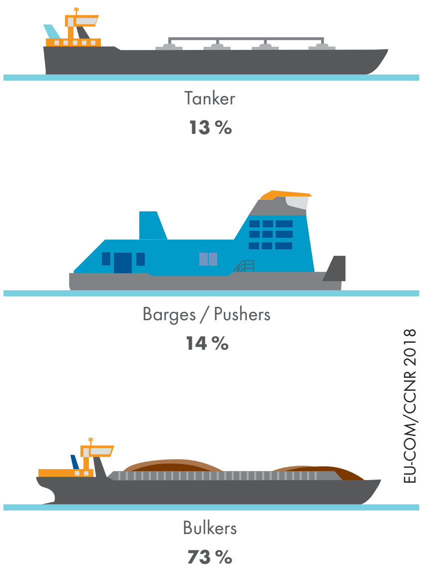
Inland navigation ships and LNG

The European inland navigation fleet currently has a total of 13,500 ships (including tugs and barges) with a loading capacity of 17 mln t. Most of these ships are in European inland navigation vessel categories IV and V (figure 30): The Large Rhine vessel designed in lengths of 110 to 135 m and capacities of 3,000 to 4,000 t or approximately 200 to 270 containers, and the Rhine-Herne canal vessel, which is 85 m long with a capacity of 1,500 t or 100 containers (CE Delft 2017; BVB 2019).

European inland navigation is focused primarily on the Rhine (85%) and Danube (15%) regions, with around 10,000 ships operating in the Rhine Basin and just over 3,000 in the Danube Basin. More than half of the Rhine fleet operates under the Dutch flag and more than half of the Danube fleet under the Romanian flag.

While a broad range of cargo, from building materials and energy resources to containers, is transported on the Rhine, steel and agricultural products dominate on the Danube. Consequently, nearly three quarters (73%) of the EU fleet consists of cargo ships; the remaining 27% is divided almost equally between tankers and tugs and barges. Tankers are particularly common on the Rhine, because of the chemical and petroleum industries located there (EU-COM/CCNR 2018, ZKR 2018).

29 TYPES OF SHIP AND THEIR SHARE OF EU INLAND NAVIGATION, 2015

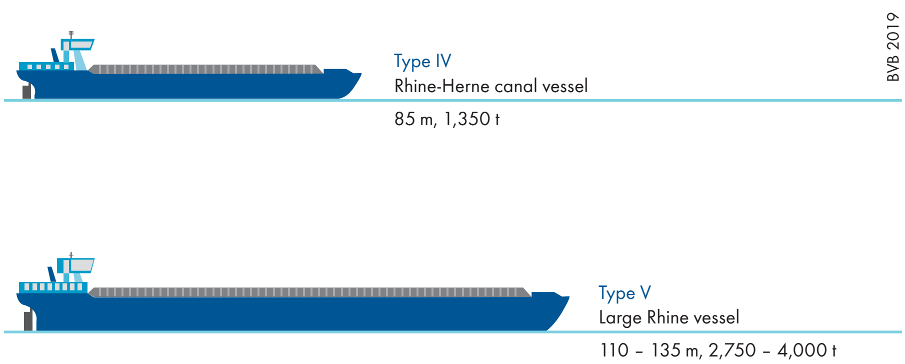


Inland navigation ships are generally very old. More than half of the ships in Belgium, the Netherlands and Germany are older than 50 years and more than 15% of them are older than 75 years. The Danube fleet is slightly newer, although the average age varies considerably from country to country.

The number of ships has declined slightly in recent years. However, as the new ships are becoming larger, the tonnage per ship has been increasing and currently stands at an average load capacity of 1,250 tons.

The annual number of new ships built in the last few years was well below one

30 MAIN TYPES OF INLAND NAVIGATION SHIP



hundred in some cases. Half of these were passenger ships or cruise liners. There has been a slight increase in the number of new ships built recently.

The number of river cruise ships has doubled in the last 15 years and now stands at around 350. More than two-fifths of these cruise ships have been built since 2010; more than 150 of the European river cruise ships are registered in Switzerland (ZKR 2018).

Investment in environmental measures for new cruise ships, such as improved efficiency, exhaust gas cleaning or alternative propulsion systems and fuels, is also on the increase, with particular attention being paid to air pollutant emissions. A combination of selective catalytic reduction and particulate filters, or alternatively an LNG propulsion system, are needed to comply with the Stage V EU exhaust gas requirements which are applicable from 2019 for inland navigation vessels (2016/1628/EU; EP/Council 2016b). As with seagoing ships, passenger ships are ahead of cargo ships when it comes to investment in environmental protection.

At present, there are **five LNG-powered inland navigation vessels** in use on European waterways. Four of these are chemical or LNG tankers and one is an inland container ship (OEIN 2018). The increased use of LNG in inland navigation is beset by technical, regulatory, infrastructural and financial obstacles. The binary operating profiles (inefficient use of dual fuel engines when travelling downstream, high power demand when travelling upstream) of inland navigation are technically challenging. Standard guidelines for the use and transport of LNG in inland navigation are still being developed. There are still too few bunkering stations and, in addition, a sector dominated (to approximately 80 %) by small and medium-sized enterprises is faced with the increased cost of building new ships or retrofitting old ones, with correspondingly long amortization periods.

The cost of LNG propulsion systems must fall significantly if they are to be used more widely. The LNG infrastructure for inland navigation is supported by Directive 2014/94/EU on the deployment of alternative fuels infrastructure (the EU AFID) and the EU action programme NAIADES for the promotion of European inland navigation. The NAIADES programme, in particular, promotes LNG propulsion systems for inland navigation, since they promise to achieve the best results in relation to the future Stage V exhaust emission standards under Directive 2015/1628/EU (EU-COM 2013).

Retrofits

New ships can be designed to be "**LNG-ready**". These ships have the on-board infrastructure to use LNG; besides a suitable engine, that includes the ability to store natural gas in liquid form, the necessary pipe and monitoring systems and a safe structural ship design (see for example ABS 2014). Thus subsequent conversion from heavy fuel oil or marine diesel to LNG is facilitated.

Besides building new ships, the fleet of LNG-powered ships can also be expanded by retrofitting. However, to date, only around 1 % of the merchant fleet has been classified as suitable for retrofitting, although there are more at the planning stage (UNCTAD 2017).

However, the conversion of existing ships to LNG-based propulsion systems is expensive and will only make a small contribution to the environmental compatibility of the existing fleet. Besides the space required for the insulated and pressure-resistant tank, which is four times that of a conventional diesel fuel tank, for the same energy content, the space required for gas treatment and the additional conditions imposed by the safety requirements for the position of the tank, conversion of the engines is an extremely challenging business. The retrofitting of diesel engines to run on natural gas requires fundamental structural modifications and is generally accompanied by a loss of power.

Furthermore, the limits for nitrogen oxides and greenhouse gases apply only to new ships, so the incentive for the operational fleet to retrofit originates only from the reduction of sulphur oxide emissions. However, the limits can also be achieved by using more expensive, but low-sulphur, marine fuels (marine gasoil or low sulphur fuel oil). LNG retrofits are therefore most suitable for subsidised projects.

4.2 SHIPS' PROPULSION SYSTEMS

The most common method of propulsion for ships to date has been the diesel engine powered by heavy fuel oil or marine gasoil. This section will first discuss the principal designs for today's ships' engines before examining more recent developments with LNG-powered gas engines.

Propulsion system designs

The power required by ships for energy provision and propulsion can be provided essentially by three different energy converters: slow speed two-stroke engines, medium speed four-stroke engines and turbines. Ships can also use combinations of these types of propulsion.

Container ships, bulkers and tankers are now almost exclusively powered by **slow speed two-stroke engines**. Since they operate at low speeds of 60 to 200 (revolutions per minute) rpm, these engines are connected directly to the ship's propeller by an intermediate shaftline. On-board power is generated by smaller auxiliary units (four-stroke engines with a generator). With an efficiency level of over 50 %, slow-speed two-stroke engines are the most efficient, and thus consume the least fuel (figure 31). No other heat engine known in engineering is more efficient.

Medium-speed four-stroke engines are more compact than two-stroke engines, for the same power output. Where space is limited, for example on ferries, large tugs and smaller container ships, a slightly higher fuel consumption is an acceptable trade-off for the small footprint of the construction. The rotational speed ranges from 300 to 800 rpm and is adjusted by a gear on the ship's propeller, which is designed as a controllable pitch propeller, with adjustable blades.

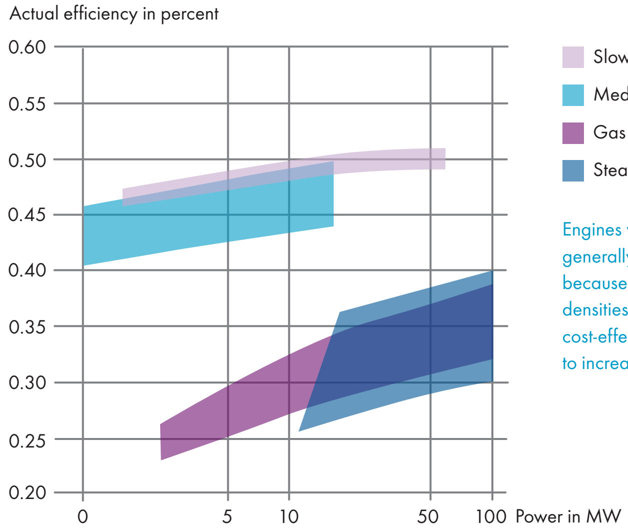
The electrical power required on these ships is usually provided by generator sets (diesel engines with generators), which consist of smaller four-stroke engines directly connected to generators. However, it is also common to connect a generator to the gear of the prime mover, which then drives it. This solution is efficient and saves running hours of the installed generator sets while the ship is in transit, but it does have the disadvantage that the entire propulsion system must be operated at constant speed for technical reasons, which is inefficient, particularly when the ship is moving at low speeds.

For these standard **diesel-mechanical** configurations it is indispensable to locate the internal combustion engines very close to the propeller. However they are extremely efficient and can be found on almost all seagoing cargo ships.

By contrast, **diesel-electric (DE)** propulsion systems have become widely established on ships that require a higher level of operational flexibility and need more electrical power than propulsion. Cruise liners are an example of this and are almost exclusively equipped with DE propulsion systems today. With these systems, large four-stroke engines are connected directly to generators to generate electricity. The electrical power generated is sufficient both for the operational requirements of the hotel operations, and to drive the propeller. Instead of diesel prime movers these systems use electrical engines to drive the propeller. However the advantage of operational flexibility is offset by the low overall efficiency, because the propulsion is subject to conversion of mechanical and electrical power and vice versa.

Piston engines, particularly diesel engines, now dominate, accounting for over 90% of ship propulsion systems. while **turbine**

31 EFFICIENCY OF SHIP ENGINES



Engines with a high power rating are generally slightly more efficient, both because they have higher specific heat densities and because it is more cost-effective to take complex measures to increase their efficiency.

propulsion systems are a niche solution. Although steam turbines were still used as a means of propulsion in the second half of the twentieth century, they were replaced by diesel engines because of their low efficiency and complex boiler operation. Natural gas or diesel-powered piston engines are now used even in LNG carriers, the last refuge of the steam turbine.

Gas turbines, which are lighter and more compact than steam turbine systems, but even less efficient, are now only used where their advantages are indispensable, particularly in naval ships and very light, fast ferries. In naval ships they are usually used in addition to conventional diesel engines to provide additional propulsion for high speeds, since the high fuel consumption is irrelevant during the short periods of operation required for escape.

The combined gas and steam turbine systems used in power plant engineering achieve particularly high overall efficiency rates of up to 60%. These systems could also be used on ships. So far, the fact that gas turbines cannot burn sulphurous heavy fuel oil has been a stumbling block for these projects; and in fact only large diesel engines are suitable for this. However, the potential to use natural gas or other low-sulphur fuels would give new impetus to these efforts. The PERFECtShip study is investigating this kind of application using the example of a container ship (DNV GL et al. 2017).

Natural gas engines

Since the beginning of this century an engine design has come into widespread use for LNG tankers, which allows them to burn diesel fuel and gas alternately (**dual fuel engines**). This design has gradually replaced the conventional gas-powered steam turbines. This is mainly due to the fuel savings (IGU 2018). Experience from using natural gas as a fuel on LNG carriers is now being put to good use in **gas-fuelled ships**, which do not carry natural gas as cargo, but only as fuel. Lower emissions are often a major driver for this.

Natural gas as a fuel differs from diesel and heavy fuel oil both because it is gas, and because it is less flammable and has limited knock-resistance. This makes it unsuitable for combustion in a diesel engine, which operates by injection of a liquid fuel into the compressed charge air at high pressures, followed by auto-ignition of the fuel. Instead, natural gas needs a source of ignition, as is usually required in a spark-ignited combustion engine.

Regardless of how the mixture is formed (outside or inside the combustion chamber), a natural gas engine needs either a spark

32 CURRENT DESIGNS FOR GAS-POWERED SHIP ENGINES

	Two-stroke		Four-stroke	
	DF Otto	**DF Diesel**	**DF Otto**	**Gas engine**
Ignition	Pilot injection	Pilot injection	Pilot injection	Spark plug
Minimum methane number	65	N/A	70	70
Maximum cylinder power	5,320 kW	6,100 kW	1,150 kW	475 kW
Combined mode possible?	Yes	Yes	Yes	No
IMO TIER III diesel	With EGR / SCR	With EGR / SCR	With EGR / SCR	N/A
IMO TIER III gas	Yes	With EGR / SCR	Yes	N/A
Methane slip	Yes	Negligible	Yes	Low

Caterpillar 2015; SINTEF 2017; Win GD 2015, 2018; MAN B&W 2018

plug or pilot injection, which is the common method for large engines. This consists of a small amount of diesel, which is ignited by the hot, compressed air and supplies the energy to ignite the natural gas-air mixture. The latter process is particularly suitable for dual-fuel engines.

The **low-pressure technology** is now commonly used in four-stroke engines and is the closest to the Otto combustion process. In gas mode, the natural gas is added during the intake stoke, compressed and then ignited by pilot injection.

The same process can be used in two-stroke engines, when gas intake occurs during pressurised gas exchange. However there is also a process closer to the diesel process, in which the natural gas is compressed with **high-pressure compressors**, injected after compression and then ignited immediately by pilot injection.

The two concepts have different advantages and disadvantages in terms of efficiency, knock-resistance and nitrogen oxide and particulate emissions. While the low-pressure process has low nitrogen oxide and particulate emissions because a homogeneous mixture is formed, the high-pressure (diesel) process is notable for its high efficiency and is independent of the knock resistance of natural gas.

Dual-fuel engines allow ships to operate in natural gas mode by one of the processes referred to above, and conventional diesel mode with liquid fuel. At present, this is a major advantage for ships operating worldwide, as the LNG bunkering infrastructure is still patchy.

However, on the down side, realization of both combustion processes requires a lot of technical and cost-intensive work. The knock-resistance of natural gas in pre-mixed mode (i.e. Otto process) necessitates somewhat lower compression ratios than those required for optimum efficiency in diesel mode. In addition, dynamic load changes are limited because of the increased tendency to knocking and the dependence on the air-fuel ratio. The air-fuel ratio changes with every load change, which results either in misfiring with increased methane slip and even engine failure, or a mixture that is too rich, causing knocking and possibly engine damage. However, current technology allows seamless switching between gas and diesel mode and mixed operation is also an option, particularly for LNG tankers.

Dual-fuel engines, unlike pure gas engines (which are Otto engines) can only be optimised for methane slip to a limited extent, and therefore have higher rates of methane slip than gas engines.

And, in the end, the classification bodies do not consider gas mode to be as reliable as diesel mode. As a result, dual-fuel engines can be used alone (particularly in single-engine systems), but with diesel mode providing back-up to ensure reliability. Pure gas engines, on the other hand, must be duplicated to comply with the redundancy requirements.

Table 32 gives an overview of the current engine designs that can be used as marine propulsion systems fuelled by natural gas. There are two designs for large slow-speed two-stroke engines, offered by two market competitors: The first is a **dual-fuel (DF) Otto engine**, in which gas is added to the charge air at low-pressure during gas exchange and the mixture is then compressed. Diesel fuel pilot injection is then timed to producing combustion.

The second is a **dual-fuel Diesel engine**, which operates in a similar way to the diesel process: The natural gas is injected into the already compressed air under high pressure just before ignition is required and ignited almost immediately by pilot injection. The principles of the premixed combustion process result in nitrogen oxide values that are lower than with the diesel-like process, but the early mix formation produces high levels of natural gas respectively methane slip. Both types of engine are able to operate in diesel mode alone, with liquid fuel, and in combined mode with both natural gas and liquid fuel.

The first type of medium- and high-speed four-stroke engines is the **DF Otto** engine, which uses the premixed combustion process in gas mode (mix intake and external source of ignition); the external source of ignition is provided by pilot injection. These DF Otto engines also produce a certain amount of methane slip because of the premixed combustion principle, but the nitrogen oxide emissions are very low. They can also operate in diesel mode with conventional liquid fuel. The second type is pure **gas engines**, which are designed according to the conventional SI combustion principle with a spark plug. These engines are consistently optimised for gas mode – unlike the DF engines, which have to fulfil the requirements for both gas and diesel mode, which means that their methane slip values are slightly lower.

Engines that operate by Otto process must use natural gas with a minimum methane number to prevent knocking. The manufacturers specify different minimum values, but a reduction in power must be expected when gas grades used fall short of required methane numbers. Operation at full power, on the other hand, generally requires a minimum methane number of around 80.

The most common engines on modern gas-fuelled ships are low-pressure, medium-speed, dual-fuel four-stroke engines, which are used on all ships, but particularly in the offshore sector. Small four-stroke gas engines, which use a spark plug for ignition, are almost as common, particularly on gas-powered ferries. This engine design is preferred in Norway after positive experiences (SINTEF 2017).

Ships have only recently started using low-pressure two-stroke engines. However, like high-pressure two-stroke engines, they offer a good propulsion solution for large container ships.

Gas turbines are rarely used on gas-powered ships. Since the LNG supply infrastructure is still patchy, it will be essential for ships to be able to run on conventional liquid fuels for the time being.

4.3 EMISSIONS

Most ships today use Diesel engines and consume heavy fuel oil or marine gas oil as fuel. They contribute a significant amount to the emission of transport-related air pollutants. The sooty particulate emissions from ships' engines are particularly high, as the presence of sulphur promotes the formation of large (and hence high-mass) particulates and there are currently no particulate filters capable of handling them. Shipping also produces much higher levels of other air pollutant emissions today than road transport or stationary facilities onshore, for example; this is because the technical exhaust cleaning systems used in power plants and road transport have only been promoted and implemented in shipping relatively recently.

Shipping also produces greenhouse gas emissions when burning primarily fossil energy sources. International maritime transport is responsible for an estimated 2.8 to 3.1 % of global CO_2 emissions

33 MARITIME EMISSION CONTROL AREAS

(IMO 2015). The current trends in the main shipping-related air pollutant and greenhouse gas emissions and the relevant regulations are discussed below.

Air pollutants

Since the end of the 1990s the Marine Environment Protection Committee (MEPC) of the International Maritime Organisation (IMO) has gradually introduced mandatory limits for emissions from seagoing ships. The first compulsory regulations to limit pollutants in exhaust emissions were established in 1997 in Annex VI to the **International Convention for the Prevention of Pollution from Ships** (MARPOL); these exhaust regulations were revised in 2008 to make them tougher. The exhaust emissions limited internationally include nitrogen oxides (NO_X), particulate matter (PM) and sulphur oxide (SO_X).

Particularly densely populated coastal areas must be protected from air pollution. Various global and local emission limits are therefore already in place. The **Emission Control Areas (ECAs)** were designated by the IMO as special zones with stricter environmental regulations, which place particularly tough restrictions on the emission of sulphur oxides (sulphur ECA), nitrogen oxides (nitrogen oxide ECA) and in some cases also particulate matter.

The ECAs currently include the whole of the North and Baltic Sea region (including the English Channel), the waters off the east and west coast of North America, including Hawaii, Canada's Great Lakes and the coastal waters of Central America.

There are considerable differences between the restrictions in each area: While the limits for sulphur oxides are based on the sulphur content of the fuel and apply to all ships within the ECA, the limits for nitrogen oxides are based on power output and apply only to ships built after the limits came into effect, which operate in the ECA. The particulate limits currently apply only within US coastal waters subject to restrictions imposed by the US Environmental Protection Agency (EPA) and apply to all ships in those waters.

While the North and Baltic Sea region is currently subject to sulphur oxide and nitrogen oxide emission limits, which will become even stricter in 2020, particulate emissions have so far been unregulated. This is partly due to the continuing disagreement about whether the particulate mass or the number of particularly fine particulates in this emission group should be limited and what method should be used to measure them.

In addition to the IMO rules under MARPOL Annex VI, the other European coastal waters are subject to the **Sulphur Directive** (2016/802/EU) adopted by the European Commission in 2012 to reduce the sulphur content in marine fuels from 3.5 to 0.5 % by January 2020.

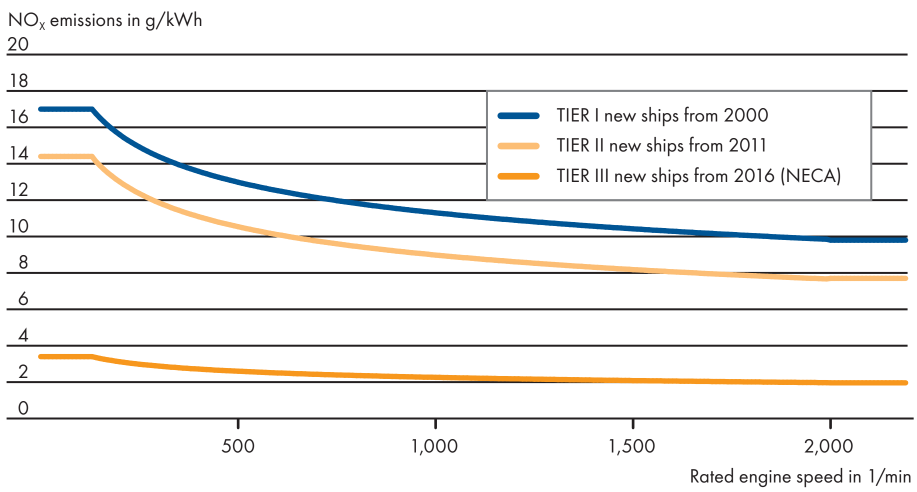
The nitrogen oxide emissions from ships' main and auxiliary engines are limited specifically in relation to their power output. Nitrogen oxides are formed during combustion in an engine from oxygen and the nitrogen added with the combustion air. The principle here is that the better the combustion, the higher the temperatures and the more NO_X is formed.

The nitrogen oxide emissions are highly dependent on the temperature and homogeneity of the mixture in the combustion chamber. Direct, high-pressure injection (the diesel process) with natural gas as a fuel does not result in a significant NO_X emissions reduction compared to diesel as a fuel. However, compression of a homogeneous natural gas and air mixture (SI combustion process) can produce significantly lower nitrogen oxides emissions. Depending on the engine design, additional measures such as catalytic reduction of nitrogen oxides or exhaust gas recirculation are therefore needed to comply with NO_X limits. As there is more time for combustion (fewer combustion cycles per unit of time), and hence for nitrogen oxide formation, in low-speed engines, higher specific limits are allowed for these engines; the limit therefore depends on the rated speed of an engine (see figure 34).

There are also two tiers of limits, which depend on the region of operation and the entry into force of the regulation respectively the date of commissioning or construction of the vessel: The IMO TIER II emission standard (introduced in 2011) is laid down in Regulation 13 of MARPOL Annex VI and applies worldwide; the emission requirements can be met by primary combustion measures.

However, since 2016, the ECAs have been subject to stricter nitrogen oxide emission limits which will also apply to the North Sea and the Baltic from 2021. The limits laid down in TIER III are up to 70 % lower than those in TIER II and

34 NITROGEN OXIDE EMISSION LIMITS



require exhaust gas recirculation, special exhaust gas aftertreatment measures or alternative engine designs. Natural gas is a particularly suitable option here, as the emission values achieved in Otto-cycle combustion process engines meet the strict requirements of TIER III.

Another relevant type of shipping-related air pollutant emissions are sulphur dioxide emissions (SO_2). It is estimated that ships generate between 5 and 10% of worldwide sulphur dioxide emissions of human origin, equivalent to an average of 7 to 15 mln t of SO_2 a year. That is two to three times the worldwide sulphur dioxide emissions of road transport, even though there are many more motor vehicles than ships (ITF 2016).

Unlike nitrogen oxide emissions, the sulphur oxide emissions are limited by regulations on the constituents of fuels, since the formation of sulphur oxides during combustion depends on the amount of sulphur in the fuel. Under the MARPOL Annex VI regulations, the content of sulphur in marine fuel will be reduced from a maximum of 3.5% today to only 0.5% (by mass) worldwide from 2020. Limits of 0.1% have applied to the sulphur content of fuel in the Emission Control Areas since 1 January 2015. These requirements make it necessary to use low-sulphur fuel.

The alternative is to use **scrubbers**. These secondary processes spray a mixture of water and sodium hydroxide or magnesium oxide into the exhaust system. The sulphur oxide content of the gas can be reduced by up to 95% as it rises through this mixture. The contaminated wash water is collected and cleaned for re-use. The sulphurous residues are either released into the sea in very dilute form or stored on board and disposed of properly on shore (figure 35).

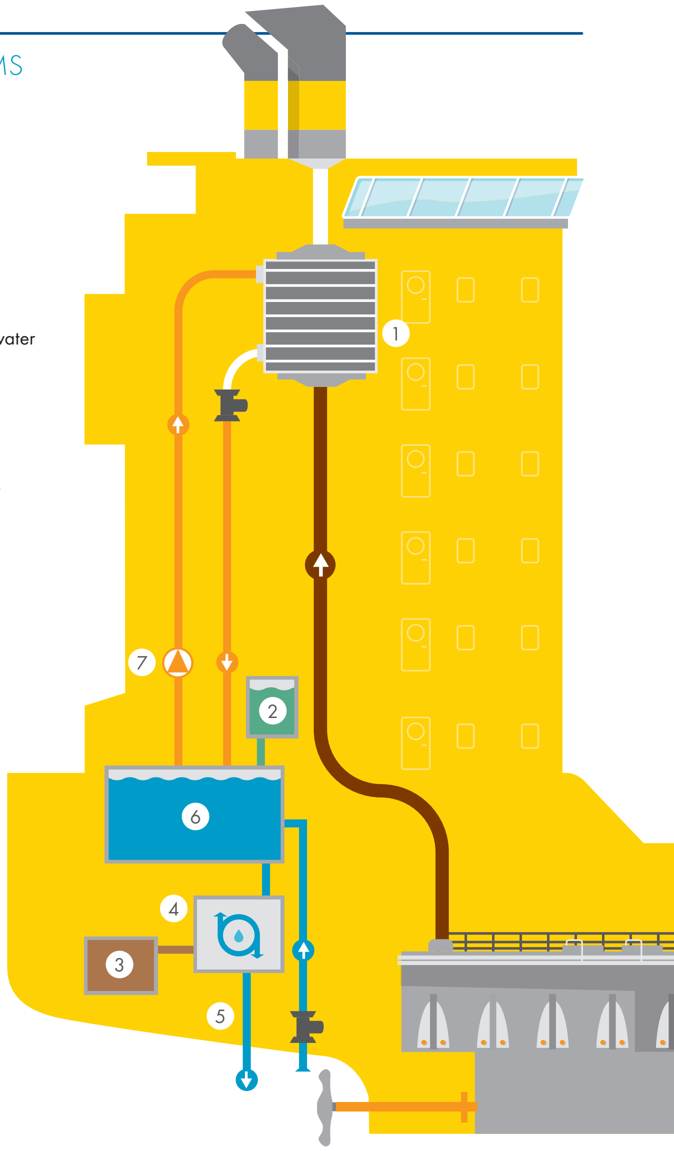
A positive side effect of scrubbers is that they also remove particulates effectively. However the exhaust gas is cold and wet when it leaves the scrubber, so there is no exhaust heat that can be reused.

35 WET SCRUBBER-SYSTEMS

1 Scrubber
2 Caustic soda tank
3 Sludge tank
4 Waste water treatment
5 Discharge of cleaned and neutralised water
6 Circulation tank
7 Circulation pump

The scrubber is operated with fresh water. The water charged with sulphur compounds is then neutralised with caustic soda and cleaned, before being recirculated to the scrubber.

If the absorption capacity is exceeded, some of the water is removed and replaced, cleaned again and stored temporarily in a tank, before being disposed of in suitable waters or on shore.



Greenhouse gases

There have been no direct restrictions on shipping-related greenhouse gas emissions to date, however the energy efficiency of ships is also regulated by the IMO Regulations on Energy Efficiency for Ships, under which greenhouse gas emissions are also reduced.

This potential for greenhouse gas reduction has been promoted by the Energy Efficiency Design Index (EEDI) for new ships since 2011 (figure 36). In addition to the EEDI, the Energy Efficiency Operational Index (EEOI) is a monitoring tool that will simplify the evaluation of fuel efficiency and the management of the fleet and provide a basis for measures to improve efficiency. Since the EEDI applies only to new ships, it will take some time before it produces any noticeable improvement in fuel efficiency,and, quite apart from that, it applies only to specific types of ship.

A 2014 greenhouse gas study published by the IMO (IMO 2015) holds out the prospect of **CO_2 emission reductions of at least 40% by 2030 and at least 50% by 2050** as compared with 2008 (figure 37, IMO 2018a). Since January 1 2019, all large ships (over 5,000 GT) have been obliged to document consumption and emission values. The data recorded is assessed by the IMO annually. A strategy containing short-, medium- and long-term measures, such as the development of low-CO_2 fuels, will be published in spring 2023. This will confirm or correct the greenhouse gas targets for shipping set in 2014.

This is also supported by EU Regulation 2015/757/EU on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport (EP/Council 2015b), which came into effect in 2018.

With regard to shipping-related greenhouse gas emissions, particular attention is paid to emissions from gas engines. Methane, the main component of natural gas, produces up to 32 % less direct CO_2 emissions on combustion than heavy fuel oil. Unfortunately, this advantage is partly cancelled out by **methane slip** in the engine. Methane slip is the term for the unburned methane in the exhaust gas. During compression in the cylinder, some of the mixture is pressed into the small gap between the piston and the piston skirt, where there is no combustion. As soon as the pressure drops in the cylinder, the mixture flows back out of the gaps and mixes with the general exhaust gas stream. Direct injection (the diesel cycle) produces less methane slip than the Otto combustion process, as the gaps are only filled with air, so the methane slip is identical to the very low fuel slip when operating with a liquid fuel.

The methane slip that occurs particularly in Otto combustion processes must be converted using the global warming potential factor for methane (F), which was 25, but has recently been increased to 30 (IPCC 2013). The additional methane emissions must be added to the CO_2 emissions. This produces the following total greenhouse gas emissions: GHG = CO_2 + F * CH_4. Methane slip of 1 % therefore reduces the advantage of lower direct CO_2 emissions when burning natural gas by around a quarter.

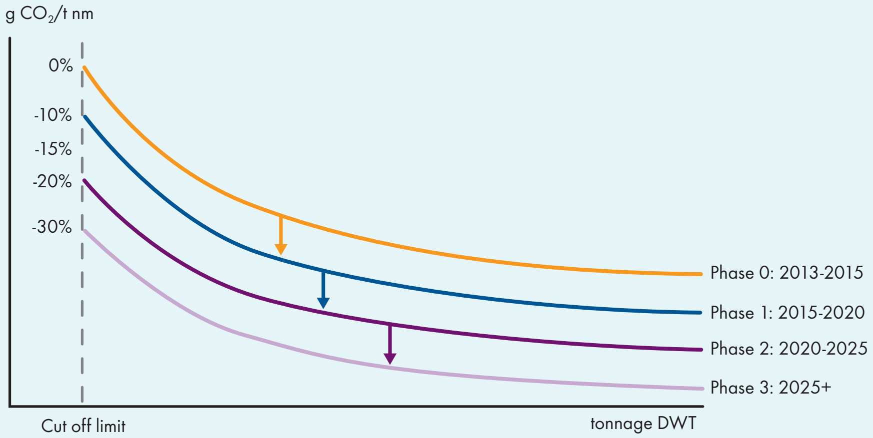
Primary or secondary measures can be taken to minimise the amount of methane in the exhaust gas stream. Primary measures include engine optimisation that has produced reductions in methane slip, and consequently the global methane

36 ENERGY EFFICIENCY DESIGN INDEX (EEDI)

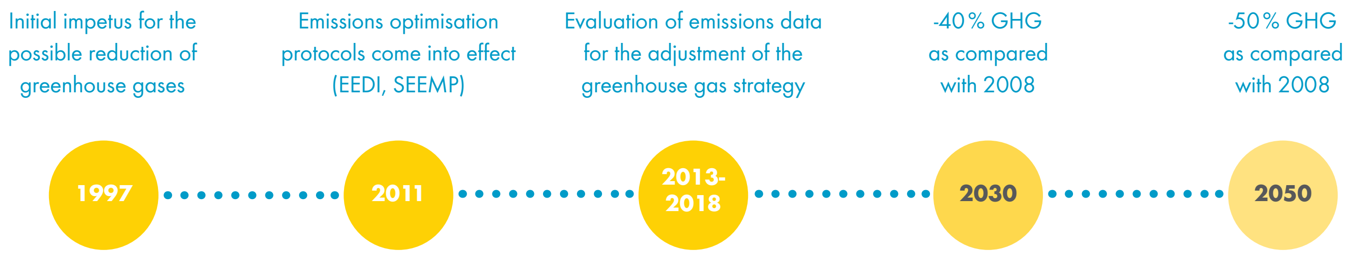
The Energy Efficiency Design Index is used to evaluate the energy efficiency of a ship on the basis of a complex formula, which takes account of the installed engine capacity, the specific fuel consumption, the type of fuel, the load capacity and the speed. The index compares the CO_2 emissions of a ship, calculated from the power output and fuel consumption, with the transport capacity. The lower a ship's EEDI, the more energy efficient it is and the less negative its impact on the environment.

An EEDI value prescribed by the IMO must not be exceeded by a new ship. The larger the transport capacity of a ship, the lower the permitted EEDI value. This limit will gradually become stricter; this will happen in four phases: The CO_2 reduction level has been set at 10 % for the first phase and will be adjusted every five years to keep pace with technological developments. The rates of reduction have been set up to 2025 and should reach 30 %. This means that new ships will have to comply with much higher energy efficiency standards from 2020 and 2025 than they did in 2015.

Continuous adjustments will also be made to broaden the scope of validity for the various types of ships. The EEDI was initially developed for the largest and most energy-intensive types of ship, primarily merchant ships such as container ships, bulk carriers and tankers.

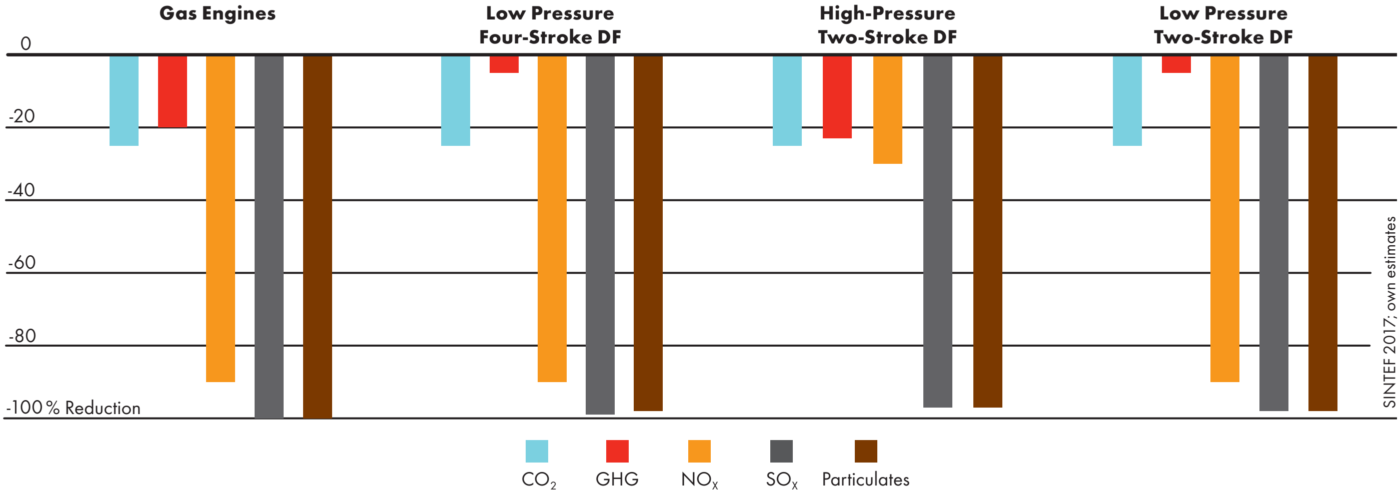


37 HISTORICAL DEVELOLPMENT OF IMO GREENHOUSE GAS REGULATIONS



IMO 2018b

38 EMISSIONS, GAS ENGINES VS. DIESEL



emissions, to date. An oxidation catalyst can be used as a secondary measure. The exhaust gas of marine engines always contains oxygen that can be used to oxidize methane slip and to reduce greenhouse gas emissions. Methane reacts with water on the surface of precious metal catalysts to produce water and carbon dioxide. These catalysts are not yet part of current shipping technology and are not installed on any ship (SINTEF 2017).

Figure 38 gives a final overview of the emission performance of gas engines: All the different engine designs (low- and high-pressure, two- and four-stroke) for operating in gas mode on ships reduce particulate and sulphur oxide emissions almost to zero. A fundamental advantage of high-pressure, two-stroke, duel-fuel engines is the potential improvement of greenhouse gas emissions. However, for the majority of propulsion systems, a positive outcome in all pollutant classes can only be achieved with the aid of specific exhaust gas cleaning systems. Further developments will be required in the future to resolve the dichotomy between reducing the majority of exhaust gas emissions and possibly increasing greenhouse gas emissions.

Inland navigation

Globally, inland navigation contributes only a small amount to air pollutant and greenhouse gas emissions. However, locally, in port areas and along shipping routes, it can be a major cause, particularly of pollutant emissions (CE Delft 2017). Emission limits in inland navigation differ depending on the area of operation. The pollutant emissions from the diesel engines of inland navigation ships are regulated by the European Union (EP/Council 2016b).

There are five stages to Regulation 2016/1628/EU: The first two stages were introduced in 1999 and 2001 and were based on engine power. Stages III and IV came into force in 2004 and applied only to new and converted ships. Stage V sets strict limits for European inland navigation from 2019, primarily based on engine power, and applies to all engines with a power output of more than 19 kW (table 39).

The emissions limited by the regulation include carbon monoxide (CO), hydrocarbons and nitrogen oxides combined (HC + NO_X) and particulate matter. Retrofitting inland navigation ships with SCR systems is a possibility for significantly reducing NO_X emissions from these ships. However, not all ships can be retrofitted because of the individual adaptations made to them.

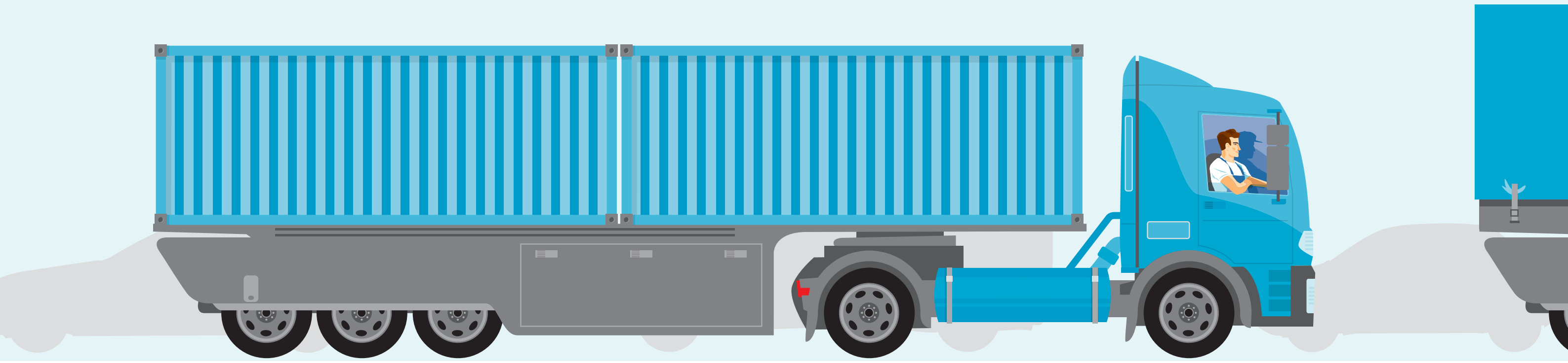
The introduction of low-sulphur diesel fuel with a maximum sulphur content of 10 mg/kg by the EU fuel quality directive, Directive 2009/30/EC (EP/Council 2009a) in 2011 led to a significant reduction in sulphur oxide emissions from inland navigation ships. Until then, inland navigation ships in Europe/Germany could use heating oil with a sulphur content of up to 1,000 mg/kg.

39 EMISSION LIMITS FOR INLAND NAVIGATION SHIPS STAGE V FROM 2019

EP/Council 2016b

Power kw	**CO** g/kWh	**HC** g/kWh	**NO_X** g/kWh	**PM mass** g/kWh	**PN** #/kWh
19 – 75	5.00	HC + NO_X max 4.70		0.30	–
75 – 130	5.00	HC + NO_X max 5.40		0.14	–
130 – 300	5.00	1.00	2.10	0.10	–
300+	5.00	0.19	1.80	0.015	1×10^{12}

5 LNG IN ROAD TRANSPORT



Besides shipping, road transport, and particularly long-haul road transport is another potential main application of LNG. The vehicles used for long-haul road transport are rigid trucks and tractor units with a high or very high annual mileage. It is much harder to electrify these vehicles than passenger cars, light goods vehicles or light- to medium-duty trucks.

Because of the high user requirements, heavy-duty vehicles (HDV) operating in long-distance road freight transport are almost exclusively powered by efficient diesel engines (Shell 2016). Driven by the desire to diversify the fuel supply and reduce air pollutant and greenhouse gas emissions, LNG is also being seen as a new powertrain and fuel option for heavy-duty vehicles in Europe.

This chapter begins with an analysis of the existing EU heavy-duty vehicle fleet (rigid trucks with or without trailers and tractor-semitrailer combinations) to determine potential applications for LNG. This is followed by a description of current LNG engine designs for HDVs and, finally, by a discussion of the status quo of powertrain-related HDV emissions, their regulation and the possible impact of LNG powertrains on them.

5.1 HEAVY-DUTY VEHICLE FLEET

Definitions

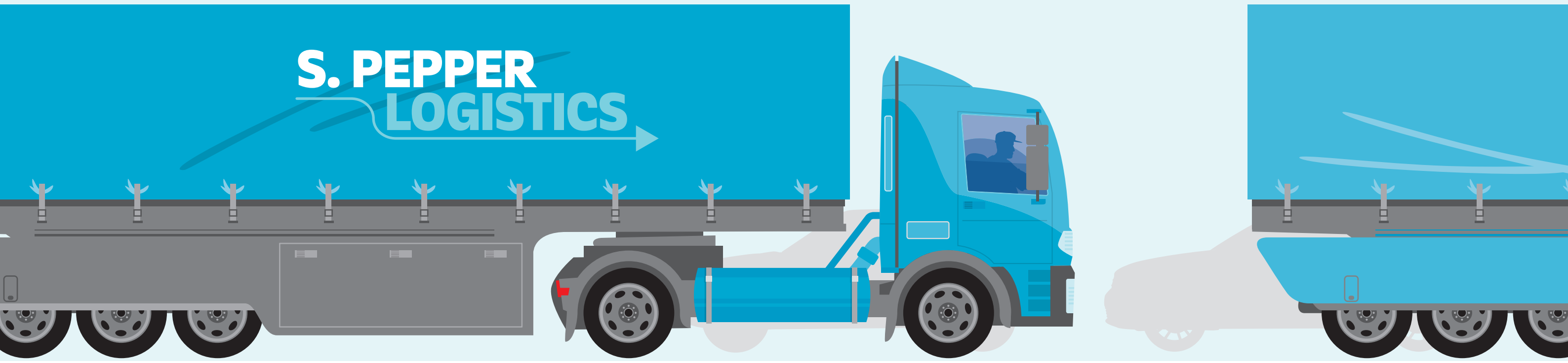
According to the European Union definition (Council 1985), a Commercial Vehicle is a type of vehicle built and equipped to carry goods (vehicle category N) or more than nine passengers including the driver (vehicle category M). In Germany, these vehicles are generally described as "Nutzfahrzeuge" (KBA 2018a). Under the framework directive 2007/46/EC (EP/Council 2007) superseded by the current Regulation 2018/858/EU (EP/Council 2018b), commercial vehicles are divided into three size categories, depending on the gross vehicle weight and the number of seats.

Category N contains trucks up to 3.5 tonnes (t) (N1), 3.5 to 12 t (N2) and over 12 t (N3) gross vehicle weight (GVW). However, common usage only distinguishes between two categories, Light (up to 3.5 t GVW) and Heavy (more than 3.5 t GVW), or uses the term Medium for category N2 (3.5 to 12 t GVW), so the classification Heavy only refers to the really heavy vehicles over 12 t. In some cases, for example in the statistics of the European Automobile Manufacturers' Association (ACEA), the Heavy category of heavy-duty trucks begins at 16 t GVW.

Vehicle category N also includes **tractor units** for towing semitrailers, where the tractor unit bears a significant part of the weight. The remaining tractors, such as road tractors (normal tractors) and agriculture and forestry tractors on wheels, are not classified as vehicles for the carriage of goods in category N (KBA 2018a).

The common term **duty vehicle** is used on the one hand as a synonym for goods vehicles (rigid trucks used to transport goods) and on the other also for vehicles designated for commercial use because they are built on the same platform as trucks for goods transport.

The term **goods vehicle** appears to be the most accurate description of vehicles for the transport of goods and, when



used below, will include tractor units. The following discussion focuses primarily on the potential main applications of LNG, namely tractor units and rigid trucks with and without trailers for long-distance road freight transport.

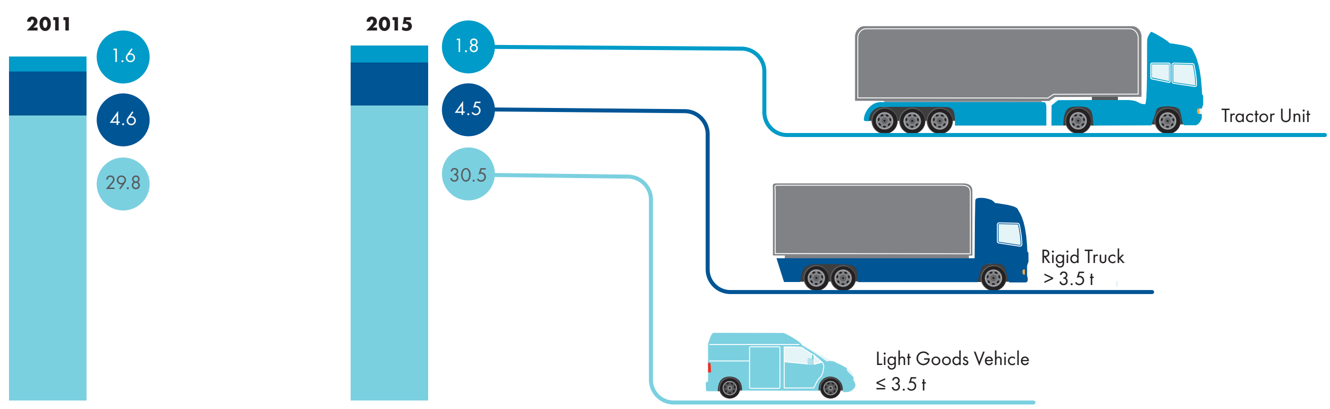
Goods vehicle fleets

The worldwide commercial vehicle fleet comprised more than 206.5 mln units in 2016. This includes tractor units and also a smaller number of buses and other commercial vehicles. The world's largest commercial vehicle fleets operate in China (80.1 mln), Japan (14.6 mln), India (11.3 mln) and Mexico (11.0 mln) (VDA 2017). In Europe, the Russian Federation operates the largest fleet, with 7.1 mln vehicles, followed by France and Spain with 6.7 and 5.2 mln vehicles. Germany, with 3.5 mln vehicles, lies in eighth position behind Poland (VDA 2017).

In 2016, the European Union had a total fleet of more than 73 mln commercial vehicles (VDA 2017, EU-COM 2018a). The goods vehicles account for more than 37.6 mln of these vehicles (EU-COM 2018a). In this case, goods vehicles include rigid trucks with and without trailers for the transport of goods and tractor units for towing semi-trailers. Other vehicles that cannot be classified as passenger cars, buses or trucks are not included in this. The category "others" includes, for example, fire service, police and civil defence vehicles. In the sections below, the terms rigid trucks and tractor units are applied when discussing goods transport activities.

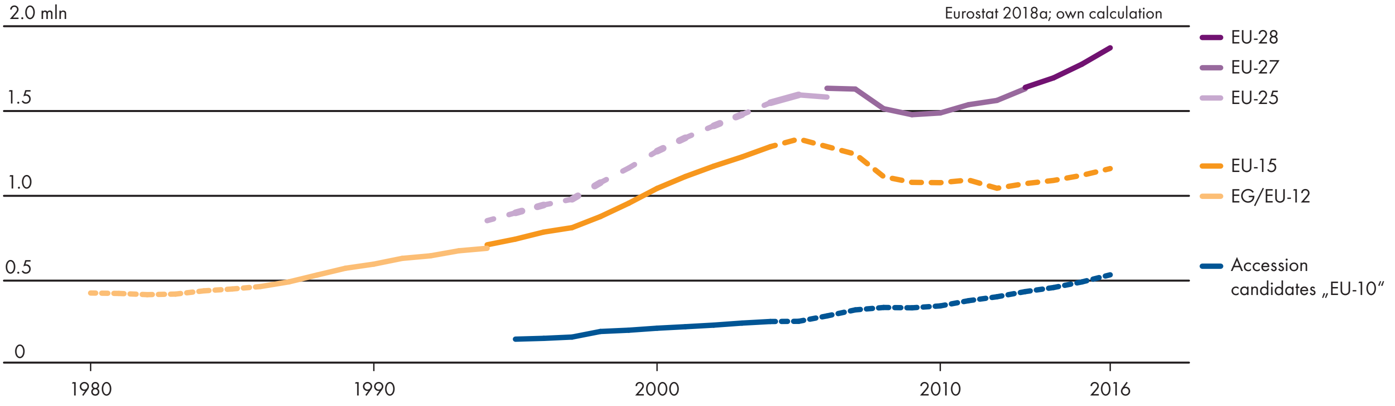
The European fleet statistics are very patchy, both in chronological and geographical terms. The only records that have been properly kept, for the most part, are the

40 SIZE CATEGORIES IN THE EU GOODS VEHICLE FLEET
2011 to 2015, in mln



Eurostat 2018a, ACEA 2017; own calculation

41 DEVELOPMENT OF THE EU TRACTOR UNIT FLEET 1980 – 2016



new registration records for tractor units. Gaps in the data have been filled by interpolation and obviously incorrect outliers have been disregarded.

The Association of European Automobile Manufacturers (ACEA) also keeps fleet statistics which the EU publishes if it has no suitable statistics of its own. However, in these statistics, vehicles in the size category above 3.5 t (N2 and N3) are separated at 16 t GVW rather than 12 t GVW. Furthermore, the statistics published relate primarily to new registrations and not the existing fleet in these categories.

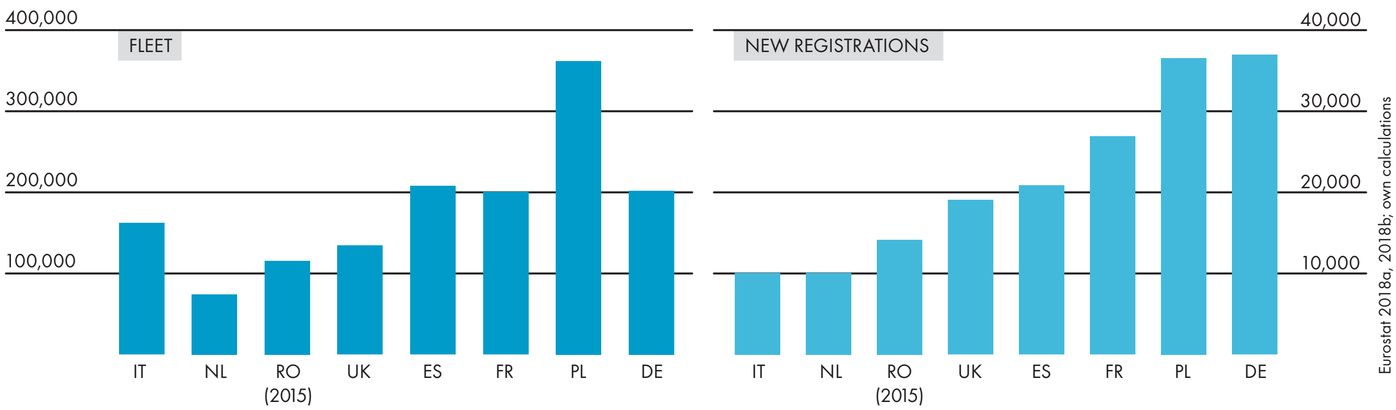
With over 80% and 30.8 mln vehicles, the light goods vehicles (LGV) of up to 3.5 t GVW account for the largest share of the vehicle fleet for goods transport (category N, figure 40). Goods vehicles of over 3.5 t GVW account for a smaller share of the fleet, with around 12% and 4.5 mln vehicles (ACEA 2017).

In the available statistics, goods vehicles are classified as medium-duty (3.5 – 16 t GVW) and heavy-duty (over 16 t GVW). The ratio, based on the share of new registrations, is approximately one to five. In other words: 6.3 mln or 17% of goods vehicles fall into the category above 16 t GVW. It is precisely these Heavy-Duty Vehicles (HDV) that are characterised by a high average mileage and a relatively high average fuel consumption. Tractor units, primarily, will be discussed below on the basis of the available data; with over 1.8 mln units, they accounted for 4.8% of the category N vehicle fleet in 2015 (Eurostat 2018a).

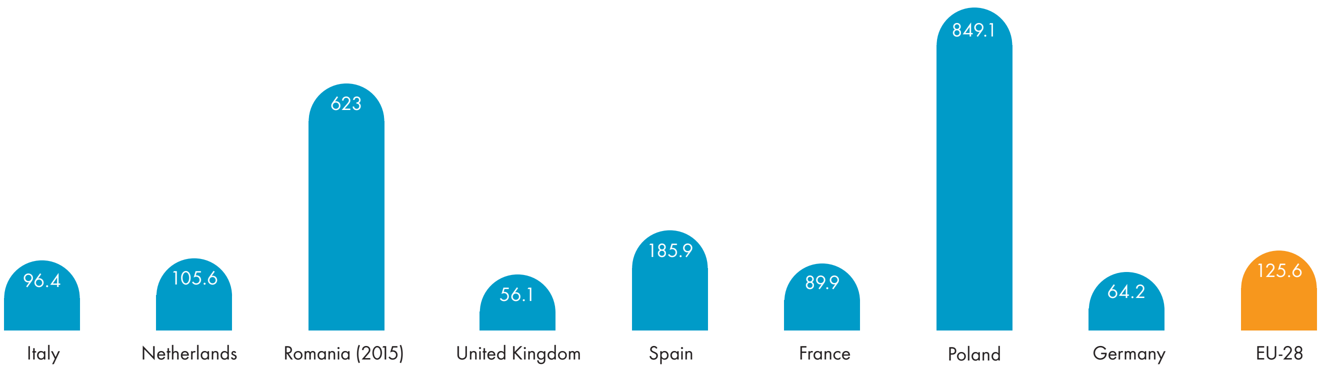
The tractor unit fleet in the EU has grown to 1.9 mln units since 2015. Around two thirds of these operate in the old EU Member States (EU 12 or EU 15) and one third in the new EU Member States in Eastern and South East Europe. Since 2010, the fleet has grown by an average of 3.8% a year, primarily in Eastern EU countries and the new accession states; the tractor unit fleet in these states is growing by over 7% a year. By contrast, it has increased by only 2.4% annually in the EU 12/EU 15 countries, and was on decline until 2012.

Eurostat's historical data for official European vehicle registrations do not seem plausible and should therefore be treated with caution. From 1980 to 1994 the fleet in Europe was actually 350,000 units lower than the official European statistics indicate. After correction, the European tractor unit fleet developed as shown in figure 41 from 1980 to 2016.

42 FLEET AND NEW REGISTRATIONS OF TRACTOR UNITS IN SELECTED EU STATES, 2016



43 TRACTOR UNIT FLEET IN RELATION TO GROSS DOMESTIC PRODUCT
2016, per billion EUR GDP

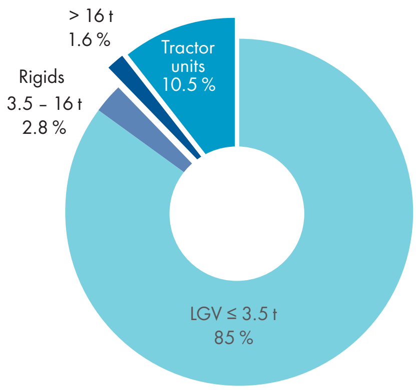


EU-COM 2018a, Eurostat 2018a; own calculation

Poland has had the largest fleet of tractor units in the EU since 2010. Its fleet has grown by 9.3 % a year on average since 1990, and continued to grow by 1.6 %, even after the economic and financial crisis in 2008, while shrinking in most EU countries. In 2016 (figure 42) Poland had a fleet of over 360,000 vehicles. It is followed by Spain, Germany and France with just over 200,000, then Italy with 162,000, the UK with 134,000, Romania with 106,000 (2015) and the Netherlands with 74,000 vehicles.

However the high fleet numbers appear in a different light when the number of vehicles is compared with the gross domestic product of the individual countries (figure 43). The gross domestic product (GDP) is a measure of the economic output of a country. In relation

44 SHARE OF SIZE CATEGORIES IN NEW REGISTRATIONS, 2016



Eurostat 2018b; own calculation

to their GDP, the values in the newer Eastern European states of the EU, such as Bulgaria, Latvia, Lithuania, Hungary, Poland, Romania, Slovenia and Slovakia, but also for Greece, with over 300 vehicles per bn EUR of GDP, are far above those for the economically more advanced states of the EU 12/EU 15.

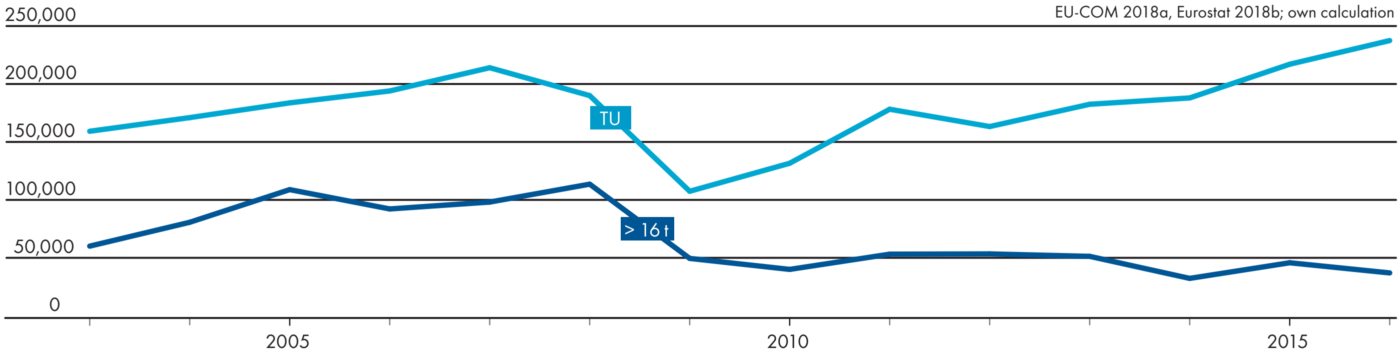
The values in the old EU states are well below 100 vehicles per bn EUR of GDP. Sweden has the lowest value, with 19 vehicles per bn EUR GDP and Bulgaria the highest with over 1,000 vehicles. This clearly indicates that the vehicle fleets of the eastern accession states transport goods both in their home countries and in the old EU 15 states.

New Registrations

The number of vehicles in the fleet increases by the number of new registrations each year, which is far more likely to respond to economic changes, and therefore fluctuates far more than the fleet itself.

45 NEW REGISTRATIONS OF RIGID TRUCKS >16 t AND TRACTOR UNITS IN THE EU 27/EU 28

EU-COM 2018a, Eurostat 2018b; own calculation



2.3 mln rigid trucks and tractor units were registered in the EU in 2016, representing a growth of 10 % (EU-COM 2017). The light goods vehicles (LGV) account for the largest share of these, with 85 % and 1.9 mln vehicles. Vehicles with a gross vehicle weight of 3.5 to 16 t account for less than 3 %. The heavy-duty vehicles over 16 t GVW account for 12 %, or just over a tenth, of new registrations (figure 44).

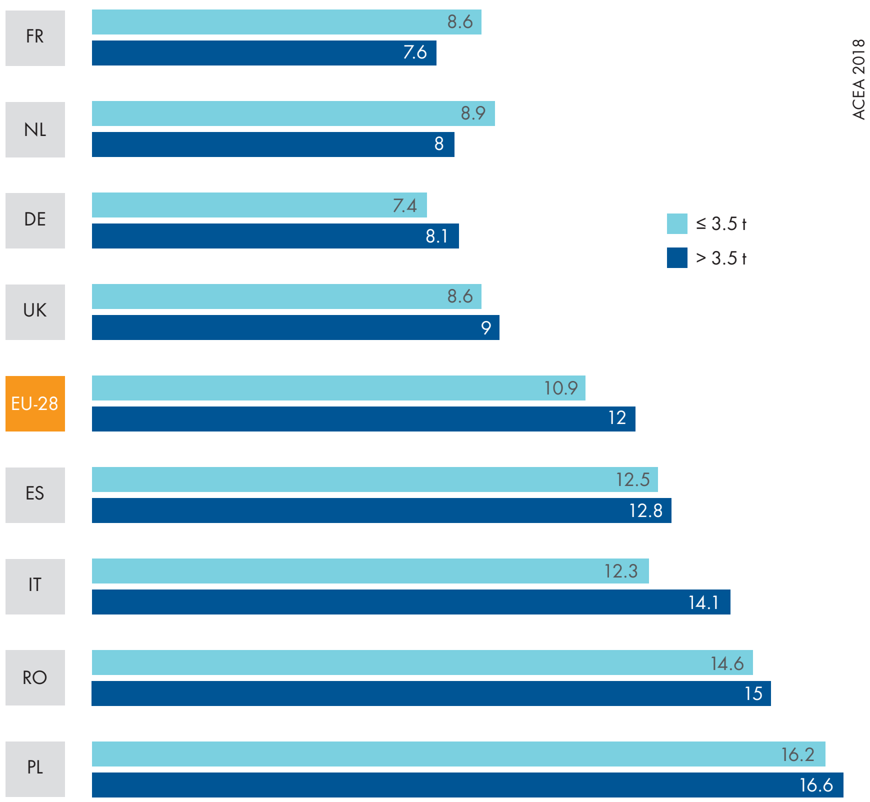
New registrations of rigid trucks (over 16 t gross vehicle weight) and tractor units fell sharply in 2009 in the aftermath of the economic and financial crisis (figure 45), when they dropped by almost half (48.3 %) to 157,000 units. In the long term, however, new registrations are growing by an average of 1.9 % a year, and stood at 274,000 vehicles in 2016.

The development of new registrations in the individual vehicle classes varies significantly. In the period 2003 to 2016, the share of rigid trucks in the heavy-duty category fell from 60,000 to 37,000, or 27.4 % to 13.5 % of new registrations. This was accompanied by a corresponding rise in share of new registrations of tractor units from 72.6 % to 86.5 %. This is equivalent to 237,000 tractor units in 2016 in comparison with 159,000 in 2003.

On the one hand, these fluctuations correspond to the development of long-distance road transport capacity in the EU which, at 1,804 bn tonne-kilometres in 2016, had not yet reached its 2007 pre-crisis level of 1,876 bn tonne-kilometres (EU-COM 2017). On the other, the downward trend in new registrations of rigid trucks illustrates the growing dominance of the combination of tractor unit and semitrailer in European goods transport.

In only eight of the EU 28 Member States 55 % of tractor units are newly registered. Germany and Poland have the biggest tractor unit markets, with a share of just over 11 % and over 36,000 newly registered vehicles each. They are followed by France (8.4 %) and Spain (6.5 %) with over 20,000 new registrations, and the UK (5.9 %),

46 AVERAGE AGE OF LIGHT AND HEAVY-DUTY VEHICLES
2016, in years



Romania (5.2 %), the Netherlands and Italy with 3.1 % each (figure 42).

Vehicle age

The high proportion of newly registered tractor units in Germany mirrors the newness of the tractor unit fleet, with an average vehicle age of 4.3 years. The powerful tractor units of more than 300 or 350 kW predominantly used in long-distance road transport are even newer in Germany, with an average age of 3.9 resp. 3.3 years (KBA 2018b).

While, according to calculations, the tractor unit fleet in Germany is renewed every 5.5 years, in Poland it is renewed every 9.9 years. Only Spain and Italy renew their vehicles less frequently, at every 10 and every 16.1 years respectively.

In 2016, the average age of heavy-duty vehicles (rigid trucks over 3.5 t GVW, tractor units and buses) in Europe was 12 years, which is around 0.3 years higher than in 2015 (ACEA 2018) (figure 46).

Luxembourg has the newest HDV fleet, with an average age of 6.6 years, followed by France, Denmark, the Netherlands, Germany, Austria, Sweden, the UK and Belgium. Slovenia, Ireland and Finland also have fleets below the average vehicle age, while those in Spain, Portugal, Italy and the remaining eastern accession states are above the average. Poland and Greece bring up the rear. The age of the fleets in the eastern accession states and the countries of Southern Europe is above the average. When considering the eastern accession states, it must be borne in mind that older vehicles tend to be used for transport in countries outside the EU.

LNG vehicles

The information about the number of registered vehicles with an LNG powertrain is very patchy. The main sources of statistical data on LNG vehicles are Eurostat, the Natural Gas Vehicle Association (NGVA) Europe and the EU Blue Corridors Project. Eurostat has no figures for tractor unit registrations. For HDV over 3.5 t GVW, figures are only kept for ten countries. In 2016, France had the largest fleet with 349 LNG vehicles, followed by Spain with 25. There were still only 168 LNG trucks in France in 2013. Eight countries had not a single LNG vehicle in 2016: Estonia, Cyprus, Hungary, Malta, Poland, Portugal, Finland and Sweden. Eurostat did not record figures for the other countries (Eurostat 2018c).

Recorded new registrations are consistent with this picture. In France, the registration of new LNG vehicles above 3.5 t GVW rose from three in 2013 to 114 in 2016, while Spain registered 20 new LNG vehicles in 2016. No additional information can be obtained from Germany's national registration statistics, as the Federal Motor Transport Authority issues figures for CNG and LNG powertrains under the combined heading natural gas vehicles.

NGVA Europe cautiously estimates the size of the total European fleet at around 4,000 LNG vehicles, primarily rigid trucks and tractor units and also some buses. More than 1,500 new vehicles have been registered recently, mainly in Spain, the Netherlands, Italy and the UK as the EU's leading LNG users. The UK is aiming towards a fleet of 350 LNG vehicles. Italy had a fleet of around 400 LNG vehicles in 2017. In addition to this, there are around 100 dual-fuel LNG/diesel vehicles. In Belgium, a haulage company has introduced 150 LNG vehicles and the fleet is set to rise by 350 vehicles to 500 LNG vehicles by 2020. A car manufacturer used more than 100 LNG trucks in Northern Germany. Some of these fleets are supported by government subsidy schemes.

The EU Blue Corridors Project provides further information (EU-COM/DGM 2018). 156 vehicles are currently operating under the Blue Corridors Project, with 24 in Portugal, 21 in Spain, 15 in France, 24 in Italy, 34 in Belgium, 4 in Sweden and 20 in Germany.

There are other relevant fleets of LNG vehicles, particularly in China and North America. In China, for example, there were already 45,000 registered LNG vehicles in 2013 and by 2017, HDV with LNG accounted for around 4% of the total fleet of over 6 mln HDV; the LNG fleet therefore comprised around 250,000 vehicles. The number of new registrations of heavy-duty LNG vehicles in China, extrapolated to 2017, amounted to 65,000 vehicles. In the USA, over 100 LNG-powered HDV were registered in 2016 (EIA 2019). In 2018, the LNG vehicle fleet, comprising rigid trucks and refuse vehicles, was 4,000 units strong.

5.2 NATURAL GAS ENGINES FOR HDV

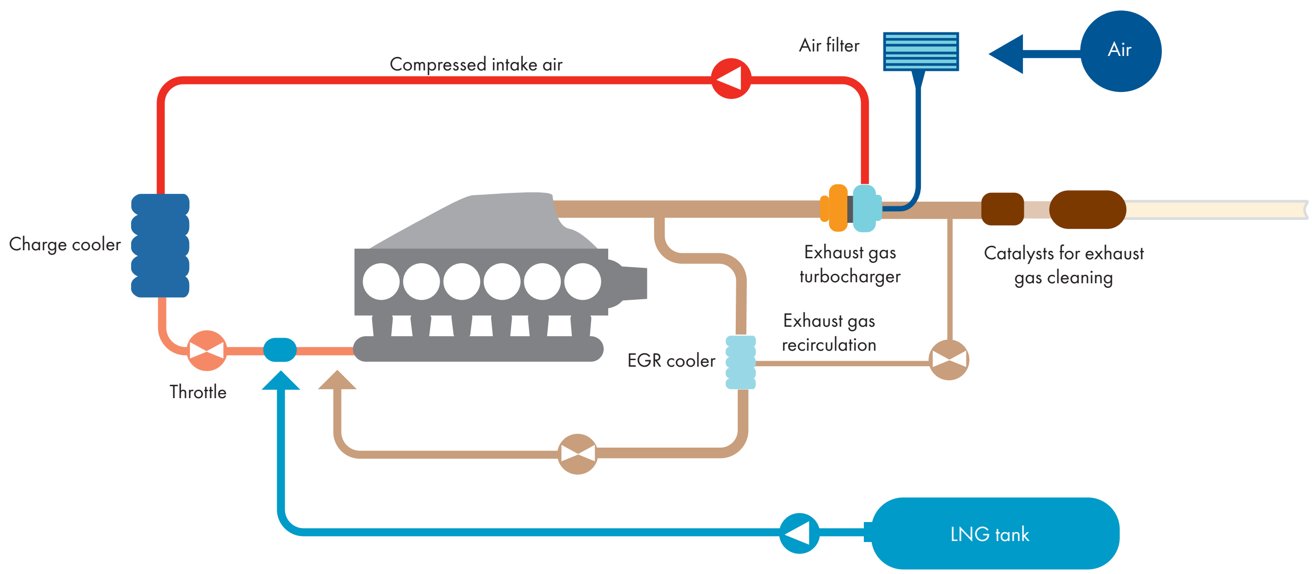
There are currently two types of engine technology for heavy-duty LNG vehicles, which comply with the current EURO VI exhaust gas emission standards under Regulation 595/2009/EC (EP/Council 2009c). These engine technologies are described below and their characteristics are compared with those of the diesel engine. The two LNG engine technologies are the spark-ignition (SI) engine and the high-pressure direct injection (HPDI) engine.

HDV with stoichiometric spark-ignition (SI) engines

In a typical SI engine, fuel is pre-mixed with air and the mixture is then compressed by the compression stroke and ignited by an external ignition spark. The power is regulated by a throttle in the intake area. The fuel is injected into the intake pipe and should be as ignitable as possible to prevent uncontrolled combustion of the mixture; in other words, the fuel must have a high octane or methane number. Since natural gas has a high methane number, it is a particularly suitable fuel for SI engines.

In stoichiometric spark-ignition engines, formation of the mix is regulated electronically to ensure that all of the fuel is burned and that there is no excess

47 DIAGRAM OF A LAMBDA = 1 GAS/OTTO-CYCLE ENGINE



air in the exhaust gas (figure 47). The exhaust gas does not contain any oxygen (Lambda = 1). To reduce the formation of NO_X, diesel engines also use exhaust gas recirculation (EGR). This reduces the temperature in the combustion chamber. The spark ignition engine is less efficient than the diesel engine because of pressure losses at the throttle and limited maximum compression. However, with the Lambda = 1 combustion concept, three-way catalytic converters (TWC) can be used for exhaust gas aftertreatment. Lambda = 1, combined with exhaust gas recirculation, reduces the pollutants carbon monoxide (CO), nitrogen oxides (NO_X) and unburned hydrocarbons in the raw exhaust gas to an amount that can be broken down by reaction with a single catalyst. This makes the stoichiometric engine design cost-effective. It can be used not only with petrol, as in passenger cars but, even more beneficially, with natural gas or LNG for HDV.

Fuel Consumption

An engine's efficiency, and hence its consumption, depends on the operating conditions (torque, speed). Truck engines often operate under high torque (or high load) and varying speed conditions (acceleration). Equally, they may operate under conditions of constant speed, but varying load (uphill and downhill) and phases where the engine's braking force is used (negative torque).

A spark-ignition engine cannot produce the same torque as a diesel engine with the same capacity, because the maximum combustion pressures in the cylinder are lower. A larger spark-ignition engine is required to obtain the same power. A spark-ignition engine consumes about 15 % more energy at high torque than a diesel engine. The lower the torque required, the higher the additional energy consumption. They are least efficient at low loads (35 % higher energy demand than a diesel engine).

The precise energy demand of an LNG truck with a spark-ignition engine in comparison with a diesel truck depends on other factors (e.g. transmission type).

A modern LNG vehicle with an Otto-cycle engine requires 18 % more energy on average than a diesel vehicle. This is mainly due to the difference in the specific energy consumption of the engine. Table 48 shows how this is reflected in the fuel consumption. A diesel truck with a fuel consumption of 30 l/100 km would consume 27 kg LNG/100 km if it were an LNG HDV with a spark-ignition engine.

48 FUEL CONSUMPTION – DIESEL V. LNG WITH SI ENGINE

Diesel	LNG SI engine
30 l/100 km	59 l/100 km
25 kg/100 km	27 kg/100 km
1,070 MJ/100 km	1,328 MJ/100 km

Natural gas Otto-cycle engines with a higher Lambda value (**lean burn engines**) would be more efficient and require slightly less energy. These natural gas SI engines were permitted under the Euro V emission limits. However, as yet, there is no exhaust gas treatment system for these lean burn engines that complies with the Euro VI emission standard.

Available trucks

There are two manufacturers of heavy-duty LNG vehicles with spark-ignition engines in Europe. Both of them offer a wide variety of chassis (e.g. tractor unit or rigid trucks) with varying tank configurations.

The engines available for the vehicles are listed in Table 49. The 13 litre class can be used for the HDV. All engines can be used in LNG and CNG vehicles, although the ranges given are achieved only with LNG and the maximum range is provided by the largest possible installed tank capacity.

LNG HDV with an HPDI engine

Diesel engines are efficient because the combustion air intake is not throttled and the engine can operate at the maximum compression ratio. The fuel is injected in the maximum compression phase and only ignites then. This design only works because diesel is ignitable. LNG, or methane, does not have the necessary auto-ignition characteristics.

The idea of the HPDI engine is to initiate auto-ignition with a small amount of diesel fuel and to inject methane into the flame produced (figure 51). Two different fuels are therefore used in sequence to operate the engine. The amount of diesel is selected so that just enough energy is released to ignite the methane subsequently injected.

Diesel is injected before maximum compression (approximately -15° crankshaft angle). When combined with the compression, this significantly increases the pressure and temperature. The gas is then injected so that the majority of it can ignite after the crankshaft has reached an angle of 0°. This produces the maximum torque.

The structure of the fuel system is illustrated in figure 51. LNG (liquid) is brought to approximately 300 bar by a high-pressure pump integrated into the tank and immediately evaporates. The heat required for this is drawn from the engine's cooling system. This is a very efficient way of providing high pressure methane gas.

49 AVAILABLE SI-GAS ENGINES FOR HEAVY-DUTY VEHICLES

Capacity litres	**Power** hp	**Torque** Nm	**Maximum range** km
9	280 - 400	1,500	Up to 1,600
13	410 - 460	2,000	Up to 1,600

50 FUEL CONSUMPTION – DIESEL VS. LNG WITH HPDI ENGINE

Diesel engine	HPDI engine	
	LNG consumption	Diesel consumption
30 l/100 km	48 l/100 km	2 l/100 km
25 kg/100 km	22 kg/100 km	1.7 kg/100 km
1,070 MJ/100 km	1,082 MJ/100 km	71 MJ/100 km

The engine therefore does not run on liquid LNG, but on the gasification product (methane gas). Without the high pressure, it would not be possible to inject methane gas into the engine's combustion chamber. In principle, the small amount of diesel is fed into the engine in exactly the same way as in a normal diesel engine. However, the injection pressure is lower (approximately 300 bar as compared with 2,000 bar in a normal diesel engine). Another distinctive feature is that an integrated injector is used, which injects both the diesel and the methane gas into the combustion chamber in a controlled way.

Fuel Consumption

As an HPDI engine works like a diesel engine, it is not surprising that it is basically just as efficient. With current versions of the HPDI engine, the energy demand over a wide operating range is a maximum of only 5% higher; it is only 15% higher in the very low load range. However, this range is virtually irrelevant for vehicle operation. It is generally accepted that a vehicle requires only around 3 to 4% more energy with an HPDI engine than with a conventional diesel engine. The fuel consumption of an HPDI vehicle is therefore 22 kg LNG/100 km plus 2 l diesel/100 km, as compared with the 30 l/100 km fuel consumption of a diesel HDV.

Available HDV

The HPDI engine was developed by a Canadian company that specialises in developing vehicles for gaseous fuels. This company holds numerous patents for HPDI technology. In 2006, it introduced a heavy, 15 litre HPDI LNG engine to the American market, but ceased production in 2013. This engine had a maximum of 550 hp and a maximum torque of 2,500 Nm.

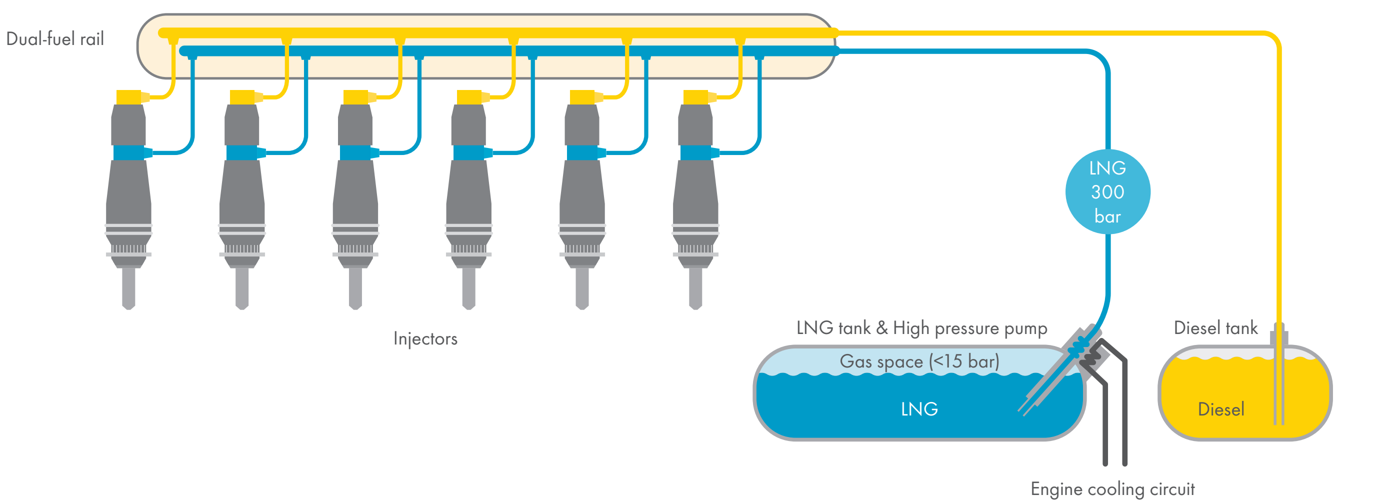
Various European and Chinese companies have since developed improved HPDI engines. The only HPDI truck currently available was launched in 2018. This truck is also available in various configurations. The HPDI engine has a capacity of 13 litres and develops 420 hp or 460 hp and a maximum torque of 2,100 to 2,300 Nm (about 10% more than the most powerful spark-ignition engines). The tank capacity gives it a range of up to 1,000 km. Diesel accounts for 5 to 10% of total fuel consumption. The exhaust gas aftertreatment works in the same way as in a normal diesel engine (SCR with urea solution and particulate filter). Other manufacturers, in China for example, are also expected to bring HPDI engines for LNG HDV onto the market (WFS 2018).

5.3 EMISSIONS

Vehicles, particularly heavy-duty vehicles are now almost exclusively powered by diesel engines. The burning of diesel fuel produces both air pollutants and greenhouse gases. The specific air pollutants from road transport in the EU were reduced significantly between 1990 and 2016, by around 86% for carbon monoxide, 99% for sulphur oxides and 60% for nitrogen oxides.

Nitrogen oxides from road transport contribute around 30% to the total nitrogen oxide emissions in the EU. According to the most recent figures (2016), the share of particulate matter emissions from road

51 DIAGRAM OF A FUEL SYSTEM FOR AN HPDI ENGINE



TOTAL COST OF OWNERSHIP

Although LNG offers an alternative supply of energy and environmental advantages, it will only attract widespread interest from haulage companies and other HDV fleet operators if the powertrain-fuel combination LNG is competitive economically when compared with the dominant powertrain-fuel combination diesel. The cost-effectiveness of an LNG HDV in comparison with a reference vehicle can be described by the "total cost of ownership" (TCO).

The TCO elements comprise the fuel costs, depreciation of the vehicle, road user charges, servicing, tyres, repairs, taxes and insurance as well as driver costs. The key data of the TCO calculation depend on numerous other factors, such as the finance model chosen (leasing versus purchase and depreciation).

Driver costs are identical for both types of powertrain (LNG and diesel) and hence do not affect the cost comparison. Besides the driver costs, depreciation and fuel costs are

transport has risen from 17% to 42% for $PM_{2.5}$ and from 30% to 60% for PM_{10} since 2000 (EEA 2018a).

On the other hand, greenhouse gas emissions from the whole of the transport sector have fallen only slightly, and only since 2008/2009. With regard to transport-related CO_2 emissions, HDV are responsible for around 5% of total EU greenhouse gas emissions or one fifth of the transport-related emissions. The greenhouse gas emissions of all heavy-duty vehicles in the EU grew by a quarter between 1990 and 2016 (EEA 2018b).

The regulations for commercial vehicle-related air pollutants have not been tightened further in recent years, since commercial vehicles already have to comply with more demanding requirements than passenger cars under the latest amendments to the emission standards (Euro standards). As a result of the dynamic development of road transport, a CO_2 regulation for heavy-duty vehicles similar to that for newly registered passenger cars and light goods vehicles is now being implemented.

The most recent status of the relevant EU regulations for the air pollutant and greenhouse gas emissions of heavy-duty vehicles is summarised in table 52.

Air pollutants

Binding, EU-wide exhaust emission regulations for rigid trucks and tractor units (vehicle category N3) were introduced by the Euro I standard in 1993. The Euro VI stage of these regulations has been in force since 2012. The exhaust emission regulations have become increasingly strict over the years and the test conditions have also continued to develop. Euro VI reduced the limits for exhaust emissions of individual air pollutants by up to 97% as compared with Euro I (Table 52). The exhaust emissions limited by law include, in particular, carbon monoxide (CO), hydrocarbons (HC) particulate mass (PM), particulate number concentration (PN) and nitrogen oxides (NO_X).

Rigid trucks and tractor units (N3) are subject to exhaust emission limits per kilowatt hour of engine power (g/kWh). In addition, the method used by the Euro VI driving cycles to measure the exhaust emissions of heavy-duty vehicles is based on harmonised global driving cycles, namely the World Harmonised Stationary Cycle (WHSC) and the non-stationary World Harmonised Transient Cycle (WHTC). The WHSC is an engine test bench test under defined conditions; the transient WHTC uses real driving cycles and normal driving conditions for commercial vehicles.

Rigid trucks and tractor units must comply with the current exhaust emission regulations when operating in practice. The exhaust emissions during operation in practice are also measured with mobile the largest components. At the moment, LNG vehicles cost far more than diesel vehicles, because they involve more expensive technology (e.g. vacuum tanks for LNG, special fuel injection). How much more an LNG vehicle costs also depends on the type of vehicle and the equipment. Only a rough figure can be given here, but it is 25 to 50% higher than a comparable diesel vehicle.

The additional costs of buying a vehicle are compensated for by savings on fuel and additional financial incentives. The fuel costs which, for haulage companies, are generally lower with LNG vehicles, have the greatest impact because LNG is often cheaper to buy than diesel fuel. The price difference between LNG and diesel is affected particularly by energy taxes on fuel. In many EU countries, energy taxes are lower for natural gas fuels (CE Delft et al. 2017). Other factors that affect the TCO result are purchase subsidies, vehicle-related charges such as vehicle tax and motorway tolls.

Before deciding for or against LNG, hauliers must collect as much information as possible about it, in particular how far an LNG vehicle fits the intended use. The price differences are not always the same. Financial incentives, most of which are only intended to get the market up and running, are not permanent and vary from country to country. In Germany, for example, there is currently a temporary reduction in energy tax on natural gas fuels, a temporary subsidy programme for the purchase of lower-emission vehicles (EUR 12,000/ vehicle in 2019) and an emissions-based, limited exemption from German motorway tolls until 2020.

An illustrative business case for a heavy-duty LNG vehicle in long-distance road transport will be developed below, comparing possible fuel prices with the possible additional costs of LNG vehicles and examining them on the basis of the distance travelled. It is assumed that an LNG vehicle with a spark-ignition engine currently costs EUR 30,000 more to buy than a comparable vehicle with a diesel powertrain and will cost EUR 20,000 more in the future. It is also assumed that the HPDI variant currently costs EUR 40,000 more and will cost EUR 30,000 more in the future.

Over a five-year period of use, a difference of 30% in the fuel costs per megajoule of energy between the LNG price and the diesel price is needed to break even (slightly less for HPDI, slightly more for spark-ignition).

measuring devices called Portable Emission Measurement Systems (PEMS). In addition to this, the durability of emission-reducing systems over typical vehicle lifetimes must be demonstrated; under Euro VI, systems in rigid trucks and tractor units are required to last for up to seven years or 700,000 km.

The air pollutant emissions of heavy-duty Euro VI vehicles operating in practice now differ very little from the exhaust emissions of the Euro VI engine test bench test (ICCT 2015). All LNG vehicles, both with HPDI and with spark-ignition, comply with the very demanding Euro VI standard. The manufacturers of spark ignition LNG vehicles point to even further significant emission reductions compared with the Euro VI standard: NO_x -40%, PM -70%, CO -90% (Stojanovic 2015). In the USA, there is even a natural gas spark-ignition engine for heavy-duty vehicles, which has extremely low NO_x emissions (CARB 2015). This would enable spark-ignition engines to comply with even stricter emission limits.

52 EXHAUST EMISSION LIMITS FOR HEAVY-DUTY VEHICLES WITH A DIESEL POWERTRAIN

Vehicle type	From 2.610 kg reference mass			
Legal basis	EU regulations 595/2009 and 582/2011			
Emission measurements	g/kWh			
Exhaust emission standard Test procedure In force since	Euro I 1993	Euro VI WHSC 2012	Euro VI WHTC 2012	Changes in %
Carbon monoxide CO	4.5	1.5	4	-67/-11
Hydrocarbons HC	1.1	0.13	0.16	-88/-85
HC + NO_X	-	-	-	-
Nitrogen oxides NO_X	8	0.4	0.46	-95/-94
Ammonia NH_3 in ppm	-	10	10	-
Particulate mass PM	0.36	0.01	0.01	-97
Particulate number concentration PN/kWh bzw. PN/km	-	$8 * 10^{11}$	$6 * 10^{11}$	-
Methane g CH_4/kWh (Gas engines)	-	-	0.5	-

A reduction in additional LNG vehicle costs and the improved engine efficiency in the future could reduce the break-even point to a price difference of around 20% between LNG and diesel. These figures are based on a hypothetical diesel price of EUR 1 per litre. A 30% reduction in the LNG price, in relation to the energy content, would correspond to a pump price of EUR 0.96 per kilogram. The effect of vehicle mileage on the economics and thus competitiveness should be borne in mind here. The assumptions made require an LNG vehicle to travel an average of 110,000 to 150,000 km a year to break even against a diesel vehicle. Future LNG vehicles will not need to travel as far if engine efficiency, particularly of spark-ignition engines, increases and the purchase prices fall. In any case, LNG is financially attractive to haulage companies whose HDV are used intensively, i.e. preferably for long-haul road transport.

At the end of the day, the break-even point is determined by the way a vehicle is used. Figure 53 shows the savings from an LNG vehicle in comparison with a vehicle equipped with a diesel powertrain after five years' use at a specific fuel price spread and depending on the annual mileage of the vehicle. As expected, the lowest savings are made with the SI-today and HPDI-today engines. At LNG costs 5% lower than diesel and a fixed annual distance of 130,000 km a year, it will not be possible to operate an LNG truck more cheaply than a diesel truck in the future. After five years, the SI-today is making a loss of around EUR 65,000, the HPDI-today a loss of EUR 40,000, the SI-future a loss of EUR 30,000 and the HPDI-future a loss of EUR 20,000.

The current LNG vehicles require an LNG price of at least 25% resp. 30% lower than diesel to reach the profitability threshold. On the other hand, future powertrains will be profitable at a fuel price difference of as little as 17% (HPDI-future) and 19% (SI-future). However, the savings made with the LNG vehicle develop differently as the price difference increases. The HPDI-future does not increase as sharply as the SI-future. As a result, the savings made with the SI-future are higher than those with the HPDI-future from a fuel price difference of 35% onwards.

The savings develop differently on the basis of the annual mileage at a fixed fuel price difference. At an annual mileage of 60,000 km, the SI-today and the HPDI-today are both unprofitable, with a loss of roughly EUR 20,000. The HPDI-future makes a loss of only EUR 5,000, while the SI-future is just above the profitability threshold. At slightly over 80,000 km a year, the HPDI-future also becomes profitable. The HPDI-today does not become profitable until it reaches 110,000 km a year, while the SI-today has to travel well over 150,000 km a year to move into profit. At more than 110,000 km a year, the saving with the HPDI-future will be higher than with the SI-future.

LNG vehicles with spark-ignition engines are also much quieter than diesel vehicles (3 to 6 decibels). Vehicles with these engines can therefore offer advantages to logistics companies that deliver goods or collect waste for disposal in urban areas in the evening or overnight.

Greenhouse gases

CO_2 is the most relevant of the greenhouse gases, but methane (CH_4) and nitrous oxide (N_2O) are also taken into account, although they have very little effect on overall vehicle emissions. As with the regulation of CO_2 emissions from passenger cars and light goods vehicles, the European Commission is preparing a mandatory CO_2 regulation for commercial vehicles above 3.5 t GVW. The USA, Canada, Japan and China already have consumption or CO_2 emission standards for commercial vehicles.

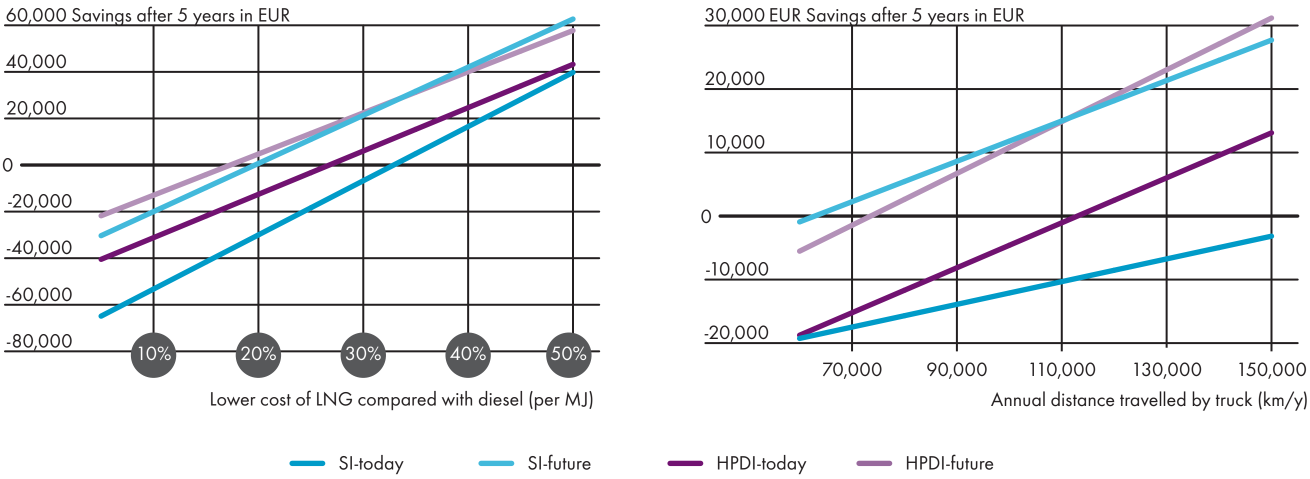
Since heavy-duty vehicles account for a high proportion of the CO_2 emissions of the EU transport sector, the focus of the European CO_2 emission regulations is on rigid trucks and tractor units over 16 t GVW, which account for 65 to 70% of the CO_2 emissions of all commercial vehicles in the EU. The CO_2 emission regulations will be extended to include lighter, or medium-duty, heavy-duty vehicles, buses and coaches at a later date (EU-COM 2018b).

The specific CO_2 emissions of heavy-duty vehicles in the EU have never been measured by a standard procedure and there is no valid data on the average fuel consumption of commercial vehicles under different conditions of use. Nor are heavy-duty vehicles manufactured in large-scale volumes. Instead, there is a wide variety of vehicles equipped for many different uses. Variations in powertrain technology, the number of axles or special bodies, for example, affect the specific fuel consumption and vehicle-specific CO_2 emissions, with the result that even the measurement and comparison of vehicle-specific consumption and CO_2 emissions presents a major challenge.

To calculate the CO_2 emissions of heavy-duty vehicles, the European Commission therefore developed the Vehicle Energy Consumption Calculation Tool (VECTO) (JRC 2014). VECTO can be used to calculate the specific energy consumption and CO_2 emissions for any heavy-duty vehicle configuration and defined use. The simulation program calculates the consumption values for

In summary, it can be said that all LNG powertrains can be operated profitably. With the current vehicle purchase price differences, a high fuel price difference of 25 to 30% in comparison with diesel will be required if they are to become profitable. The new powertrains will be profitable from a difference of less than 20%. As the LNG fuel price difference increases, the powertrains are likely to become cheaper, in fact EUR 10,000 to EUR 15,000 cheaper for each additional 10% difference in the LNG price. The profitability of the powertrains will also increase by EUR 5,000 to EUR 10,000 for each additional 10,000 km a year travelled. At a high annual mileage of over 110,000 km the HPDI is more profitable both now and in future, while at a low mileage only the future SI is.

53 SENSITIVITY OF THE COST-EFFECTIVENESS OF LNG: PRICE DIFFERENCE AND ANNUAL DISTANCE TRAVELLED



Assumptions: 7% interest; 130,000 km/y, lifetime 5 years, diesel EUR 1/litre. LNG truck (SI): Today 20% less efficient than diesel, in future 10% less efficient LNG truck (HPDI): Today 5% less efficient and 5% pilot diesel, in future as efficient as diesel and use of 5% pilot diesel.

the whole vehicle from measured data for the main components relevant to consumption, namely the engine, tyres, bodywork, transmission, axles and auxiliary components (EU-COM 2018b).

The CO_2 emissions for newly registered heavy-duty vehicles will be regulated in a second stage. In concrete terms, according to a European Commission proposal, a 15% reduction in CO_2 emissions should be achieved by 2025 as compared with the obligatory calculations for new heavy-duty vehicles to be carried out with VECTO in 2019; this target is broken down into grams of CO_2 per tonne kilometre or grams of CO_2 per cubic kilometre for the individual manufacturers. The objective for CO_2 emissions is to achieve a 30% specific reduction in 2030 as compared with 2019; progress towards this will be monitored in 2022. The procedures for calculating manufacturer-specific CO_2 emissions will take particular account of commercial vehicles with very low or zero emissions.

VECTO (version 3.3.0.1250) takes account of the use of LNG or natural gas. No decision has yet been made about which emission factor will be used for LNG. At the moment, natural gas is taken into account generally and has a CO_2 emission advantage of around 23% over diesel in energy terms, which means that, in engines of the same efficiency, 23% of CO_2 emissions could be saved by using natural gas, which would be a relatively simple way of achieving the majority of the CO_2 saving target (JRC 2016). The emission factor for LNG may prove to be even more advantageous. However, it can only be achieved with an engine with a similar level of efficiency, such as a diesel-like HPDI engine. Only around 5% of the possible 23% saving would be achieved with a modern spark-ignition engine, which is 18% less efficient on average. This shows how advantageous HPDI engines could potentially be.

It is often feared that the "methane slip" from LNG vehicles will be too high. Methane slip is the unburned methane emitted with the exhaust. Euro VI requires gas engines to comply with a limit of 0.5 g/kWh, which ensures that methane slip has virtually no impact on the truck greenhouse gas balance. VECTO does not measure methane slip.

6 PRO-LNG SCENARIOS FOR SHIPS AND TRUCKS

This chapter will show how LNG could become an established fuel for seagoing ships and heavy-duty vehicles in the goods transport market by 2040 as part of an ambitious "Pro-LNG scenario". Shipping will be examined on the basis of the global merchant fleet, and the goods vehicle fleet on the basis of heavy-duty vehicles for long-distance road transport in the EU.

Inland navigation vessels will not be included in the scenario analysis, firstly because there are too few of them – very few European countries have an inland navigation fleet to speak of – and secondly because their low-power engines consume less fuel than those of seagoing ships. Besides, there is not enough data on inland navigation vessels, at least for European modelling.

The Pro-LNG scenario describes possible future developments, in which LNG will gain market share as a fuel for heavy-duty vehicles and ships, due to the creation of some of the necessary conditions. Since an accelerated introduction of a new energy and powertrain technology is considered, the scenario developed for LNG is not a trend scenario that merely extrapolates trends from the recent past; it goes much further than this.

Therefore the scenario assumed should be regarded as an alternative powertrain and fuel-specific scenario, which makes optimistic assumptions for establishment and market penetration of LNG. The results of this **Pro-LNG scenario** are compared with a development in which LNG plays no part.

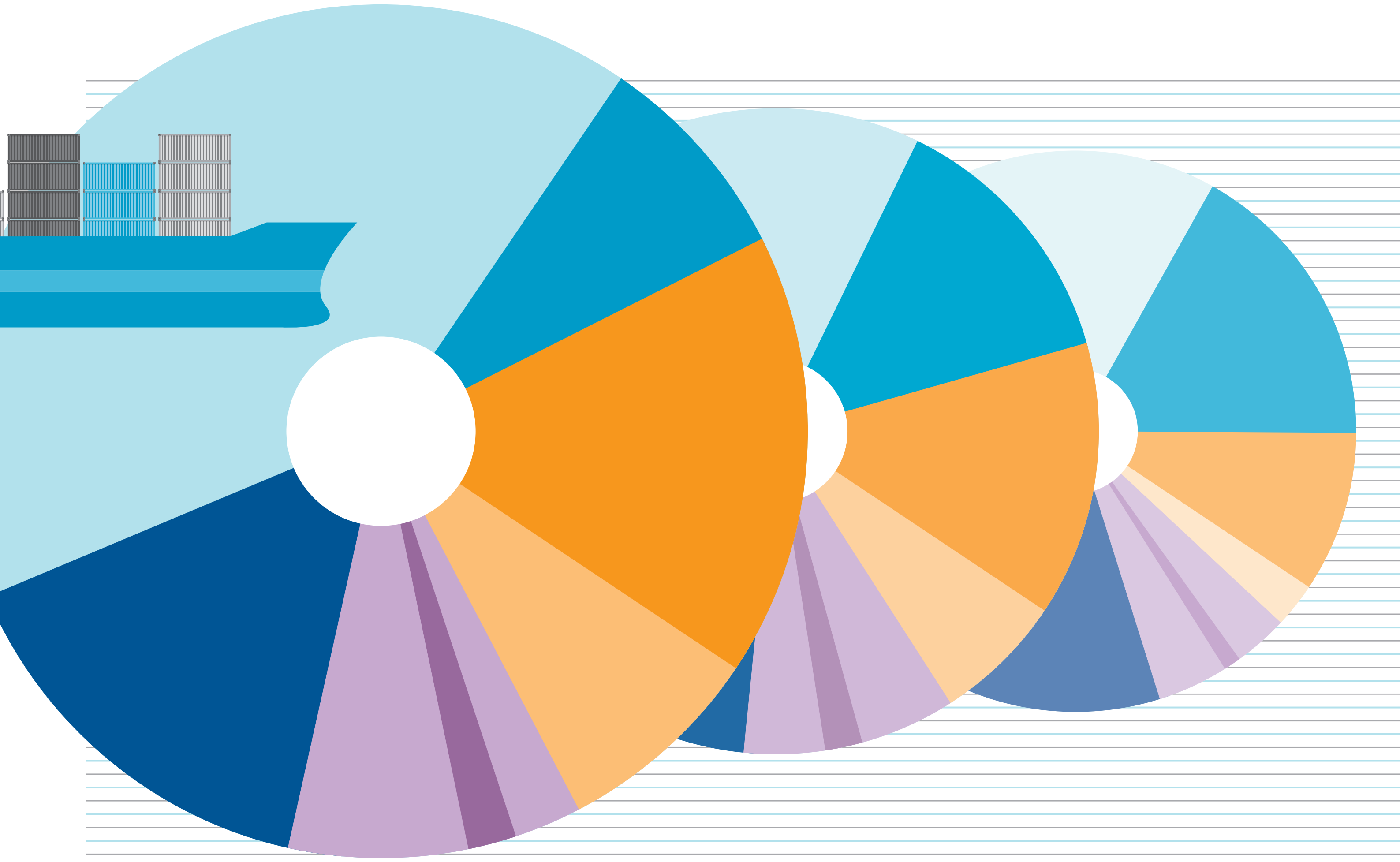
Although the share of LNG ships and LNG vehicles increases steadily in the Pro-LNG scenario, it cannot be assumed that the dominant powertrain technology – the diesel powertrain – can be wholly replaced in the period considered, i.e. diesel powertrains will still form the backbone of ship and HDV propulsion by 2040. Instead, a substantial part of the existing fleet will be exchanged for LNG vehicles and ships, in order to determine the potential impact of LNG technology on fuel consumption and greenhouse gas emissions. The LNG implementation pathways considered can be achieved by regular fleet turnover.

Other alternative powertrains and fuels, such as biofuels and electrical powertrains, including hydrogen fuel cells, will not be examined in this scenario. The focus will be solely on the **effect of LNG powertrain technology and LNG fuel** on the dominant technology, in other words the diesel powertrain and diesel fuel.

Finally, it should be pointed out that the projection of possible futures for LNG in ships and heavy-duty vehicles is a scenario and scenarios are not forecasts. Nor is the Pro-LNG scenario a target scenario. Instead it aims to "**explore**" future powertrain and fuel developments and to present a possible and plausible development for LNG in shipping and road freight transport.

In a first step, the method and approach used for the following quantitative scenario analyses are presented. The fundamental framework conditions and drivers for the Pro-LNG scenario are then described qualitatively. In the third step, the development of the future transport demand and transport tonnes-kilometres (tkm) of ships and heavy-duty vehicles is illustrated on the basis of relevant international and European transport scenarios.

The expected transport trends and further assumptions are then used as a basis for developing Pro-LNG scenarios for shipping and heavy-duty vehicles. Finally, the main quantitative results of the scenarios are presented.

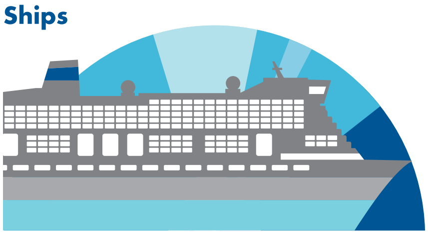


As this is a differential analysis, it includes the possible substitution of LNG powertrains for diesel powertrains in ships and HDV in the respective fleets, the respective LNG fuel consumption and the diesel or heavy fuel oil consumption replaced by LNG fuels, as well as the possible impact on the greenhouse gas emissions of the use of LNG fuels by seagoing ships and heavy-duty vehicles.

6.1 METHOD AND APPROACH

A similar method is used for the scenario sections for ships on the one hand and rigid trucks over 16 t GVW and tractor units on the other. That applies particularly for the desired outputs (LNG fleets 2040, LNG consumption and impact on greenhouse gas emissions). However they differ because of the data and sources available for each sector and the respective transport conditions. The method and approach for the scenarios for HDV and ships are therefore outlined in separate sections.

Ships



The analyses and forecasts of SEA Europe (the Shipyards' and Maritime Equipment Association) were used as a source for the development of ship new constructions (SEA 2017, 2018). The UNCTAD (United Nations Conference on Trade and Tariffs) databases were consulted as a source of information about the global merchant fleet (number of ships, composition, age etc.) (UNCTAD 2017, UNCTADstat 2018); the annual report of the German Naval Command (Deutsches Marinekommando) was also used (DM 2018).

Assumptions about the relationship between new and scrapped ships in the main classes of ship were derived from these sources. LNG propulsion systems are phased in to each category of ship depending on the suitability or affinity of the ships for LNG propulsion systems and LNG fuel. The total of all categories of ship examined provides an idea of the development of the whole fleet of ships and the share of LNG ships in that fleet. As seagoing ships have long service lives, scrapping plays a minor role in fleet changes for a scenario horizon of 2040.

The fuel consumption of ships is determined by the power required under the particular operating conditions and the specific fuel consumption. The latter is as important as the effectiveness and efficiency of the propulsion system. Ships' engines are by far the most efficient prime movers and there is very little potential for increasing their efficiency. In addition, a further increase in efficiency conflicts with the targets for exhaust gas emissions such as nitrogen oxides. The scenario therefore assumes that there are no further efficiency increases or that any increases are negligible. That also applies to the engines or propulsion systems using LNG as a fuel. There is essentially no difference in efficiency between natural gas (LNG) and diesel engines.

The power required by a ship is fundamentally affected by its speed, as it increases by a power of three to four with speed. This indicates that fast ships require considerably more power than slow ships of the same size. Containers and cruise liners, for example, require considerably more power than bulk carriers and oil tankers. The draught and displacement of a ship, weather conditions (including wind direction and the direction of the current) and the condition (roughness) of the outside of the hull and propellers also affect the energy consumption (Bialystocki/Konovessis 2016).

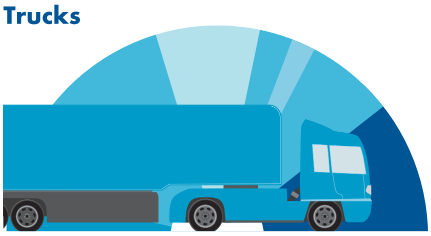
In addition to the power required to propel a ship, the on-board electricity requirements must also be taken into account, because this energy is also produced by the engines. Cruise liners, for example, require almost as much energy for their complex hotel operations as they do for propulsion and this energy is also required when they are in port. The last relevant factor is the efficiency of the overall system. This includes the efficiency of the design (how much propulsion is needed to reach a particular speed) and on-board operation (how power-saving measures are implemented in the hotel operation).

The fuel consumption of the types of ship considered is estimated on the basis of empirical values for the average amount of power required for propulsion and on-board operations. Simplified operating and power profiles are used to distinguish between time at sea (propulsion and on-board power are required) and time in port (only on-board power is required); the annual number of days in use is also estimated (in a similar way to IMO 2015). Efficiency increases achieved by the ship's design and on-board electricity consumption are taken into account in accordance with the guidelines of the Energy Efficiency Design Index (EEDI).

The current efficiency and specific fuel consumption are applied over the entire scenario period. In the end, the annual LNG consumption is derived from the share of the power requirements when at sea and in port and the specific fuel consumption. The latter is converted into the respective amounts of fuel via the assumption of energy equivalence (equal specific energy consumption for diesel and natural gas engines) and the calorific values of natural gas or liquid fuel. The total amounts of LNG and the liquid fuel replaced are determined.

The greenhouse gas emissions of the fleet of LNG ships examined are calculated by means of energy source-specific greenhouse gas factors, taking account of the possible effects of methane slip. The resulting greenhouse gas emissions for LNG ships are compared with those for diesel-powered ships.

Trucks



A model is produced for rigid trucks over 16 t GVW and tractor units in the EU 28, in order to determine the age profile of the fleet and to extrapolate it up to 2040. This is based on country-specific data (EU 28) from Eurostat's (the statistical office of the European Union) long-term data series for the registration of new tractor units (Eurostat 2018b) and the size of the tractor unit fleet (Eurostat 2018a) from 1979 onwards, and on the ACEA's (European Automobile Manufacturers Association) country-specific statistics for the registration of new rigid trucks over 16 t GVW from 2003 onwards (ACEA 2017). The number of heavy-duty vehicles in the fleet is calculated simply as the difference between all commercial vehicles and those vehicles of over 16 t GVW (Heavy Commercial Vehicles) and tractor units.

In the first stage of modelling, mortality curves are produced from the cohort-related data for heavy-duty vehicles and these are used to determine the number of vehicles in each vehicle class that are retired each year. The sum of these cohort-related data is the current total number of heavy-duty vehicles from a particular year in the fleet. In the second stage of modelling, the vehicle fleet for the two classes of heavy-duty vehicle under consideration with an LNG powertrain is developed. The penetration of the LNG powertrain throughout the vehicle fleet investigated is described by means of the annual difference between the fleet of all vehicle classes and the fleet of vehicles with an LNG powertrain.

In the next calculation stage, a steadily increasing share of LNG truck registrations up to 2040 is assumed on the basis of the number of heavy-duty vehicles registered in 2016. This produces a fleet that contains heavy-duty vehicles both with a diesel powertrain and with a gas engine fuelled by LNG. Both heavy-duty vehicles with a gas engine with a stoichiometric air-to-fuel ratio of Lambda = 1 (spark-ignition engine) and heavy-duty vehicles with HPDI (High Pressure Direct Injection) gas engines are phased in. Since the two types of LNG engine are not equally efficient, the assumed market penetration of each type may result in differences in the expected demand for LNG fuel.

A specific, average fuel consumption for each year is derived from the resulting vehicle fleet composition. This is based on a specific, average fuel consumption for the three types of HDV powertrain examined – diesel and two alternative gas powertrains – in the reference year 2016. The specific, average diesel (in litres) and LNG (in kg) consumption of a fleet vehicle per 100 km is then determined from this. This calculation takes account of the fact that, as a result of technological developments, new trucks with both diesel as well as gas powertrains will become more efficient from year to year, so the specific fuel consumption for newly registered heavy-duty vehicles will steadily fall.

A specific, average consumption value for a HDV is used as a basis for calculating the annual fuel demand of an LNG vehicle and the diesel fuel consumption it replaces. This is done by multiplying the vehicle fleet for each year by the annual average distance travelled by each vehicle and the specific average fuel consumption. The annual average distance travelled is based on the German transport performance survey (IVT 2017). This bottom-up approach produces the absolute demand for LNG fuel and the simultaneous diesel fuel saving for heavy-duty vehicles in the Pro-LNG scenario. It can then be compared with the diesel fuel substituted.

Finally, energy source-specific greenhouse gas factors are used to determine the annual absolute greenhouse gas emissions of the vehicle fleet from the absolute LNG consumption. Different greenhouse gas factors are used depending on whether the LNG is produced from fossil or renewable (bio) resources. The greenhouse gas calculation also takes account of methane slip. The resulting greenhouse gas emissions for the LNG truck fleet are compared with those of heavy-duty vehicles fuelled by diesel fuel (B7) instead of LNG.

6.2 FRAMEWORK AND DRIVERS

Before moving on to the quantitative scenarios, the most important framework conditions and determining factors for the launch of the LNG market are described in an analysis of the socio-economic environment. The factors influencing LNG development are divided into four categories: Society and politics, users and operators, technology and powertrains and energy and fuels.

Firstly, society and politics establish important basic conditions which affect the way people choose and use vehicles, powertrains and fuels. Some political and social trends are also enforced by customer demand. In the end, transport service providers must reflect their customers' requirements and expectations, and these affect the selection of modes of transport or the choice of powertrain and energy source.

The decision to use particular configurations of powertrain and fuel is made by the operators of heavy-duty vehicles and ships. When making this decision, both the road freight transport and shipping operators are guided first and foremost by technical and economic criteria, and particularly the Total Cost of Ownership, to enable them to provide transport services efficiently. Other "soft" user preferences, which do not relate to technical or economic parameters, are sometimes also considered.

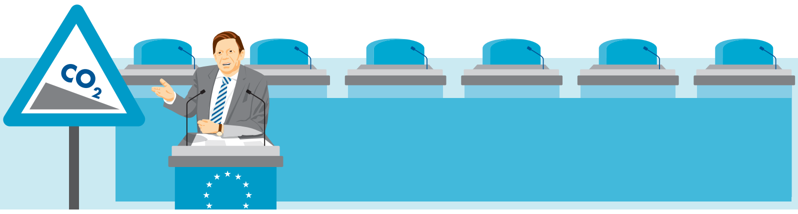
The overall costs for heavy-duty vehicles and ships are affected both by investment in the technology and the availability and price of the fuel, which includes the cost of the infrastructure and logistics needed to supply the fuel. It is assumed that the use of LNG does not entail any substantial disadvantages in terms of personnel, insurance, servicing and maintenance costs, in comparison with the main competitors hitherto (diesel, marine gasoil and heavy fuel oil), and these have therefore not been considered here.

Those using LNG as an alternative fuel ultimately want any remaining differences between LNG and conventional fuels to be balanced out by future developments in the fuel infrastructure and technology. It is also assumed that no restrictions on the amount of goods transported will be imposed on users. Furthermore, the more advantageous running costs in terms of energy and exhaust gas aftertreatment should make LNG a more attractive option for the user than petroleum-based fuels in the long term, particularly for ships.

Each of the four categories of influencing factors is described separately for shipping and road transport, although some common frameworks are required for both modes of transport. For example, sufficient availability and competitive pricing are essential to the expansion of LNG.

As a baseline, it can be assumed that the LNG infrastructure will develop in line with the EU AFID Directive (EP/Council 2014) but, in an LNG-specific scenario, will go beyond this.

An extensive network of large LNG import terminals, from which tankers or trucks can supply small storage terminals, from which, in turn, bunkering barges or tank vehicles can supply LNG to smaller ships and fuelling stations, appears to be the optimum solution from a macroeconomic perspective. Supplying single ships under individual contracts with LNG suppliers, on the other hand, increases the bunkering and logistics costs for the distribution of LNG to the consumer, because the infrastructure is not sufficiently developed.



SHIPS

Ambitious national and international energy, environmental and transport policies place greater demands on shipping. Public pressure is greatest on the operators of passenger ships, particularly cruise liners, but it increasingly extends to shipping via ports and coastal settlements.

Political attention focuses primarily on the air pollutant emissions from shipping (SO_X / particulate matter / NO_X), particularly near residential areas. As a result of its increasing share of global greenhouse gas emissions, shipping also finds itself in the spotlight of international climate policy. Given the predicted growth in maritime transport, the primary objective is to reverse the trend in shipping-related greenhouse gas emissions.

National and international policy-makers rely on a bundle of ship-, propulsion- and fuel-related measures to achieve their environmental targets. The further development of the energy efficiency index for seagoing ships (EEID) contributes to a reduction in the specific greenhouse gas emissions of ships. The international shipping sector is involved in regional emissions trading, which provides additional incentives for achieving greenhouse gas savings through efficiency, operation and/or fuels. In the end, legislation is introduced to regulate propulsion-related methane emissions also, because of the growing proportion of LNG ships in the fleet.

An increasingly strict air pollution policy leads to even more stringent emission standards for seagoing and inland navigation ships. In addition to this, the Emission Control Areas (ECAs) for international shipping are constantly extended worldwide, resulting in an increased global demand for low-emission propulsion systems and fuels (such as LNG).

International shipping, and particularly the main classes of cargo ship – container ships, bulk carriers and tankers – is dominated by diesel technology. So far, LNG is the only serious alternative to diesel as a fuel and propulsion system for shipping. However, to accelerate market penetration, LNG fleet operators must be compensated for the higher cost of investment and operation. National and regional (EU) support schemes are therefore subsequently developed for LNG ships, infrastructure and fuels. However for shipping, unlike road transport, there are no fiscal options (fuel taxes), as bunker fuels are not taxed internationally. Inland navigation, on the other hand, can be supported in the same way as road transport.

HEAVY-DUTY VEHICLES

National and international authorities pursue ambitious energy, environmental and climate targets for road transport. The growing international division of labour and the associated global boom in logistics lead to a disproportionate increase in greenhouse gases from road freight transport. As a result of this, the commercial vehicle sector comes increasingly under the spotlight of environmental policy; this is particularly true of heavy-duty vehicles, which operate mainly on long-distance routes and by far account for the greatest share of the final energy consumption of road freight transport.

Road freight transport must reverse the current trend by reducing its greenhouse gas emissions worldwide in the future. HDV must also contribute more towards air quality improvements and noise reduction in road transport. A number of regulatory and funding measures are introduced to achieve these political aims.

The CO_2 limits for heavy-duty vehicles introduced towards the end of the 2010s are developed continuously up to 2040. The EU standards for the reduction of CO_2 emissions from commercial vehicles make LNG an attractive fuel both for the vehicle industry and for users, because it has a lower carbon content than diesel. Regional CO_2 and renewable energy regulations also offer incentives for phasing in fuel components low in greenhouse gases, such as biogas or synthetic gas from renewable energies.

Alongside the climate policy, the air pollution and noise policies also become stricter, particularly in urban areas. This favours clean and quiet technologies and fuels for heavy-duty vehicles, such as LNG and spark ignition engines fueled by LNG.

However, it is still very difficult to establish alternative powertrains and fuels alongside diesel technology, particularly in long-distance road freight transport. Policy-makers therefore also pursue a funding policy that is broadly open to any technology for alternative powertrain and fuel options. This benefits LNG vehicles, which have higher investment costs than diesel vehicles. However, targeted financial support for LNG vehicles in the market establishment phase improves the long-term commercial competitiveness of LNG vehicles by driving costs down. Funding measures for the expansion of the LNG infrastructure and LNG vehicles are supported by energy tax measures such as temporary reductions in fuel taxes or lower tolls.

USERS AND OPERATORS

SHIPS

For shipowners, the diesel engine continues to be the economic standard in maritime transport because of its cost-effectiveness. However, with the extension of ECAs, it becomes increasingly expensive to comply with international emission limits with diesel technology, as it requires either investment in exhaust gas aftertreatment equipment (scrubbers, catalysts) or the management of different fuel mixtures (various types of heavy fuel oil and marine gasoil). Scrubbers, in particular, which are tail pipe aftertreatment systems, are unable to achieve sufficient market acceptance.

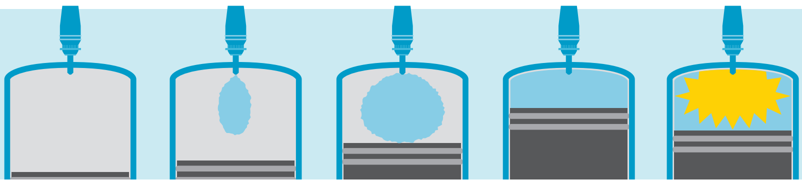
Driven by the early adopters in the cruise and ferry sectors, the use of LNG gradually becomes more widespread among seagoing and inland navigation ships. Dual-Fuel engines are installed initially as an alternative propulsion system in new ships; in addition, an increasing number of diesel ships are subsequently retrofitted. Incentives are created for ship builders and operators to consider natural gas-fuelled propulsion systems for their fleets, not least by the regional funding of new ships and retrofits.

HEAVY-DUTY VEHICLES

Diesel continues to be the standard powertrain technology for road freight transport, particularly long-distance transport, in terms of its cost-effectiveness and efficiency. However, haulage companies and fleet operators in the road freight transport sector are under increasing pressure from their customers to reduce greenhouse gas emissions, air pollutants and noise emissions still further. This can no longer be achieved by optimising the diesel powertrain, not least because of the ever stricter emission regulations.

For the foreseeable future, electric powertrains will only come into widespread use for heavy-duty vehicles travelling short daily distances. Some users and fleet operators therefore see the advantage of the lower pollutant and noise emissions of HDV running on LNG. Government support also makes the use of LNG technology attractive. The haulage companies can utilise the advantages of LNG technology to gain a competitive advantage which they can use when dealing with shipping agents and supply customers, for example.

TECHNOLOGY AND POWERTRAIN SYSTEMS



Only slight improvements in efficiency reserves can be achieved in the backbone of international shipping, the slow-speed two-stroke engine. In the short term, no alternative propulsion systems and fuels are available, particularly for sea shipping. The development of natural gas-operated ship propulsion systems is therefore accelerated by international and, increasingly, regional regulations with significant usage restrictions.

Dual-fuel engines gain wide acceptance in shipping since they are more efficient and reliable than diesel propulsion systems. Their air pollutant emissions are also much lower when operating in gas mode, which offers ship operators a genuine competitive advantage, given the higher air pollution levels in the ECAs and in sea and inland navigation ports.

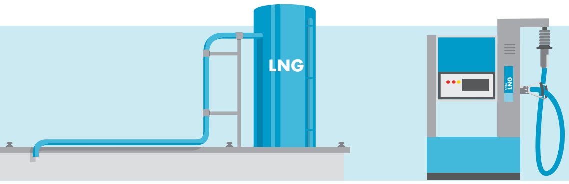
Gas propulsion systems also have lower combustion-related CO_2 emissions than diesel engines because of the lower carbon content of the fuel. Technological solutions for reducing operation-related methane emissions are developed and implemented in the medium term as a result of regulatory incentives for improved vehicle technology.

Diesel powertrain technology is also advancing. European regulations on fuel consumption, CO_2 and exhaust emissions, and air pollution standards are continually moving forward. However, the technological expense of additional efficiency measures and exhaust gas aftertreatment in vehicles continues to rise in the medium term.

Given the steady rise in development and production costs, it is more difficult for the diesel powertrain to maintain its position as the sole powertrain technology for all commercial vehicles and commercial vehicle applications. While electrical powertrains are gaining wider acceptance for lighter goods vehicle applications, the use of LNG-natural gas technology in the heavy-duty vehicle class is growing.

A lot of progress is made with the technological development, particularly of gas engines, for example. Gas powertrains for spark ignition engines are able to reduce the efficiency gap with diesel vehicles. For the registration of new vehicles, natural gas powertrains also offer the advantage of lower direct greenhouse gas emissions than diesel vehicles.

ENERGY AND FUELS



SHIPS

Global natural gas resources prove to be even larger than expected today. The sharp increase in production and growing international trade in liquefied natural gas (LNG), coupled with the rapid expansion of LNG terminals, ensures that LNG is widely available. The number of LNG bunkering stations increases rapidly with the aid of government support. LNG can be bunkered at all major international sea ports and in ECAs.

The wide availability and competitive pricing of LNG make it attractive to shipping, particularly when compared with the other compliance options in the ECAs. LNG is therefore used much more frequently in the ECAs. Inland navigation benefits from the expansion of the LNG infrastructure for road freight transport.

Although shipping is under increasing pressure from stricter greenhouse gas regulations, there is as yet no real possibility of using alternative fuels other than LNG in shipping in the medium term. Hence, only fossil variants of marine fuels are considered here.

HEAVY-DUTY VEHICLES

Global natural gas resources prove to be even larger than expected today. The sharp increase in production and growing international trade in liquefied natural gas from North America, Africa and the Middle East, provides the transport sector with a new, competitively priced energy source. Home heating and electricity production also release natural gas for the European transport sector in the long term.

As long-distance road freight transport primarily uses long-distance transport corridors, a relatively small number of LNG refuelling stations is needed to cover the network. Therefore, a suitable LNG infrastructure can be established relatively quickly along the main long-distance road freight transport routes.

Under pressure from greenhouse gas regulations, fossil LNG is blended with 30 % biogas, as is now the case with CNG (Compressed Natural Gas) marketed in Germany. Power-to-Gas projects are occasionally also used to reduce emissions.

6.3 LONG-TERM TRANSPORT FORECASTS

Quantitative scenarios for freight transport with LNG ships and HDV are based on the projected freight transport tonne-kilometres, which are determined essentially by the distances travelled by the vehicle or ship. The development of freight transport tonne-kilometres correlates closely with the development of economic activity. Economic growth and international trade determine the demand for transport services.

Global reference scenarios for all modes of transport are provided by the Organisation for Economic Cooperation and Development's (OECD) International Transport Forum (ITF) (OECD/ITF 2017); for the EU, the European Commission prepares an EU reference scenario for the transport sector (EU-COM 2016). The main assumptions and results for the modes of transport mainly relevant to LNG – shipping, inland navigation and road freight transport – are summarised below.

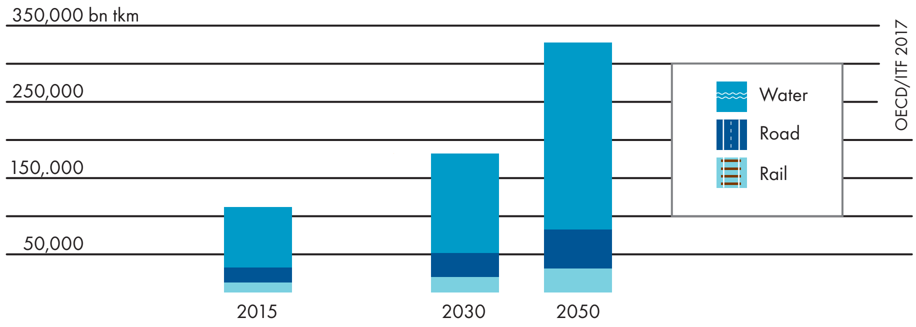
Global freight transport projections

The basic scenario of the International Transport Forum expects global freight transport performance to grow significantly from around 112,000 to around 329,000 bn tonne-kilometres in 2050 (OECD/ITF 2017, figure 54). Shipping is particularly important, since it accounts for 71 % of today's global freight transport in tonne-kilometres. Road and rail transport follow with 18 % and 11 % respectively. The North Pacific, the Indian Ocean and the North Atlantic are the major global routes.

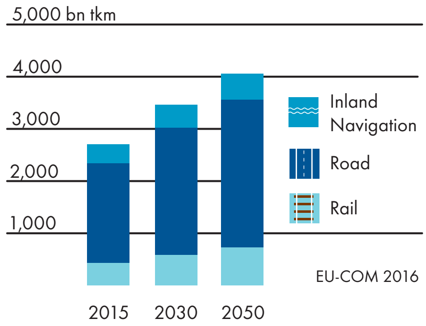
In the OECD, road transport accounts for the largest share of freight transport tonne-kilometres of land-based modes of transport (road and rail, excluding inland navigation) by a ratio of about 2 to 1 (OECD/ITF 2017). Inland navigation has barely any significance internationally, as very few countries have major inland navigation routes and the data for this is also incomplete. According to the most recent figures (2016), inland navigation accounted for 6.1 % of inland transport volumes in the EU (Eurostat 2018e). Compared to the other modes of transport airfreight transport in tonne-kilometres is rather small.

The transport of maritime shipping is expected to more than triple from around 80,000 bn tonne-kilometres to 245,000 by 2050. But road and rail will also transport two-and-a-half times more than today by 2050; road freight transport will increase globally by just under 20,000 to over 50,000 bn tonne-kilometres (OECD/ITF 2017).

54 DEVELOPMENT OF GLOBAL FREIGHT TRANSPORT



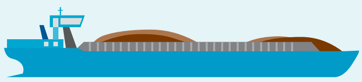
55 DEVELOPMENT OF EU FREIGHT TRANSPORT



European freight transport projection

According to the current EU reference scenario for 2050, freight transport in the European Union will increase from around 2,600 to just over 4,000 bn tonne-kilometres, an increase of 58 %, in the period 2010 to 2050 (EU-COM 2016, figure 55). This is due partly to higher economic growth and the continuous expansion of the Trans-European Transport Networks (TEN-T).

Road freight transport has a share of around 75 % of the European modal split (excluding maritime transport, as at 2016, Eurostat 2018e). Road transport will increase from around 1,800 to over 2,800 bn tonne-kilometres between 2010 and 2050 – a rise of 57 %. The corresponding share of road transport in the modal split will fall only very slightly (EU-COM 2016). The current ITF base scenario forecasts that the transport performance of all land-based modes of transport will double by 2050 (OECD/ITF 2017). Shipping – marine transport within the EU and maritime trade with third countries outside the EU – will increase by around 70 % by 2050. Inland navigation (including short sea shipping) will increase from around 361 to 500 bn tonne-kilometres, or by 39 % (EU-COM 2016). In spite of the uncertainty about long-term economic development, most economic and transport forecasts or projections are based on the assumption of economic growth, growing trade and



LNG IN INLAND NAVIGATION

There is also potential for using LNG in inland navigation, although it is much lower, quantitatively speaking, than in shipping and road freight transport. Inland navigation ships have a share of only 6.1 % in the EU modal split; over 70 % of transport by inland navigation ships in the EU takes place in only two countries (Germany and the Netherlands) and around 85 % of EU inland navigation in the Rhine basin (EU-COM/CCNR 2018).

In addition, the approximately 13,500 EU inland navigation ships have a relatively low fuel demand and it will take a long time to phase in LNG propulsion systems given the low fleet renewal rate. Nevertheless, EU inland navigation could still take on a pioneering role in mobile applications for LNG if, for example, public funding were available to retrofit old ships, or build new ones, with LNG propulsion systems with the aim of improving air quality, or to expand the LNG infrastructure in accordance with the EU AFID.

The **LNG Masterplan for Rhine-Main-Danube** is a project to explore the potential of LNG in EU inland navigation ships. Quantitative analyses of the LNG infrastructure and LNG demand of EU internal navigation for the Rhine and Danube region were carried out as part of this project, which was funded within EU's TEN-T programme.

The possible development along the Rhine and Danube was investigated in a reference scenario and a scenario of high and low LNG demand for each river. These scenarios estimated the LNG demand for short sea shipping, inland navigation and commercial vehicles for 2020 and 2035 (BCI et al. 2015). The resulting annual LNG demand estimates for inland navigation along the shipping routes considered are shown in Table 56.

The scenarios of the two studies on which the LNG demand was based assume that, in addition to inland navigation, short sea shipping, road transport and industry will generate further LNG demand which, particularly for road transport,

56 LNG DEMAND OF EU INLAND NAVIGATION TRANSPORT FOR 2020 AND 2035

	Development of the LNG demand (in 1,000 t)					
Waterway	**Low scenario**		**Reference scenario**		**High scenario**	
	2020	2035	2020	2035	2020	2035
Lower Rhine	9	379	126	1,149	360	2,147
Upper Rhine	2	84	30	241	76	385
Danube		264		307		335

BCI et al. 2015; FHOÖ et al. 2015

will be around five times higher than the demand for inland navigation. In other words the LNG demand of inland navigation alone will not be sufficient to provide the necessary LNG infrastructure along both of the river corridors. Instead, a broader LNG demand will be required, from road transport, industry or short sea shipping. The reference scenario puts the total demand of inland navigation along the Rhine and Danube corridor at over 1.5 mln t of LNG a year, by far the highest potential LNG demand being in the Lower Rhine region. However, it must be said that the range of the LNG scenarios is very wide because of the high level of uncertainty about price developments and basic regulatory conditions in the individual regions.

a corresponding increase in the demand for freight transport volume and tonne-kilometres. A steady increase in vehicle mileage can therefore be assumed for the quantitative estimation of future LNG use in ships and HDV. Even if further progress is made on efficiency in logistics and vehicle powertrains, the question is how much the demand for an alternative fuel such as LNG could increase, given this growth in transport.

SCENARIO FOR SHIPPING

After the framework conditions and drivers for the development of the shipping sector have been discussed and scenarios for the future freight transport tonne-kilometres have been presented, a quantitative scenario forecast for global shipping will be outlined in three stages:

In the first stage, the development of the global shipping fleet will be extrapolated up to 2040 on the basis of the main classes of ship. In the second stage, the absolute LNG fuel consumption and the marine gasoil and heavy fuel oil consumption replaced will be estimated. And in the third stage, energy source-specific greenhouse gas factors will be used to determine the greenhouse gas emissions resulting from the estimated fuel consumption for LNG, and these will be compared with the greenhouse gas emissions originating from the marine gasoil and heavy fuel oil consumption replaced.

A separate quantitative analysis will not be carried out for inland navigation. Instead, the available quantitative scenario forecasts for the possible expansion of LNG in European inland navigation along the Rhine and the Danube are summarised in the box above.

Fleet projection

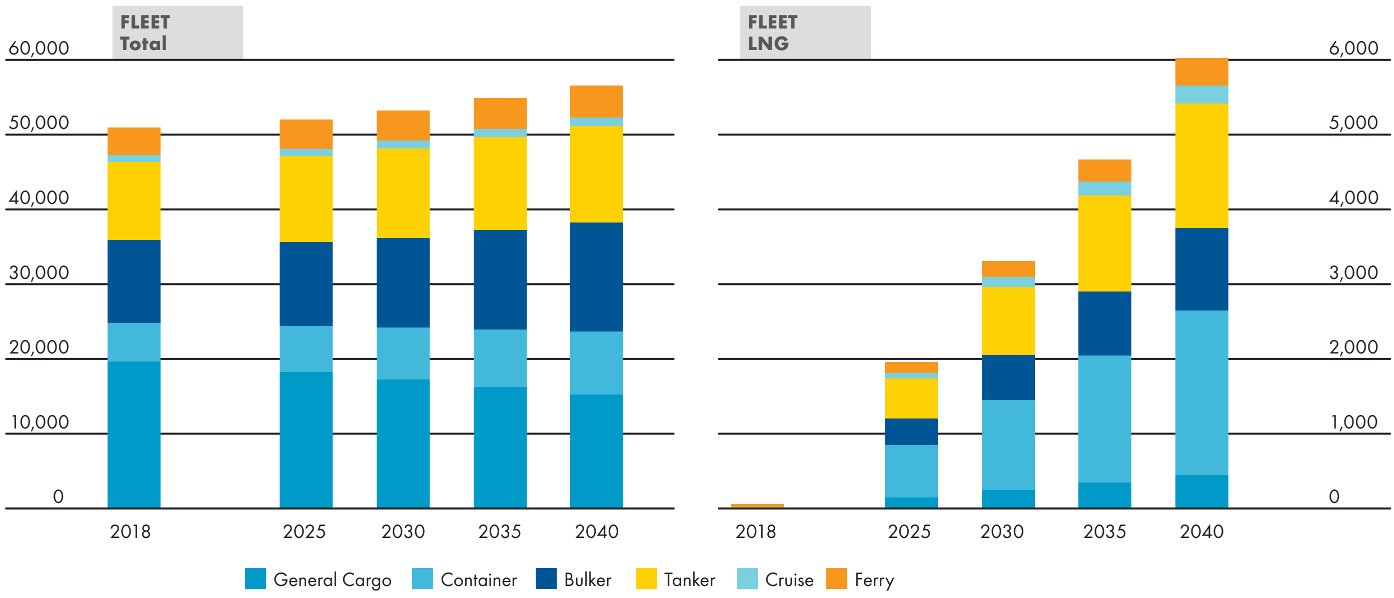
The forecast for the shipping fleet up to 2040 is divided into the different types of ship described in Chapter 4, namely multi-purpose vessels, container ships, bulk carriers, oil tankers and passenger ships and cruise liners.

The method used is to estimate the number of scrapped and new ships as a proportion of the total number of ships of a particular type. The average size of the reference ships is assumed to be constant, as both smaller and ever larger ships are being built in each class. For example, larger numbers of smaller container feeders are needed, but the size of the large container ships is increasing all the time. The same applies to cruise liners: although ever larger cruise liners are being built for mass tourism, smaller ships are often also required for exclusive cruise market segments and particular destinations. The assumptions for each type of ship are described below.

It is assumed that the scrappage rate of multi-purpose vessels is roughly equal to the rate of construction of new vessels. However the renewal rate will increase slightly from 1.5 to 3 %, as more than half of the ships are currently over 20 years old (UNCTADstat 2018). The growth of the multi-purpose vessel fleet will stagnate, however, as an increasing amount of freight is transported in containers. It is assumed that 100 new ships will be built each year in the period examined, 20 of which will be equipped with LNG propulsion systems (DNV GL 2018, SEA 2017).

The rate of construction of new container ships will exceed the scrappage rate. At present 150 to 200 ships are scrapped a year (SEA 2017). This is a relatively low number, because the container ship fleet is relatively new at the moment, with an average age of 10 years. The number of scrappages is likely to increase again from

57 DEVELOPMENT OF THE GLOBAL SHIPPING FLEET



2025, and will include even relatively new ships (SEA 2017).

According to current figures, around 250 new ships are built a year. However, this number will rise in future, as a large number of small and medium-sized feeders will be needed for the large carriers. In the period examined, it is assumed that 300 new ships will be built a year, 100 of which will be equipped with LNG propulsion systems.

The scrappage rate for bulk carriers is assumed to be 4% a year, corresponding to an average age of 25 years. The rate for building new ships is slightly higher, at 5%, which corresponds to an annual fleet growth of 1%. This follows from the assumption that there will be an increase in the shipping of bulk goods from 2020 (SEA 2017), since the rising demand for real products is associated with a rising need for raw materials.

In 2016, orders for new ships hit a historical low, at only 48 (SEA 2017). This scenario assumes that 500 new bulkers will be built a year, 10% of them (i.e. 50 ships) equipped with LNG propulsion systems (DNV GL 2018).

It also assumes that oil tankers will be scrapped at the same rate as bulk carriers, i.e. 4% a year. However, as fewer oil products will be transported in future, the fleet will shrink by 1% a year. At present around 250 new ships are added to the fleet every year (SEA 2017).

In the long term, there are likely to be 200 new tankers each year, 75 of which will be equipped with LNG propulsion systems (DNV GL 2018). The large proportion of LNG ships is explained by the fact that public pressure persuades oil tanker operators to spend effort on making their ships more environmentally friendly.

The public pressure to reduce emissions leads to the assumption that 75% of new passenger ships and cruise liners will be fuelled by LNG. A low scrappage rate is also assumed, particularly for passenger ferries, as old ships usually continue to operate in emerging and developing countries.

New passenger ships will be built at a moderate rate, as passenger transport by ship falls in favour of air transport. It is assumed that the fleet will grow by 2% a year, particularly on the European and North America markets (SEA 2017). In absolute figures, there are likely to be 20 new ships each year, 15 of which will be equipped with LNG propulsion systems (SEA 2017).

The cruise industry, on the other hand, will grow relatively rapidly. The scrappage rate will be negligible as the fleet is relatively new. However, in absolute terms, the figures for new and existing ships are low; 15 new ships are likely to be built a year, 12 of which will be equipped with LNG propulsion systems.

The development of the fleet of each type of ship overall, and of those with an LNG propulsion system, is shown in figure 57. The overall fleet of ships in the classes examined will increase by more than a tenth and container vessels will be the most dynamic class of ship. LNG ships will grow much more rapidly than the overall fleet, but from a low base. Container ships and cruise liners will also take the lead here. LNG penetration will be low in other sectors, such as multi-purpose vessels, which have very low renewal rates.

Fuel Consumption

The LNG consumption of each ship is calculated by type of ship. The ship-specific consumption is estimated first on the basis of the power demand and usage profiles, selecting the order on the basis of the complexity of the operating profiles.

Slow-speed two-stroke diesel engines are taken as the reference engine for container vessels, bulk carriers, oil tankers and multi-purpose vessels; passenger ships are powered by various medium-speed four-stroke diesel engines. An average level of efficiency (over the whole power range) of 45 % is assumed for both engine types. This level of efficiency is also assumed in natural gas mode.

Taking account of the heating value of LNG, this results in a calculated volumetric demand of 8.7 m^3/MWd (cubic metres of LNG per megawatt of engine power per day). To allow for fluctuations in the heating value and any additional consumption, a demand of 10 m^3/MWd is taken into account below. The consumption of liquid fuel is estimated in a similar way; the difference results from the lower heating value and significantly higher density. The calculated heavy fuel oil demand is 4.9 m^3/MWd. To allow for the same safety margin of about 15 %, a volumetric demand of 5.6 m^3/MWd is taken into account below.

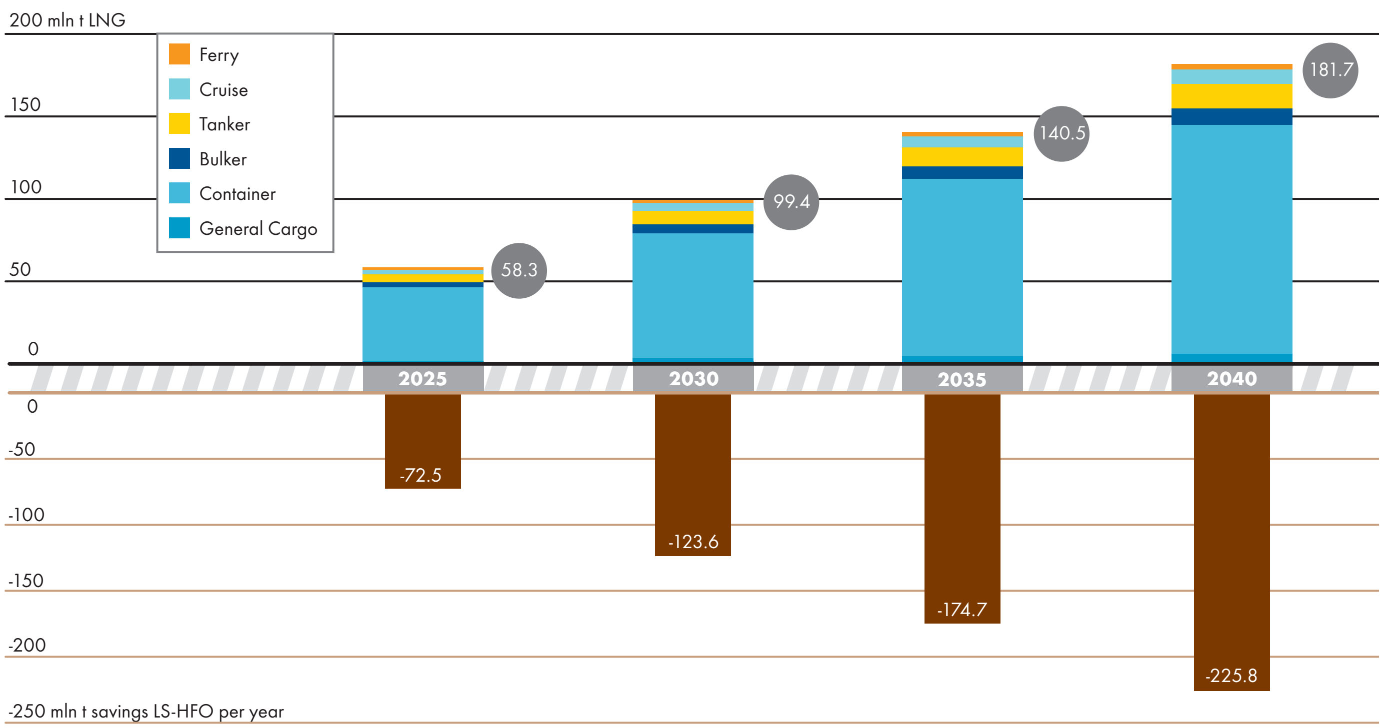
The increases in the efficiency of the ships (propulsion system and on-board operation) specified in the EEDI are taken into account. However, it is assumed that the average size of ships grows to the same extent as their potential efficiency increases. This effect has been seen in container ships and cruise liners in recent years, although the engine power has remained roughly the same. The energy, and hence fuel consumption per ship therefore remains more or less the same in the period examined.

A modern cruise liner of approximately 6,000 PAX has a diesel- or gas-electric propulsion system with an installed electrical power of approximately 60,000 kW, around 35,000 kW of which is required at sea and around 10,000 kW in port. This assumes that all of the power required is generated by the marine fuel, and that no external on-shore power supply, for example is used. If time is split equally between port and sea, the resulting daily consumption is therefore approximately 225 m^3. Tank volumes of 3,000 m^3 are therefore reasonable to achieve a range of fourteen days. A cruise liner consumes just under 80,000 m^3 LNG in around 350 operating days.

A modern container ship of approximately 20,000 TEU has an installed propulsive power of around 55,000 kW. At an average propulsive power of 37,000 kW and an on-board power demand of 3,000 kW, the daily consumption is therefore 400 m^3 and the annual consumption, over 350 operating days, is 140,000 m^3 LNG. To achieve a reasonable range, a container ship requires a tank volume of at least 15,000 m^3.

The annual consumption for bulk carriers and oil tankers is estimated in a similar way. Both types of ship have an average propulsive and on-board power demand of approximately 8,000 kW and are at sea for around 250 days. They spend the rest of the time in port, where the on-board electricity demand is negligible (<1,000 kW). This produces an annual demand of 20,000 m^3 LNG.

58 DEVELOPMENT OF FUEL CONSUMPTION IN SHIPPING



Multi-purpose vessels require approximately 15,000 kW propulsive and on-board power when at sea and 2,500 kW when in port. They spend roughly half of their time at sea and half in port. This produces an annual demand of 30,000 m³ LNG. Passenger ferries require about 10,000 kW propulsive and on-board power when at sea and approximately 1,000 kW when in port. Assuming a half-day operating profile over the whole year, this produces a demand of 20,000 m³ LNG.

Finally, the absolute fuel consumption of the individual categories of ship is calculated by combining it with the forecast number of ships and then compiled for the forecast total fleet of ships.

Figure 58 shows how much LNG is consumed a year by all ships of each type in the period examined. The total LNG consumption could reach 180 mln t by 2040. Given the current annual marine fuel consumption of approximately 330 mln t, primarily of heavy fuel oil (IMO 2016), this seems very high.

This is due to the growth in the maritime transport performance and the number of ships. Container ships are the main reason for the high LNG consumption. They consume the most fuel not only because they have the most powerful engines, but also because the largest number of them have LNG engines. They are also the fastest-growing type of ship.

Container ships will therefore have the highest LNG consumption in 2040, at 140 mln t. Tankers (15 mln t), bulk carriers (10 mln t) and cruise liners (9 mln t) are some way behind this.

LNG is replacing marine gasoil and heavy fuel oil as a marine fuel. It should preferably be used in regions with high regulatory emission requirements (for example ECAs). However, as the supply of marine gas oil is limited (IMO 2016), LNG is mainly replacing heavy fuel oil.

Assuming that the LNG propulsion system is as efficient as the diesel propulsion system, the categories of ship referred to above would have consumed the following amounts of heavy fuel oil in 2040: Cruise liners, 11 mln t, container ships 173 mln t, bulkers 12 mln t, oil tankers 19 mln t, multi-purpose vessels 7 mln t and passenger ships around 4 mln t of heavy fuel oil a year.

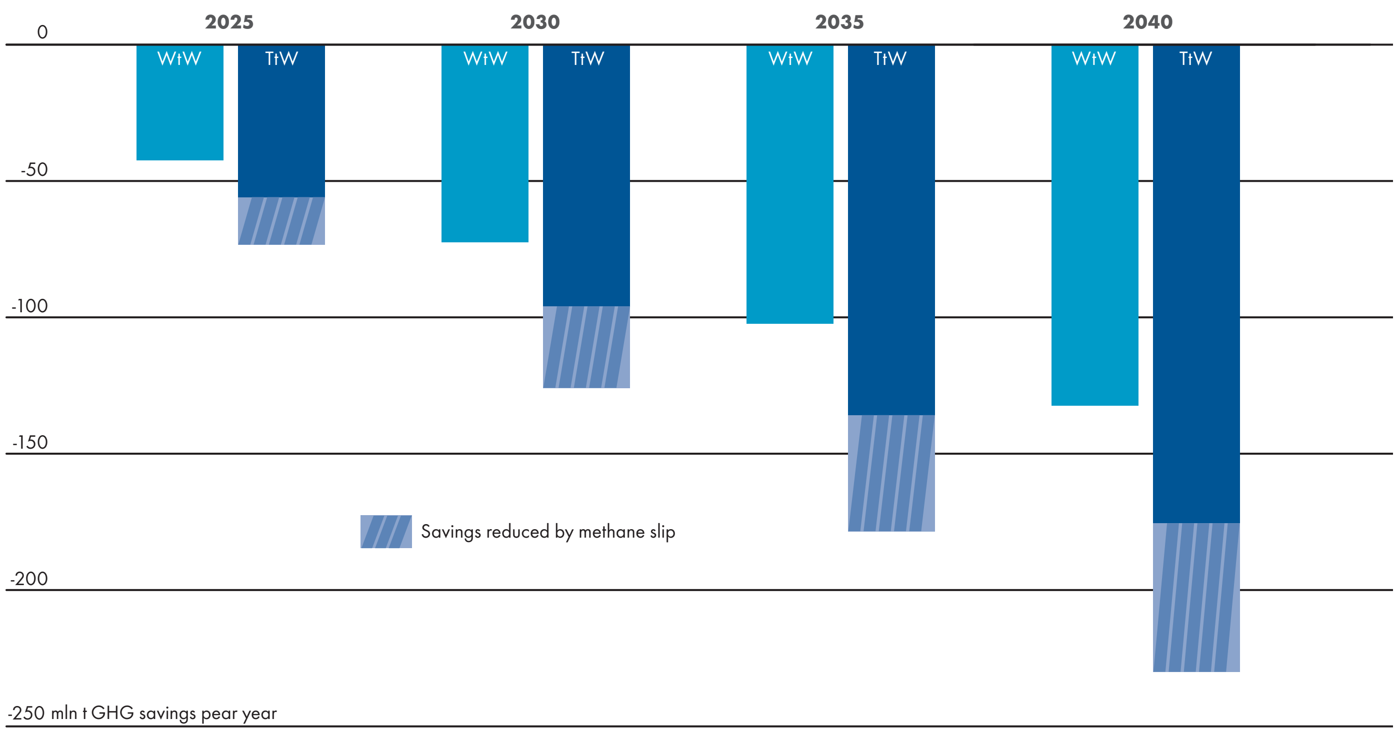
In total, LNG ships replace up to 226 mln t of marine fuels a year in 2040. It should be borne in mind here that ships with diesel propulsion systems are still slightly more efficient than LNG ships, so this should be seen as the maximum estimate of the amount replaced.

Greenhouse Gas Emissions

The differential impact of the use of LNG on greenhouse gas emissions from shipping is determined from the consumption data for LNG ships and the amount of liquid fuel they replace.

Figure 59 shows the greenhouse gas savings achieved by burning LNG instead of heavy fuel oil. A low-sulphur fuel oil (LSFO), which must be used by the majority of seagoing ships from 2020 to comply

59 SAVINGS OF GREENHOUSE GAS EMISSIONS FROM SHIPS



with the IMO sulphur limits, is taken as a reference fuel for this. This produces annual savings of around 230 mln t of CO_2 emissions in 2040 from the use of LNG, from a purely Tank-to-Wheel perspective.

It is assumed here that the average methane or natural gas slip is around 1 % of the quantity of LNG used. This shows that the effect of methane slip reduces the advantage of LNG in terms of greenhouse gas potential by less than a quarter (equivalent to around 54 mln t) to 176 mln t. The greenhouse gas advantage over burning HFO is only cancelled out when methane slip rises above 4 %.

If engine methane slip can be reduced even further, for example by future IMO regulations and accelerated development of technical solutions, greenhouse gas emissions can be reduced to even lower levels. However, from the perspective of today's technology, it will not be possible to exploit the full theoretical potential for eliminating methane slip completely.

While only direct Tank-to-Wheel greenhouse gas emissions have been taken into account until now, emissions in the upstream chain – from the supply of LNG and LS-HFO (Well-to-Tank), will be included in the next stage.

As fossil LNG causes slightly higher specific greenhouse gas emissions in the upstream chain than low-sulphur heavy fuel oil, the absolute greenhouse gas savings in the overall balance (Well-to-Wheel) will fall by around 43 mln t from 230 mln t Tank-to-Wheel to around 187 mln t in 2040.

Allowing for 1 % engine methane slip, a saving of 132 mln t of greenhouse gas emissions will still be achieved in 2040 by using LNG.

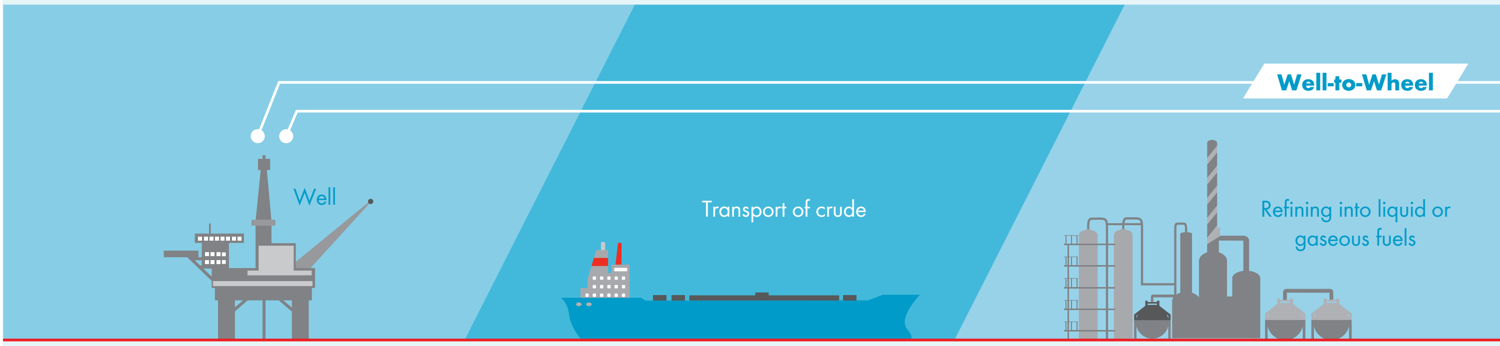
GREENHOUSE GAS FACTORS FOR FUEL

With regard to greenhouse gas emissions, a distinction must first be made between Tank-to-Wheel emissions (TtW), which are produced when fuel is burned in the engine, and Well-to-Tank emissions (WtT), which are caused by the production and supply of the fuel. Well-to-Wheel or Well-to-Wake emissions (WtW) are used to assess the entire supply and usage chain of the fuel, from the source to conversion into kinetic energy. The energy usage chain of the fuel up to full combustion of an energy unit (MJ) without considering engine efficiency is called **Tank-to-Combusted** (TtC) in the discussion below, while the whole energy usage chain is called **Well-to-Combusted** (WtC).

Burning fossil energy sources produces carbon dioxide, which largely determines the greenhouse gas balance of internal combustion engines. Depending on the engine technology, if natural gas is used as a fuel in internal combustion engines it can also escape in its unburned state and release the greenhouse gas methane (methane slip). Other greenhouse gases can also occur in the upstream chains of all fuel types or energy sources. The most important of these other greenhouse gases (methane and nitrous oxide) are also taken into consideration in the overall greenhouse gas balances. Where reference is made to CO_2, the other greenhouse gases are also included in CO_2 equivalents. The terms greenhouse gas (GHG) emissions and CO_2 emissions are therefore used largely synonymously below.

The specific greenhouse gas emission factors were compiled on the basis of the fuel production pathways and fuel-specific combustion factors from the last edition of the Well-to-Wheel study by the Joint Research Centre (the European research platform of the European Commission), Eucar and Concawe (JEC 2014a, JEC 2014b). The European Commission also took account of the basic data from the JEC study when establishing typical and standard values for reducing greenhouse gas emissions for biofuels in the EU Renewable Energy Directive (EP/Council 2009a, 2018b) and the EU Fuel Quality Directive (EP/Council 2009b) (ICCT 2014a).

Diesel fuel / marine gasoil The Well-to-Tank emission factors of the JEC study (JEC 2014a) for diesel fuels were adjusted in line with the recalculation of the greenhouse gas intensity of crude imports into the EU (ICCT 2014b). The greenhouse gas intensity of the diesel fuel from an average European refinery was taken into account according to the



SCENARIO FOR HEAVY-DUTY VEHICLES IN THE EU

After the basic conditions and drivers for the development of road freight transport have been discussed and scenarios for future truck transport have been presented, a quantitative scenario forecast for heavy-duty vehicles in the EU will be outlined in three stages: First of all, the heavy-duty vehicles fleet will be extrapolated up to 2040. It comprises rigid trucks over 16 t and tractor units with semitrailers. The discussion below does not always distinguish between the two. For simplicity, heavy-duty vehicles are also taken to include tractor units.

In the second stage, the absolute LNG fuel consumption and the diesel fuel consumption replaced will be estimated. And in the third stage, energy source-specific greenhouse gas factors will be used to determine the greenhouse gas emissions resulting from the estimated fuel consumption for LNG, and these will be compared with the greenhouse gas emissions from the diesel fuel consumption replaced.

Fleet projection

The need to renew the vehicle fleet regularly results in the registration of new vehicles every year. The number and proportion of newly registered vehicles depends on the development of the vehicle fleet, the age of the vehicles and the number of vehicles retired from service.

Since rigid trucks and tractor units are the most likely vehicles to use LNG fuel, they are the only vehicles considered in the Pro-LNG scenario.

There were 1.82 mln tractor units and 351,000 heavy-duty trucks of over 16 t GVW in the EU 28 in 2016. There are currently no statistics for exactly how many of these vehicles had a gas (CNG or

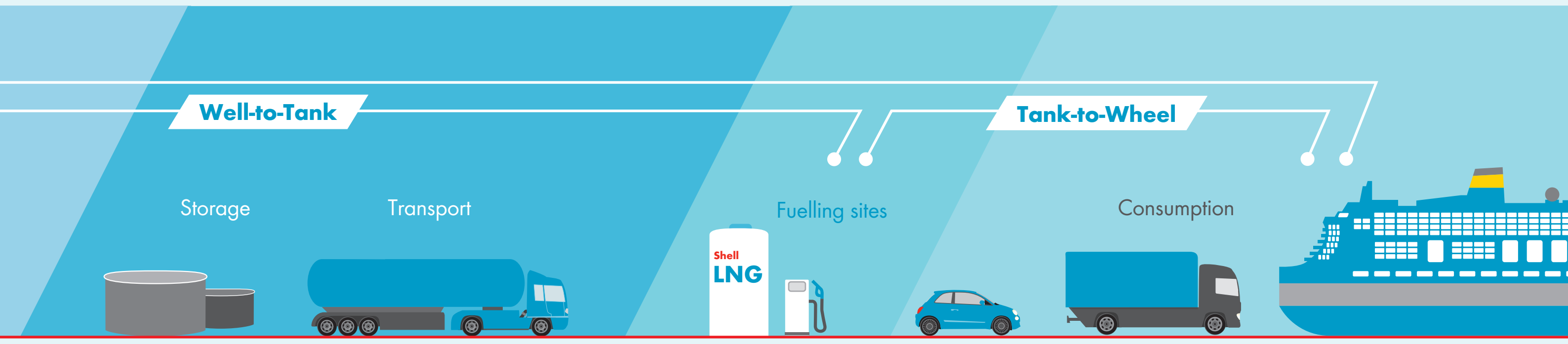
model developed by Concawe in 2017 (Concawe 2017). The CO_2 emission factors for combustion correspond to those of the last JEC Tank-to-Wheel study (JEC 2013). The sulphur content of the diesel is below 10ppm. The same greenhouse gas emission factors were assumed for diesel for long-distance transport and for marine gasoil over the total energy supply and usage chain.

Heavy fuel oil (HFO) The Well-to-Tank and Tank-to-Combusted greenhouse gas intensities of heavy fuel oil for use in shipping were calculated by LBST (LBST 2019) with the method used in the JEC study (JEC 2014a). The greenhouse gas intensities of refinery products were based on the recalculation of the greenhouse gas intensity of crude imports into the EU (ICCT 2014b) and the Concawe model (Concawe 2017).

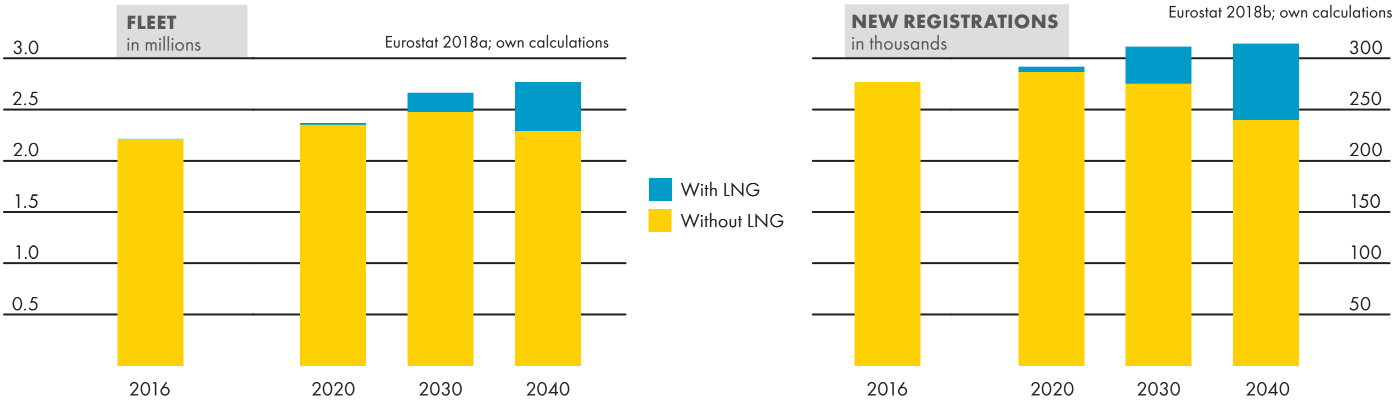
Low-sulphur heavy fuel oil (LS HFO) The Well-to-Tank and Tank-to-Combusted greenhouse gas intensities of low-sulphur heavy fuel oil are based on the calculations for heavy fuel oil but include an additional hydrotreating stage for desulphurisation. It is assumed that the hydrogen is produced either from natural gas steam reforming or from renewable electricity by electrolysis. Heavy fuel oil is assumed to have a residual sulphur content of 0.23 %, which is between the global sulphur content limit of 0.5 % for bunker fuels (very low sulphur fuel oil) which will come into force in 2020 and the sulphur content limit of 0.1 % which has applied in ECAs since 2015 (ultra low sulphur fuel oil). Thus, the influence of desulphurisation on the greenhouse gas intensities of heavy fuel oil can therefore be taken into account principally in the greenhouse gas calculations.

Liquefied natural gas (LNG) It is assumed that the future LNG demand of long-distance transport and shipping will be covered by direct imports and that the LNG will be distributed to vehicles and ships in liquid form. However, the Well-to-Wheel values of the JEC study (JEC 2014a, JEC 2014b) were recalculated by the same method on the basis that liquefaction plants are becoming more efficient (it was assumed that the LNG is imported from the Middle East). The decentralised liquefaction of natural gas (EU mix) from the natural gas network at the dispensing point was also examined as a variant (LBST 2019).

Biogenic fuels (liquid and gaseous) These fuels can be obtained from a variety of plants and substances and produced by different methods; the Well-to-Tank emissions



60 TRENDS FOR HDV FLEET AND HDV NEW REGISTRATIONS IN THE EU



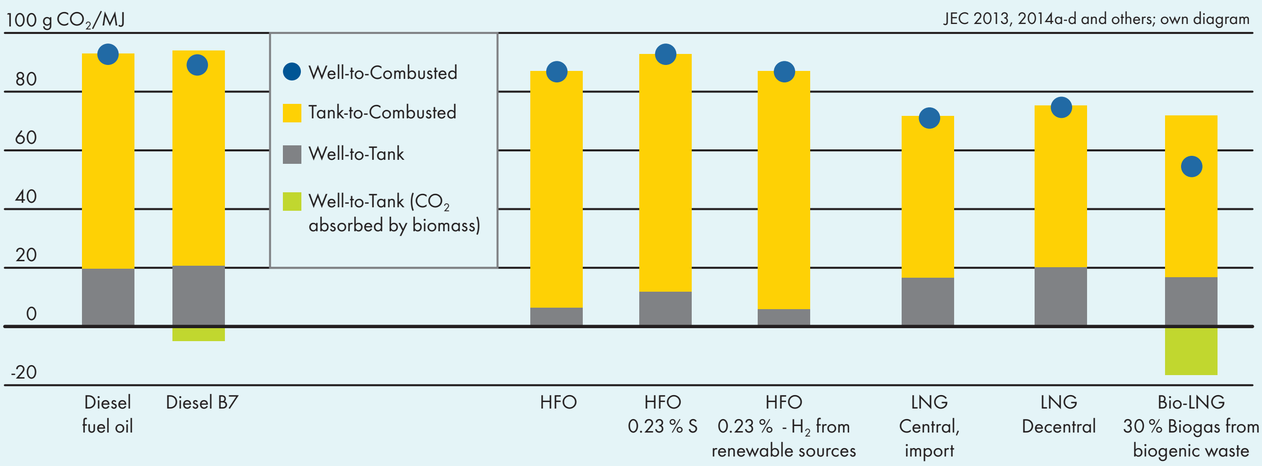
LNG) powertrain. Experts estimate that more than 4,000 LNG heavy-duty vehicles are now in use in the EU 28. 1,642 new LNG vehicles were registered in the EU in 2018 alone (NGVA 2018). In all, around 225,000 new tractor units and 88,000 new rigid trucks of over 16 t GVW were registered in the EU in 2016.

In the Pro-LNG scenario, the numbers of existing and newly registered tractor units are extrapolated up to 2040. The number of new rigid vehicles and tractor units registered annually rises to 307,000 in 2040. This results in a fleet of 2.42 mln tractor units (figure 60). Including rigid trucks > 16 t, the fleet numbers 2.76 mln vehicles.

The Pro-LNG scenario assumed that 10 % of new registrations of trucks over 16 t GVW in 2040 will be LNG trucks and that one in four newly registered tractor units will have LNG tanks and a gas engine. On the basis of these assumptions, the heavy-duty LNG vehicle fleet will be around 480,000 in 2040. Around 17 % of all rigid

can therefore vary significantly. For the production of biofuels, combinations of plant varieties and production processes were selected to ensure that the minimum CO_2 savings and the mandatory CO_2 reduction rate required by the EU Renewable Energy Directive 2001/2018/EC (EP/Council 2018b) and the EU Fuel Quality Directive 30/2009/EC (EP/Council 2009b) can be fulfilled by all of the fuels. Biogas from waste has Well-to-Tank greenhouse gas intensities considerably below the minimum CO_2 savings required (JEC 2014a). By contrast with fossil fuels, biomass absorbs the same amount of CO_2 from the atmosphere by photosynthesis in the growth phase as it subsequently releases during combustion. This amount of CO_2 is included in Well-to-Tank emissions as a negative CO_2 emission (as in ifeu 2012). The CO_2 emissions produced by burning biofuels are fully included in the Tank-to-Wheel emissions, i.e. according to their fuel-specific characteristics (JEC 2014b). Methane and N_2O emissions from gas engines were converted into CO_2 equivalents with the respective global warming potential factors of 30 and 265 (IPCC 2013). Figure 61 shows CO_2 factors for selected fuels over their energy supply and usage chain. A distinction is made

61 GREENHOUSE GAS FACTORS FOR SELECTED FUELS



trucks and tractor units will have an LNG powertrain: 20,000 rigids trucks of over 16 t GVW and 460,000 tractor units.

Fuel Consumption

To determine the LNG fuel demand, vehicle mileage in the potential main area of use of LNG, long-distance road freight transport, must be estimated first of all. As separate statistics are not kept for the mileage of heavy-duty vehicles in the EU, a plausible assumption had to be made.

According to the latest survey of vehicle mileage in Germany (IVT 2017), tractor units drive an average of 110,864 km a year. Assuming that long-distance road freight transport develops similarly in the EU, because of the integration of the European economy and transnational logistics concepts, this was taken to be the annual mileage driven by all heavy-duty vehicles with LNG engines in the EU over the whole of the period covered by the scenario. Users will also prefer LNG vehicles for use in long-distance road freight transport because of the total cost of ownership TCO (see box on TCO), so that the LNG trucks, which are more expensive to buy than diesel vehicles, are worth the investment considering all of the costs over their operating life.

Another factor for the calculation of the energy or fuel demand is the specific fuel consumption of rigid trucks and tractor units. The assumptions of (thinkstep 2017) shown in table 62 were adopted for this.

The comparison of the energy demand highlights the efficiency differences between the powertrains. The diesel is the most efficient, followed by the LNG vehicle variant with HPDI (around 4 % less efficient) and with SI (around 15 % less efficient). Another parameter for the calculation of fuel consumption is the development of fuel-saving technologies, in particular;

62 SPECIFIC FUEL CONSUMPTION OF HEAVY-DUTY VEHICLES IN 2016

Parameter	Otto-cycle / gas with Lambda 1	HPDI	Diesel
Fuel Demand	26.7 kg/100km	22 kg/100 km plus 1.8 l Diesel/100 km for ignition	31.5 l/100km
Energy demand Tank-to-Wheel	1,314 MJ/100 km	1,171 MJ/100 km	1,125 MJ/100 km

thinkstep 2017

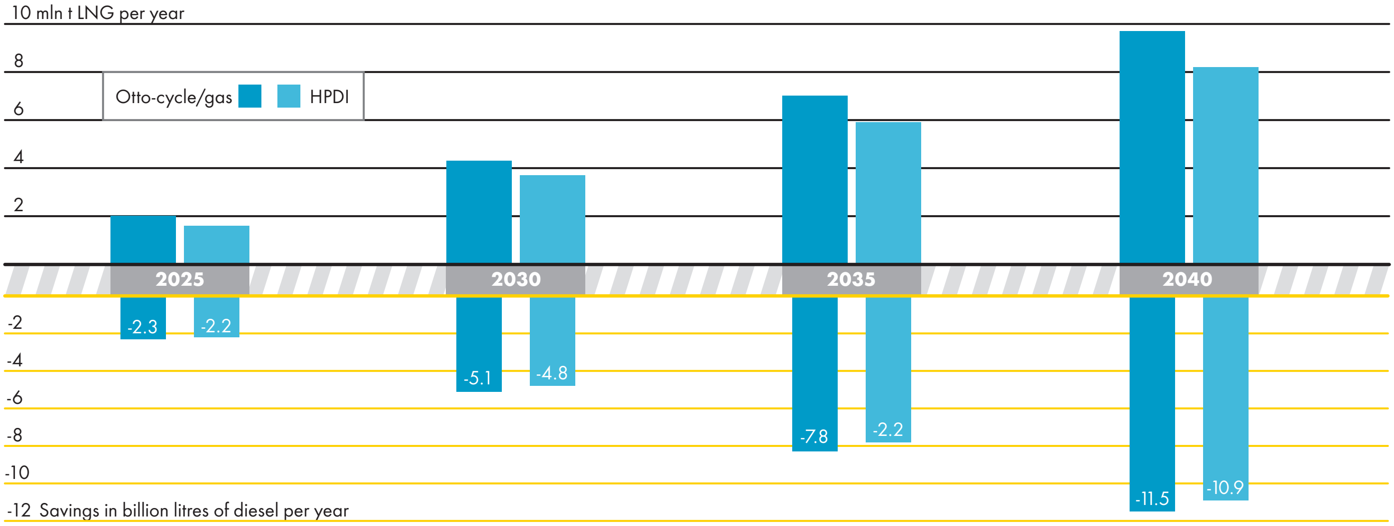
between the CO_2 emissions produced by combustion of an amount of fuel with an energy content of 1 MJ (Tank-to-Combusted) and those released during the production and supply of fuels (Well-to-Tank). The negative Well-to-Tank CO_2 emissions shown in the figure represent the amount of CO_2 absorbed from the atmosphere by the biomass during growth. The greenhouse gas emissions over the whole supply and usage chain (Well-to-Wheel/Wake) take account of the negative and positive greenhouse gas emissions.

When using standard commercial diesel fuels (B7 with a 7 % vol. biodiesel content), around four fifths of the CO_2 emissions are produced during combustion and only one fifth during fuel production and supply. The Well-to-Combusted greenhouse gas intensities for a B7 fuel are around 4 % lower than those of a diesel fuel with no biofuel content, but the Tank-to-Combusted greenhouse gas intensity is slightly higher because of the higher carbon content of the added biodiesel. However, over the whole Well-to-Combustion balance, the CO_2 absorbed from the atmosphere by the biomass during growth in the Well-to-Tank phase compensates for these increased greenhouse gas emissions.

The Well-to-Combusted emissions of heavy fuel oil are lower than those of diesel fuel. Here, higher emissions during combustion are counterbalanced by lower greenhouse gas emissions in the upstream chain (WtT), which are due primarily to the simplicity, and hence low energy use, of production in the refinery. The desulphurisation of heavy fuel oil to a residual sulphur content of 0.23 % in a hydrotreatment stage increases the Well-to-Tank emissions by 7 % because of the use of hydrogen from steam reforming of natural gas. However, if the hydrogen for hydrotreatment is produced from renewable electricity by electrolysis, the Well-to-Combusted greenhouse gas intensities of low-sulphur heavy fuel oil are around the same as those of the heavy fuel oil in its former state, with a high sulphur content.

The CO_2 emissions of LNG per unit of energy over the whole energy supply and usage chain are lower than those of diesel. The distribution between the upstream chain and direct CO_2 emissions of LNG is similar to that of diesel fuel; compared to heavy fuel oil LNG's upstream greenhouse gas emissions are higher. If LNG is not liquefied until it reaches the refuelling station, in other words production is decentralised, the Well-to-Tank greenhouse gas intensity is around 5 % higher than that of LNG produced centrally in the country of origin and imported into Europe. A 30 % content of biogas from waste materials can reduce the Well-to-Combusted greenhouse gas intensity by around 23 %.

63 HDV FUEL DEMAND



efficiency improvements can be achieved both in the vehicle powertrain and in the construction of the vehicle and the way it is operated. Possible technological options for commercial vehicles were described in detail in the Shell Commercial Vehicle Study (Shell 2016).

In the Pro-LNG scenario it was assumed that new vehicles would be 20 % more efficient by 2030 and 30 % more efficient by 2040 than they are today (2018); the same assumptions were made for Otto-cycle/gas engines and for diesel and HPDI powertrains. The Pro-LNG scenario also investigated two engine technology variants: one for vehicles with an Otto-cycle gas engine or an SI engine operated at a stoichiometric combustion air ratio of Lambda = 1, and one for vehicles with an HPDI gas engine similar to a diesel. The aim of this is to work out the differences in the fuel consumption and greenhouse gas emissions of the two variants caused by the efficiency differences between the two types of powertrain: the vehicle with an HPDI engine consumes 11 % less final energy than with an Otto-cycle/gas engine.

The LNG fuel demand of rigid trucks and tractor units increases steadily for both variants, with the same assumptions for LNG market establishment. The LNG demand of the Otto-cycle/gas engine is generally higher and rises from 2 mln t in 2025 to around 9.7 mln t in 2040 (figure 63).

The demand of the HPDI variant is lower, at around 1.5 mln t in 2025 and 8.2 mln t in 2040, because the engine is around 11 % more efficient. However, since it is a dual-fuel technology, the HPDI gas engine also requires diesel fuel for ignition. Around 134 mln litres of diesel fuel are required for this in 2025 and around 644 mln litres in 2040 in addition to the LNG fuel. The diesel fuel saving of the HPDI engine is reduced by the amount injected as pilot fuel to 10.9 mln litres in 2040.

The 480,000 heavy-duty LNG vehicles replace the annual fuel consumption of 480,000 heavy-duty diesel vehicles in 2040. These 480,000 diesel vehicles would have consumed 11.5 bn litres of diesel fuel in 2040. The diesel fuel saving of the HPDI variant with a mix of LNG and diesel burning is slightly lower.

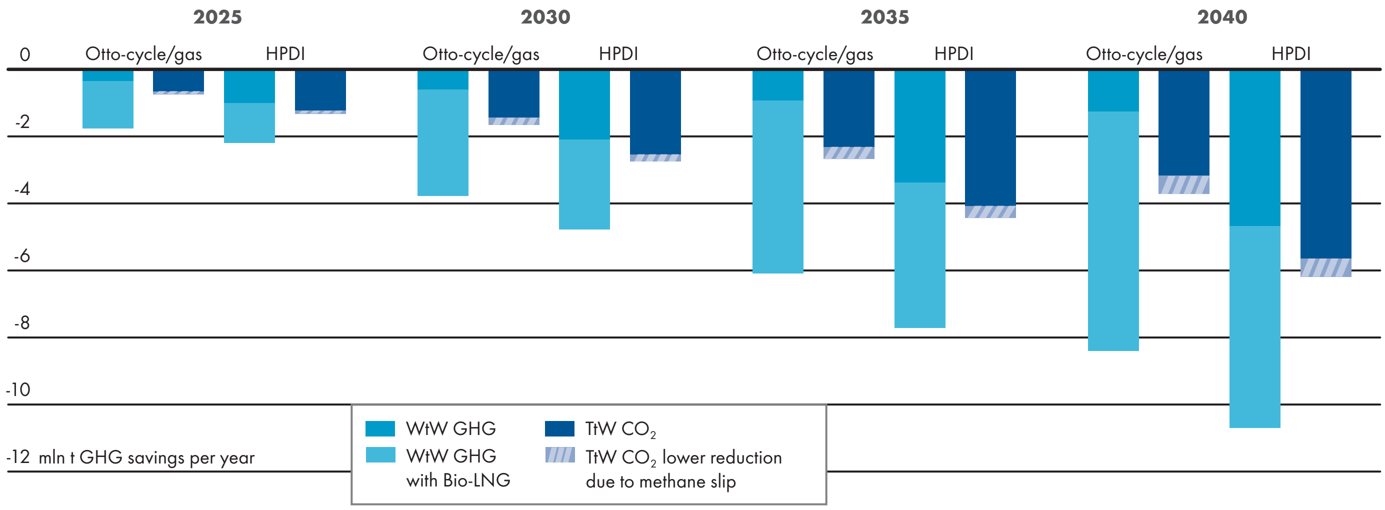
Greenhouse Gas Emissions

The greenhouse gas emissions of heavy-duty vehicles can be determined by combining the absolute LNG fuel consumption with energy source-specific greenhouse gas factors. For this calculation, it was assumed that fossil LNG is liquefied centrally and therefore has specific greenhouse gas emissions of 3.53 kg CO_2 per kg LNG burned (Well-to-Wheel). It was also assumed that, from 2030, around 20 % of the LNG will be supplied by local liquefaction plants, which liquefy natural gas from the pipeline network directly at refuelling stations. This change in the method of supplying LNG increases the greenhouse gas emissions to 3.56 kg CO_2 per kg LNG (Well-to-Wheel).

The annual greenhouse gas emissions of heavy-duty vehicles are calculated from the respective annual fuel demand of the LNG vehicles variants with Otto-cycle/SI gas engine and with HPDI engine. The annual CO_2 emission saving is then determined by factoring in the diesel fuel (B7) saved by replacing heavy-duty diesel vehicles with heavy-duty LNG vehicles. This calculation is made both for a 100 % fossil natural gas and, as an alternative, for an LNG containing 30 % Bio-LNG. The specific greenhouse gas emissions then fall to 2.80 kg CO_2 per kg LNG (WtW) and, from 2030, to 2.83 kg CO_2 per kg LNG (WtW).

Using purely fossil LNG in Otto-cycle/gas engines produces a saving of 3.7 mln t of direct CO_2 emissions (TtW) or 1.2 mln t of CO_2 emissions over the whole LNG fuel chain (WtW) in 2040. Using HPDI

64 SAVINGS OF GREENHOUSE GAS EMISSIONS FROM HDV



gas engines increases the potential CO_2 savings in 2040 to 6.2 mln t Tank-to-Wheel and 4.7 mln t Well-to-Wheel.

In addition, methane slip (the escape of unburned methane into the atmosphere) may also occur in the gas engines, and low levels of nitrous oxide emissions have also been reported (thinkstep 2017). Methane emissions must therefore be included as greenhouse gases in the emission balance of any comparison between gas engines and vehicles with a diesel powertrain.

The value of 0.349 g methane per kilometre for LNG trucks in the Pro-LNG scenario applies both to Otto-cycle/SI gas engines and to HPDI engines (thinkstep 2017). This is slightly below the Euro VI emission limit for methane. It is important to consider methane as an additional greenhouse gas because it has a significantly higher global warming factor (30) than CO_2 (1).

Both HPDI engines and SI engines have a total methane slip of 0.5 mln t of greenhouse gas in 2040, as shown in figure 64 for TtW emissions.

LNG offers the possibility of adding a large amount of biogas, thereby significantly reducing the balance of Well-to-Tank emissions by the amount of the CO_2 absorbed by the biomass from the atmosphere during the growth stage. The addition of 30% biogas from biogenic waste can produce a further significant reduction in the Well-to-Wheel CO_2 emissions of heavy-duty vehicles. Using 30% Bio-LNG, with high specific greenhouse gas savings, increases the greenhouse gas savings obtained with LNG over the whole LNG fuel chain to 8.4 mln t or 10.7 mln t a year in 2040, again depending on the engine variant; this is equivalent to an additional greenhouse gas emissions saving of slightly under 20% when using Bio-LNG in the HPDI variant and slightly over 20% in Otto-cycle/SI gas engines in comparison with fossil LNG. Adding more Bio-LNG could produce even higher greenhouse gas savings than those achieved with fossil LNG and hence also with diesel fuel and diesel powertrains.

To ensure that the CO_2 emissions can be reduced by using Bio-LNG, sufficient Bio-LNG must be available. The EU LNG Blue Corridors project investigated the EU-wide potential for the production of Bio-LNG, and estimated that it would amount to 72 petajoules of Bio-LNG in 2030 (EU COM/DGM 2015).

In the Pro-LNG scenario a maximum of 27.5 petajoules will be required in 2030 and a maximum of 61.5 petajoules in 2040 with a Bio-LNG share of 30%. Therefore, EU-wide Bio-LNG demand in the Pro-LNG scenario remains below the Bio-LNG potential calculated in the project study.

Nitrous oxide (N_2O) is another highly potent greenhouse gas which, according to the latest research, is emitted at low levels during combustion in both heavy-duty LNG vehicle variants (thinkstep 2017). As the amounts are very small for both gas engine variants, they are not relevant to the quantitative comparison and are not included in the calculation. Low levels of CO_2 emissions from exhaust gas aftertreatment in an SCR (selective catalytic reduction) system are not included either (TNO 2014).

With a 30% Bio-LNG share, the 480,000 or so heavy-duty LNG vehicles in 2040 therefore reduce the annual greenhouse gas emissions of the HPDI engine variant by up to 10.7 mln t Well-to-Wheel, which is around 29%, compared with the same number of heavy-duty diesel vehicles. When using Otto-cycle/SI gas engines these greenhouse gas emission savings are slightly lower, at just under 8.4 mln t, or 24%, Well-to-Wheel.

SHELL LNG STUDY

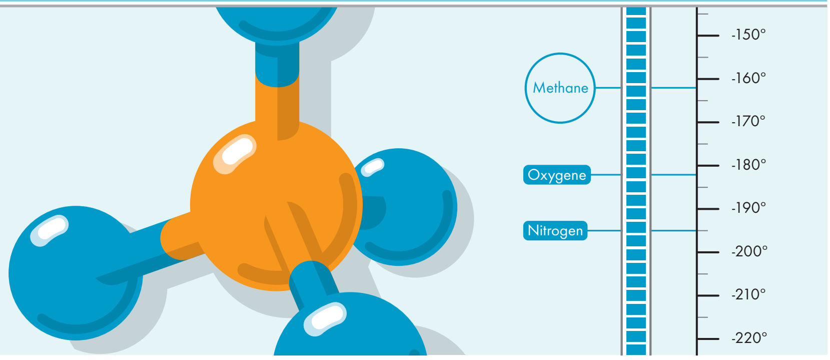
SUMMARY AND CONCLUSIONS

In the past years, Shell has produced a number of scenario studies on important future energy issues. As a new energy for applications in the transport sector, LNG (Liquefied Natural Gas) is generating an increasing amount of interest in the energy and transport industries, but also beyond them. In view of this, Shell is now presenting an energy source study on LNG.

Shell has been a leader in the global LNG industry since the 1960s. It has produced a new energy source study on LNG in collaboration with the German Aerospace Centre's Institute of Transport Research and Hamburg University of Technology's Marine Engineering Working Group.

The study examines current LNG production, the role of LNG in the global energy sector and LNG supply. It focuses particularly on the prospects for new end-user applications of LNG in the transport sector, especially in shipping and long-distance road freight transport with heavy-duty vehicles.

The main results of the Shell LNG study are summarised in six sections below. The study concludes by considering which accompanying policy measures could support LNG developing into an important component in the supply of energy for shipping and road transport.



1 TECHNICAL CHARACTERISTICS

LNG is not a natural source of energy, but is produced from natural gas. As it is a cryogenic liquid, LNG has specific properties. However it shares characteristics with its base material natural gas and its main component methane, that do not depend on its physical condition.

LNG is produced from **natural gas** by technical processes. Natural gas is a gaseous substance. Its **composition** can vary depending on where it is found and how it is processed. The main component of natural gas is the saturated hydrocarbon methane (CH_4). The composition of renewable alternatives to fossil natural gas, such as biomethane, Synthetic Natural Gas from biomass (Bio-SNG) or synthetic Power-to-Gas (PTG) diverges to some extent from that of fossil natural gas.

Natural gas has a low density and a low energy content per unit volume - much lower than that of liquids. Natural gas has to be "compressed" for some applications, particularly in the mobility sector. One way of doing this is to liquefy it. During **liquefaction**, natural gas is cooled to a point where its physical state changes from the gas phase to the liquid phase, which has a high density and a high energy content per unit volume.

A series of processing stages is required to obtain a product (LNG) with consistent technical characteristics. First, the feed gas must be purified and treated. After treatment the gas consists mainly (usually up to 90%) of methane.

Purification and treatment is followed by liquefaction. Today, most natural gas liquefaction plants use multi-stage cooling processes with mixed refrigerants because of the efficiency benefits they provide. These processes cool the gas to -161°C. Natural gas liquefaction is an energy-intensive process. Around 0.08 megajoules of energy are expended to liquefy one megajoule of natural gas.

Methane gas, the main constituent of LNG, is 0.7 kg/m^3 under standard conditions, making it lighter than air (approx. 1 kg/m^3) and rapidly evaporates in the open air. LNG has an average density of 450 kg/m^3. This makes it half as heavy as heavy fuel oil (970 kg/m^3) and slightly less than half as heavy as diesel fuel (832 kg/m^3).

Methane has a very low **boiling point**. Only a few gases have a lower boiling point. The normal boiling point of methane is -161.5 °C and 1.013 bar. The critical temperature above which methane cannot be liquefied is -82.6 °C. The volume of liquid methane at 1 bar is **600 times** less than it is at atmospheric temperature and pressure. LNG is used industrially at different pressures. There is "cold LNG" and "saturated LNG", which is stored at slightly higher pressure.

LNG is stored and transported as a boiling **cryogen** (very low-temperature liquid). To minimise pressure increases, cryogenic liquefied gases must be stored in well-insulated tanks. If heat from outside penetrates the storage tank, some of the liquid evaporates (**boil-off gas**). The boil-off rate for large tanks is generally 0.1 % a day; for smaller, poorly insulated LNG tanks it will be 1 % a day. The boil-off gas can be used to cool the rest of the liquid, it can be re-liquefied or used as fuel.

As LNG is a mixture of substances, the composition of the liquid phase varies depending on the boiling point of its individual components; during boil-off the methane content is reduced. This phenomenon, which has an adverse effect on the quality of the fuel, is also known as **LNG ageing**. To avoid LNG ageing, LNG evaporation and evaporation losses must be minimised by insulating tanks and making intensive use of LNG vehicles.

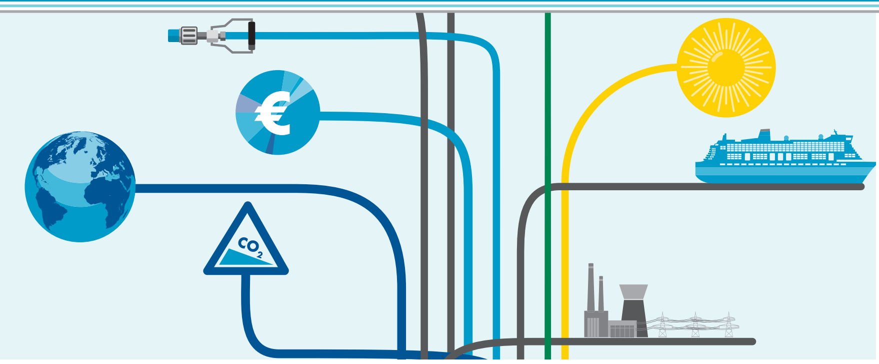
Based on its **gravimetric heating value**, natural gas, and hence also LNG, has a higher energy content than diesel fuel. For pure methane it is 50 MJ/kg and for natural gas (in the EU mix) around 45 MJ/kg, while diesel fuel has only 43 MJ/kg. The marine fuels marine gasoil and distillates are close to diesel; heavy fuel oil, with a density of about 1 kg/l, is heavier and has an energy content of only 40.5 MJ/kg.

As regards **volumetric energy density**, LNG has around 60 % of the energy content of a litre of diesel fuel, i.e. around 21 MJ/l LNG as compared with around 36 MJ/l diesel. The energy content per sales unit of LNG (in kilogrammes) is around 40 % higher than that of diesel (in litres). The volumetric energy density of LNG is just over half (53 %) that of heavy fuel oil (39.7 MJ/l). So LNG is considerably closer to the liquid fuels than compressed natural gas (CNG) at around 7 MJ/l. But a drawback of LNG is that cryogenic liquids have to be stored in heavy, insulated fuel tanks.

Another advantage of natural gas/methane is that it has much better knock-resistance than gasoline and can reach octane numbers of up to 130. Petrol engines can achieve high levels of efficiency with methane. Finally, liquefied natural gas has a low sulphur content of around 2 ppm.

In 2012 the shipping industry consumed 8 mln t of LNG, primarily in LNG carriers (LNGC); that figure could rise to as much as 12 mln t of LNG by 2020.

So far, LNG has played very little part in European long-distance road freight transport, as it fuels only a few thousand heavy-duty vehicles. There is a whole raft of standards for safe handling of LNG as a substance, but as yet no specific standard for LNG as a fuel.



2 THE GAS SECTOR

Almost all long-term global energy scenarios indicate that gas is the fossil fuel whose share in the global energy mix will increase the most. The importance of LNG as an energy source for the global energy industry will increase even more rapidly.

The global gas demand currently (2017) stands at 3,752 bn m^3 and is expected to increase by around 45 %, or 1,647 bn m^3 by 2040 to around 5,400 bn m^3.

Gas currently accounts for 22 % of the world's energy mix, and 25 % of the EU's. By 2040 its share of the global energy mix is expected to rise to 25 % as well.

The main drivers of gas consumption are power generation and industry. Gas consumption is still relatively low in the transport sector. However, transport, particularly shipping and road transport, is seen as a growth area for gas and especially for LNG.

There is an abundance of gas resources worldwide. Global gas resources are currently estimated at 800,000 bn m^3. At the current production level the gas resources technically available will suffice to meet gas demand for over **210 years**.

The main gas producing regions are North America, particularly the USA at around 760 bn m^3, Russia, at 650 bn m^3 and the Middle East at 620 bn m^3. The largest conventional gas producers are

Russia, Iran and Qatar. The country with the largest unconventional gas production is the United States. Conventional gas accounts for the lion's share of world production, at just under 80%.

Besides fossil sources, renewable gases are also possible alternatives to LNG. These include biomethane produced from biogas, Synthetic Natural Gas (SNG) and Power-to-Gas (PTG) fuels. The high production and supply costs present a major challenge to all renewable gas substitutes. Their share of gas supply is correspondingly small: Just under 20 bn m^3 of biogenic gas was produced in the EU 28 in 2016, equivalent to just over 4% of the current EU gas consumption of 463 bn m^3.

Around 770 bn m^3 of natural gas are traded internationally at present (2017), corresponding to about one fifth of global gas consumption. With imports of around 350 bn m^3, the EU is the world's largest gas importer, followed by China, Japan and Korea. Russia, the Middle East, the Caspian region and Australia, on the other hand, are major gas exporters.

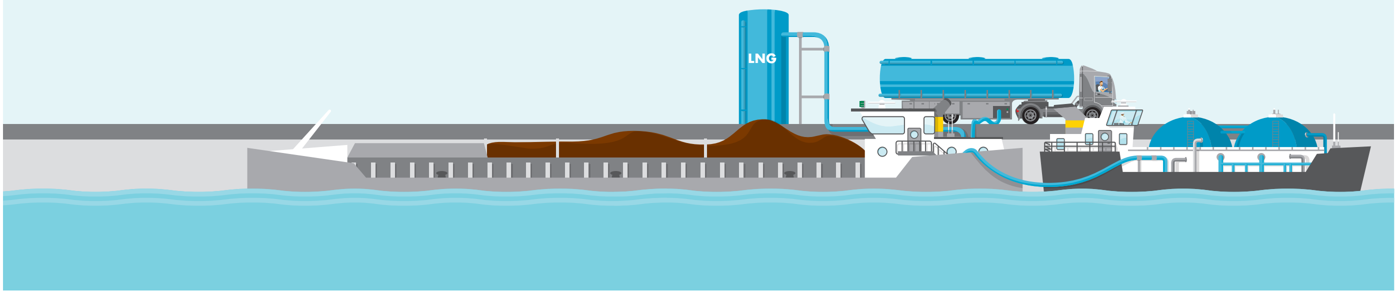
60% of the international gas trade runs through pipelines. Over 40% is traded as LNG; most recently (2017) that amounted to just over 330 bn m^3 or around 230 mln t of LNG. All in all, the LNG imports of Asiatic countries are dominant. Europe imports around 47 mln t of LNG in total.

The trend indicates that demand for liquefied natural gas is growing much faster than that for natural gas overall. The International Energy Agency (IEA) expects the global gas trade to grow by around two-thirds by 2040; and **LNG will account for over 80% of this growth**. The trade in LNG, and hence its availability, would therefore increase by a factor of two-and-a-half in less than 25 years. In 2040, almost 60% of the global gas trade would take the form of LNG, which would account for approximately 14% of global gas consumption, as compared with 8 to 9% today.

There are still considerable gas price differences between the major consumer regions Europe, North America and Asia. Gas prices are highest in Asia and lowest in the USA, with Europe in the middle. The price differences are due primarily to availability and access to gas resources. The boom in North American shale gas is having a considerable impact on gas markets and prices.

The liquefaction of natural gas is an important factor in LNG supply costs. The **consumer price** will also include transport and storage costs and, particularly, national energy taxes.

3 SUPPLY CHAIN AND INFRASTRUCTURE



The first and last stages of the LNG supply chain – up to raw gas treatment and after regasification – are virtually identical to those for natural gas in gaseous form. However it is distinguished from pipeline gas by liquefaction, transport in liquid form, and re-gasification. Consumers also increasingly use LNG as an end product in liquid form; this is a new stage in the value chain.

Liquefaction transforms gas into a product that can be transported and traded worldwide. At present the **hub-and-spoke model** is the dominant LNG supply model, which involves centralised liquefaction in large industrial facilities (LNG trains), transport and distribution. Large-scale LNG trains have LNG liquefaction capacities of 3 to 8 mln t a year.

There are now also much smaller gas liquefaction facilities with annual capacities of less than 0.5 mln t (mini scale) or 0.1 mln t (micro scale). **Floating LNG facilities**, which take gas directly from production, liquefy it to form LNG and store it, are a more flexible and cost-effective variant.

The nominal global capacity of LNG **liquefaction plants** is around 370 mln t of LNG. Qatar (77 mln t) and Australia (66 mln t) have by far the largest liquefaction capacities. In Europe, only Norway has a gas liquefaction terminal at the moment, with a capacity of 4.3 mln t.

The LNG is transported from the gas liquefaction terminal to a receiving terminal in special ships, called **LNG carriers** (LNGC). Since it began in 1964, the shipping of LNG has developed at a startling pace. There are now around 230

LNG carriers worldwide. The LNG in these carriers must be kept at a very low temperature during transport. As the carriers have no active cooling on board, the tank systems have extensive insulation, which minimises evaporation of LNG (boil-off). Most LNG tank systems are designed for a boil-off rate of 0.15 % per transport day; the best LNGCs achieve boil-off rates of 0.08 % of transported gas per transport day. The boil-off gas is generally used to power the ship.

There are two types of LNG carrier, depending on the type of storage system used. The Moss Rosenberg design, which has several spherical tanks and the membrane tank system, which is more space-efficient.

Most modern LNG carriers have storage capacities of 150,000 to 180,000 m^3 and the largest are equipped with membrane tanks which reduce the amount of dead space. They can now transport over 260,000 m^3 of LNG. The global LNG carrier fleet has a total transport capacity of 76.6 mln m^3. There are also smaller carriers which are used to supply smaller amounts of LNG or for fuelling.

At the destination, the gas is converted back into the gaseous state in special **regasification units**. These are mainly fixed units, but flexible **floating storage and regasification units (FSRU)** can be used as an alternative.

There are currently 140 regasification units and around 30 FRSUs worldwide, providing global LNG regasification capacities of 850 mln t. This is more than twice the gas liquefaction capacity.

Japan has the largest LNG reception capacities, with just under 200 mln t, followed by Europe with 30 regasification units and capacities of 160 mln t. The European regasification units alone are therefore able to receive over half of the global LNG supply. In addition to liquefaction and regasification units, an increasing number of LNG storage facilities is being built, although they currently have a capacity of only 30 mln t.

LNG is produced, traded internationally, transported and stored almost exclusively in large industrial units. Until now, LNG activities have been described as **large-scale LNG** in terms of their production, transport and storage capacities. However, new LNG activities, such as consumer applications in the mobility sector, require much smaller LNG distribution and supply units. The terms used to describe the scaling down (miniaturisation) of the hitherto large-scale LNG activities are **smallscale LNG**, or **retail LNG**.

The EU's alternative fuels infrastructure directive, formally Directive 94/2014/EU (the **AFID**) states that LNG bunkering stations should be put in place at major maritime and inland ports, and LNG refuelling stations at 400-km intervals along the roads, of the core Trans-European Transport Network (TEN-T) by 2025.

The EU Member States currently have around **150 LNG refuelling stations**, the majority of which are in Spain (41) and Italy (50). There is also a growing number of small-scale LNG import, export and liquefaction facilities, and over 1,000 small storage facilities. For shipping, there are currently 40 to 50 **LNG bunkering stations** in Europe.

4 LNG IN SHIPPING

Shipping is one of the main sectors in which LNG will potentially be used as a fuel. Although in the past it has been used almost exclusively to power long-distance LNG carriers, the picture is changing for LNG in shipping. In the face of increasingly strict air pollutant emission requirements, the shipping industry is looking for alternative fuels. At present LNG is the only serious, marketable alternative to oil-based marine fuels.

Maritime fleet

The global merchant fleet currently (2017) has a total capacity (deadweight tonnage, DWT) of over 1.9 bn t distributed among roughly 93,000 ships. Bulkers and tankers combined account for about 23 % of the fleet and 53 % of the total capacity. The most dynamic ships in the industry, with the most powerful engines, are the **container ships**. These account for just over 5 % of the merchant fleet, but for around 13 % of its capacity. Because of the direct relationship between the user and the transport service, 4,428 passenger ships and 458 cruise liners are taking a **pioneering role** in the use of low-emission engines and fuels.

However the number of LNG ships is still small compared with the merchant fleet. In addition to the aaprox. 230 LNG carriers (LNGCs), 125 **LNG-fuelled ships** were operating worldwide at the end of 2018. Around a quarter (33 ships) of the LNG fleet are passenger ferries which operate mainly in Northern Europe.

LNG ships are found particularly in emission control areas in the EU and North America. The world leader, with around half of the global fleet of LNG-fuelled ships, is **Norway**. The order books indicate a trend towards larger ships like tankers, container ships and cruise liners. By the mid-2020s the LNG shipping fleet is expected to have increased to around 400 ships.

The European inland fleet currently has a total of 13,500 ships with a loading capacity of 17 mln t. At present, there are five LNG-fuelled inland ships in use on European waterways. Four of these are chemical or LNG tankers and one is an inland container ship.

Ship engines

Ships are basically powered by three types of engine: Container ships, bulkers and tankers are almost exclusively driven by **two-stroke slow speed engines**. These are the most efficient, at over 50%, and thus consume the least fuel. **Four-stroke medium speed engines** are preferred where space is limited. **Turbine engines**, on the other hand, are a niche solution.

Since the turn of the millennium, an engine design has been developed for LNG tankers, which allows them to burn diesel fuel and gas alternately (**dual fuel engines**). This design has gradually replaced the conventional gas-powered steam turbines. The main reason for this is the fuel savings. Experience from using gas as a fuel on LNG carriers is now being put to good use in gas-fuelled ships.

The most common of the current gas-fuelled ships are the low-pressure medium speed dual-fuel four-stroke engines. High- and low-pressure low speed two-stroke engines have also been gaining a foothold as powertrain solution for LNG-powered ships. The use of gas turbines is an exception among gas-powered ships.

Emissions

Ships contribute a significant amount to the emission of transport-related air pollutants. International maritime transport is also responsible for around 2.8 to 3.1% of global CO_2 emissions.

Since the end of the 1990s the International Maritime Organisation (IMO) has gradually introduced mandatory limits for emissions from ships. In addition to this, **Emission Control Areas (ECAs)** have also been established. These are special zones with particularly tight restrictions on the emission of sulphur oxides (sulphur ECA), nitrogen oxides (nitrogen oxide ECA) and in some cases also particulate matter. The ECA areas currently include the whole of the North and Baltic Sea area, the waters off the east and west coast of North America, including Hawaii, Canada's Great Lakes and the coastal waters of Central America.

The **nitrogen oxide emissions** from ships' engines are limited specifically in relation to the unit of energy generated. Current NO_X emission limits, particularly for ECA zones, require exhaust gas recirculation, special exhaust gas treatment or alternative engine designs. Gas is a particularly suitable fuel to comply with NO_X regulations. The emission values achieved by gas combustion comply with the strict requirements of IMO TIER III emission regulations.

Ships also generate an estimated 5 to 10% of the **sulphur dioxide emissions** caused by humans. Unlike nitrogen oxide emissions, sulphur dioxide emissions are mainly limited by regulating the constituents of the fuels. Alternatively, the sulphur limits in force since 2015, and those that will apply from 2020, can also be met by using exhaust gas scrubbers or LNG.

There have not so far been any direct restrictions on **greenhouse gases** caused by marine transport. However, the energy efficiency of ships is regulated by the IMO Energy Efficiency Design Index (EEDI). This also helps to reduce greenhouse gas emissions.

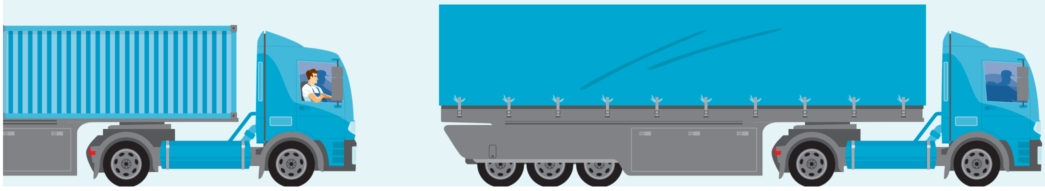
Based on a greenhouse gas study published by the IMO in 2015 **CO_2 emission reductions of at least 40% by 2030 and at least 50% by 2050 in comparison with 2008 levels** are aspired.

Gas engines are receiving particular attention in connection with shipping-related greenhouse gas emissions, since combustion of methane, the main constituent of natural gas, produces up to 32% less direct CO_2 emissions than heavy fuel oil (HFO). However this advantage is reduced by **methane slip** in the engine.

Current technical engine developments are attempting to restrict methane slip. Another possible solution is to reduce the amount of methane in the exhaust gas with catalytic exhaust aftertreatment. These technical solutions would reduce the greenhouse gas emissions of LNG-powered ships further and help to make shipping more climate-friendly.

Inland shipping can be a significant cause of local air pollutant emissions in ports and along waterways. EU Non-Road Mobile Machinery Regulation 2016/1628/EU has introduced tight regulations of air pollutant emissions from inland shipping. Here too, LNG engines offer an additional solution to selective catalyst reduction (SCR) exhaust gas purification systems.

5 LNG IN ROAD TRANSPORT



Besides shipping, long-distance road freight transport is another potential main application of LNG. The vehicles used for road freight transport are rigid trucks and tractor units (HDV) with a high annual mileage. Because of the high user requirements, HDV used for long-distance goods transport are almost exclusively powered by efficient diesel engines. Driven by the desire to diversify the fuel supply and reduce air pollutant and greenhouse gas emissions, LNG is also being seen as a new powertrain and fuel option for heavy-duty vehicles in Europe.

Heavy-duty vehicle fleet

There are currently (2016) 37.6 mln goods vehicles on the roads in Europe, including rigid trucks for goods transport and tractor units towing semi-trailers. Over 80 %, or 30.8 mln, of these are light goods vehicles up to a maximum permissible laden weight or the equivalent term gross vehicle weight (GVW) of 3.5 t. Around 12 %, or 4.5 mln vehicles are over 3.5 t GVW.

Rigid Trucks and tractor units have a high annual mileage and fuel consumption. The vehicles in which LNG could be used are: 350,000 rigid trucks over 16 t GVW and 1.8 mln tractor units. With over 360,000 vehicles, Poland has the largest tractor fleet, followed by Spain with 200,000, Germany and then France.

2.3 mln new rigid trucks and tractor units were registered in the EU in 2016. The heavy-duty vehicles (rigid trucks over 16 t GVW and tractor units) account for just over a tenth of newly registered vehicles. European long-distance road freight transport is dominated by tractor-semitrailer combination vehicles. Germany and Poland have the biggest tractor markets, with just over 11 % and over 36,000 newly registered vehicles respectively each. The average age of the heavy-duty vehicles (over 3.5 t GVW) in Europe is around 12 years. Tractors are much newer on average.

According to the latest expert estimates, there are currently around 4,000 LNG vehicles in the EU, most of which are rigid trucks and tractor units, as well as some buses and coaches. More than 1,500 new vehicles have been registered recently. Spain, the Netherlands, Italy and the UK are leading LNG users in the EU. China in particular (over 200,000 vehicles) and North America (over 4,000) also have sizeable LNG truck fleets.

Gas engines for HDV

There are currently two different engine technologies for heavy-duty LNG vehicles that fulfil the European exhaust emission standard EURO VI. These are the stoichiometric petrol/gas engine (also spark ignition or SI engine) and the high-pressure direct injection (HPDI) engine.

Stoichiometric SI engines can be designed very easily for gas or LNG (because of the high methane number). Three-way catalysts can be used for cost-effective exhaust gas aftertreatment in SI engines.

SI engines are not as efficient as diesel engines. A larger SI engine is required to obtain the same performance as a comparable diesel engine because of the lower compression ratio. An LNG vehicle with an SI engine would need up to 18 % more energy than a diesel vehicle on average. Lean burn SI engines would be more efficient, but there is no Euro VI exhaust gas aftertreatment system for these engines as yet.

Two manufacturers will be marketing heavy-duty LNG vehicles with SI engines in Europe; the 13-litre class will be used for the highest performance HDV. All engines can be used both in LNG and CNG vehicles.

The idea of the **HPDI engine** is to initiate auto-ignition with a smaller amount of diesel fuel and to inject methane into the flame produced. The LNG is pre-heated and then injected into the combustion chamber at 300 bar, like diesel, only in gas form. The amount of diesel is selected so that just enough energy is released to ignite the methane subsequently injected.

Diesel accounts for 5 to 10 % of total fuel consumption. Exhaust gas aftertreatment works in the same way as in a normal diesel engine (SCR with urea solution and particulate filter). As an HPDI engine works in the same way as a diesel engine, a vehicle with an HPDI engine needs only about 3 to 4 % more energy than a conventional diesel engine. The first HPDI engine was unveiled in 2006. There is currently only one series production HPDI truck on the market in Europe.

Emissions

At present almost all heavy-duty vehicles use diesel engines and emit both air pollutants and greenhouse gases. From 1990 to 2016, the specific air pollutant emissions of road transport in the EU were reduced significantly, while the greenhouse gas emissions of all heavy-duty vehicles rose by a quarter in the same period.

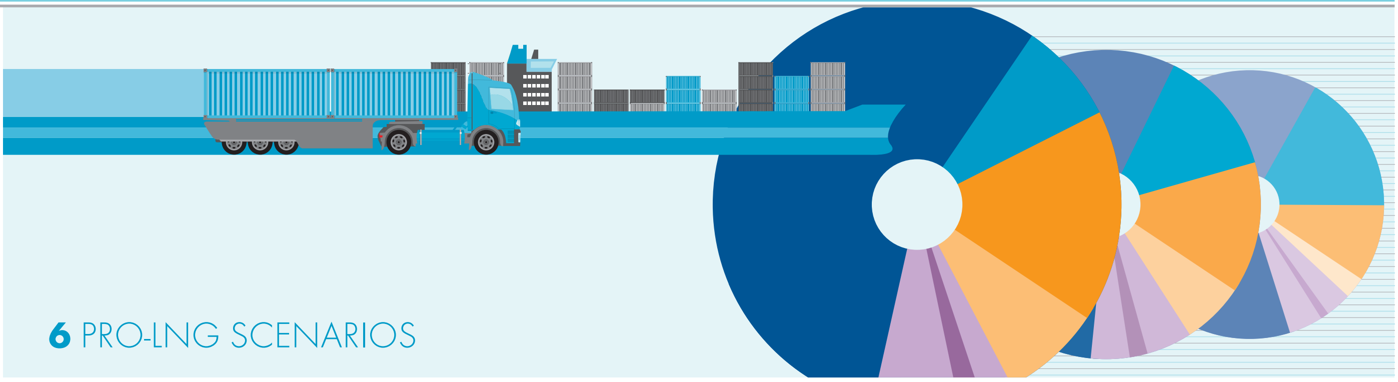
The EU Euro VI exhaust regulations have applied to rigid trucks and tractor units since 2012. The exhaust limits are set per kilowatt hour engine work (mg/kWh). Like stoichiometric SI engines, all LNG trucks with high pressure direct injection fulfil the Euro VI standard.

The manufacturers of LNG vehicles with SI engines point to further significant emission reductions against the Euro VI standard. SI engines would be able to meet the requirements of even stricter exhaust emission limits. LNG vehicles with SI engines are also much quieter than those powered by diesel engines. The Euro VI exhaust standard also sets a limit of 0.5 g/kWh for methane emissions, which ensures that methane slip has virtually no impact on the truck greenhouse gas balance.

As with the regulation of CO_2 emissions from passenger and light-duty vehicles, the European Commission is preparing a mandatory CO_2 regulation for vehicles above 3.5 t GVW, which account for 65 to 70 % of CO_2 emissions from all commercial vehicles in the EU.

To calculate the CO_2 emissions of heavy-duty vehicles, the European Commission developed the Vehicle Energy Consumption Tool (VECTO) with European vehicle manufacturers. VECTO calculations will now be used to reduce the CO_2 emissions of new vehicles by 15 % by 2025 and 30 % by 2030.

VECTO allows for a 23 % reduction in greenhouse gas emissions when using LNG or natural gas as a fuel. A 23 % CO_2 emissions saving could be achieved with gas, with the same engine efficiency (HPDI engine); a saving of about 5 % would be achieved by using a current SI engine.



6 PRO-LNG SCENARIOS

Finally, scenario technique is applied to show how LNG could become an established fuel for shipping and heavy-duty vehicles by 2040. LNG for shipping is examined in the context of the global merchant fleet, and LNG for road transport in that of heavy-duty vehicles in the EU. Inland shipping is not examined in any more detail in the scenario analysis. An ambitious, powertrain/fuel-specific alternative scenario (Pro-LNG scenario) is assumed for each transport sector considered.

Fleet development up to 2040 is predicted in the light of the long-term transport forecasts for global shipping and European road transport; a substantial proportion of each fleet is gradually replaced by new LNG ships/vehicles. The relative impact of LNG technology on the fuel consumption and greenhouse gas emissions of ships and heavy-duty vehicles is then estimated.

Scenario for shipping

The development of the global shipping fleet is predicted up to 2040 on the basis of the main classes of ship. These are general cargo ships, container ships, dry bulk cargo carriers, oil tankers and passenger ships and cruise liners. New LNG ships will be phased into this fleet.

The **total number** of ships in the classes examined will rise by just over a tenth from 51,000 to over 56,000 by 2040. While there will be an increase in all categories of ship, the number of general cargo ships will fall significantly as a result of increasing containerisation. Container ships, which will grow by approx. 5,200 to around 8,500 units, are the most dynamic class.

LNG ships will grow much more rapidly than the overall fleet to just over 6,000 units in 2040, and more than a tenth of the global shipping fleet examined will then be powered by LNG. The speed of the penetration of LNG into the different classes of ship depends both on the number of newly registered ships in each class and on how many of them are LNG ships. According to the figures for new LNG ships, container ships are number one, with tankers and bulk cargo ships coming second and third.

Container ships (2,200 units) will account for the peak value of the LNG units in the fleet in 2040, followed by tankers (1,660 units) and bulk carriers (approximately 1,100 units). A substantial share of passenger ships and cruise liners will also be LNG ships, although in total there will only be 600 LNG-powered PAX ships in 2040.

The **fuel consumption** of each ship will be calculated by type of ship by estimating the average annual ship-specific consumption on the basis of power demand and operating profiles, assuming average efficiency levels for each type of engine. Container ships have the highest fuel consumption at approximately 140,000 m^3 LNG a year, followed by cruise liners at 80,000 m^3 LNG a year; the other classes of ship considered consume 15,000 to 20,000 m^3 LNG a year.

Total maritime LNG consumption could reach 180 mln t by 2040. Given the current annual marine fuel consumption of approximately 330 mln t, this seems high. This is due to the growth in the shipping fleet and in the transport performance in maritime traffic. However container ships are the main reason for the high LNG consumption. Their fuel consumption is the highest not only because they have the most powerful engines but also because they have the largest number of LNG engines.

As a result, container ships will have the highest LNG consumption in 2040, at 140 mln t. Tankers (15 mln t), bulk carriers (10 mln t) and cruise liners (9 mln t) are some way behind this. LNG ships could account for up to 226 mln t of marine fuel in total in 2040.

The differential impact of the use of LNG on **greenhouse gas emissions** from shipping is determined from consumption data for LNG ships and the amount of liquid fuel they replace. Energy source-specific greenhouse gas factors for pure fossil LNG and low sulphur fuel oil are used for this.

Replacing 226 mln t of low sulphur fuel oil with just over 180 mln t of LNG in 2040 would produce a saving of around 230 mln t of direct CO_2 emissions. If we also assume methane slip of around 1 % of the LNG used, the benefit of LNG for the global warming potential falls by roughly a quarter, equivalent to around 54 mln t, to 176 mln t.

If we include the greenhouse gas emissions from the production respectively provision of LNG and HFO (Well-to-Tank), the absolute greenhouse gas savings of the overall Well-to-Wheel balance fall to approximately 132 mln t of greenhouse gas emissions in 2040.

Scenario for heavy-duty vehicles in the EU

The development of the fleet of heavy-duty vehicles in the European Union is extrapolated up to 2040. Rigids trucks (above 16 t GVW and tractor units) are the most likely to use LNG as a fuel, so we will confine our analysis to them.

There were 1.82 mln tractor units and 351,000 rigid trucks in the EU 28 in 2016. Around 4,000 heavy-duty vehicles run on LNG. If the current trend in registrations continues, there will be 307,000 newly registered rigid trucks and tractor units in 2040. This produces a total **vehicle fleet** of 2.76 mln units comprising 2.42 mln tractor units and 360,000 rigid vehicles over 16 t GVW.

We have assumed that LNG vehicles will account for 10 % of newly registered rigid vehicles in 2040 and that one in four newly registered tractor units will be an LNG vehicle, which results in a total of 75,000 newly registered LNG vehicles in that year. This ultimately produces a fleet of around 480,000 heavy-duty LNG vehicles comprising 20,000 rigid trucks and 460,000 tractor units. Around 17 % of all heavy-duty vehicles in 2040 would therefore have an LNG engine.

The **absolute LNG consumption** and the consumption of diesel replaced by LNG can be estimated on the basis of assumptions for typical road transport mileage and vehicle-specific fuel consumptions.

In addition to the diesel engine as the standard power unit, two types of LNG engine were considered: a petrol/gas or SI engine and an HPDI engine similar to a diesel. A heavy-duty vehicle with an HPDI engine currently has a final energy consumption around 11 % less than a heavy-duty vehicle with a petrol/gas engine.

If we assume similar market development for both engine types, the LNG demand for petrol/gas engines will reach about 9.7 mln t in 2040. The LNG demand for HPDI engines in the same year will be slightly lower, at 8.2 mln t. The 480,000 heavy-duty LNG vehicles will replace the annual fuel consumption of 480,000 heavy-duty diesel vehicles in 2040. These 480,000 heavy-duty diesel vehicles would otherwise have consumed 11.5 bn litres (SI engines) or 10.9 bn litres (HPDI engines) of diesel in that year. In addition to this, the HPDI engine will still need diesel for ignition and this will account for 644 mln litres in 2040.

The differential impact of LNG on **greenhouse gas emissions** from road transport is determined from the consumption data for heavy-duty LNG vehicles and the amount of liquid fuel they replace. Energy source-specific global warming factors for pure fossil LNG, for LNG containing 30 % biomethane and for diesel fuel containing 7 % biodiesel (B7) are used for this.

Using pure fossil LNG in SI engines delivers savings of 3.7 mln t of direct CO_2 emissions (Tank-to-Wheel); methane slip which translates into around 0.5 mln t of greenhouse gas should be deduced. Greenhouse gas emissions over the whole LNG chain (Well-to-Wheel) are 1.2 mln t less than those of heavy-duty diesel vehicles.

Using HPDI vehicles increases the potential 2040 greenhouse gas savings to 6.2 mln t of CO_2, Tank-to-Wheel, minus around 0.5 mln t of methane slip. Well-to-wheel greenhouse gas savings amount to 4.7 mln t.

Using 30 % Bio-LNG, with high specific greenhouse gas savings, increases the greenhouse gas savings obtained with LNG over the whole LNG fuel chain to 8.4 mln t or 10.7 mln t a year in 2040, again depending on the type of vehicle; this is equivalent to an additional greenhouse gas saving of about 20 %. Higher Bio-LNG contents can achieve even higher greenhouse gas savings in comparison with fossil LNG and hence also in comparison with diesel engines.

With an HPDI engine, this equates to a maximum emission saving of 29 % in comparison with the same number of heavy-duty diesel vehicles.

POLICY ASKS FOR LNG APPLICATIONS IN SHIPS AND HEAVY-DUTY VEHICLES

As a new energy source, LNG can make an important contribution to the diversification of the energy supply to the shipping and road transport sectors. LNG can also improve the emission balances of internal combustion engines particularly in ships and when it is produced from renewable energy sources.

LNG application technologies have made significant progress in recent years. However LNG has only just started on the pathway to broad commercial use in the retail sector. Retail applications therefore need further support and funding from the government and society. What actions and measures would be needed to develop LNG into an important component of the supply of energy for ships and heavy-duty vehicles?

Important Policy Asks are formulated below, which may help to create and improve the framework conditions for a low-emission LNG retail economy in the future.

PROMOTING SMALL SCALE AND RENEWABLE ENERGY FACILITIES

LNG has been manufactured on a large scale from fossil natural gas reserves for 50 years, but to secure an adequate LNG supply, smaller (mini or micro) LNG storage, production and distribution facilities are needed across the board. This is particularly true given that LNG is to be produced increasingly from renewable energies such as biomass.

As there are currently hardly any small Bio-LNG or PTG-LNG facilities, there are both economic and R&D policy incentives required for entering this market. PTL-LNG facilities can equally be used to develop technologies for supplying renewable hydrogen and thus take a step on the pathway towards renewable fuels.

EXPANDING THE RETAIL-SCALE INFRASTRUCTURE

The creation of a widespread LNG supply network for ships and heavy-duty vehicles is a prerequisite for developing LNG into an available and acceptable alternative fuel for users in the transport sector. Ships and long haul heavy-duty vehicles need a far less dense supply network than private motor vehicles, but here, too, it is advisable to achieve a sufficient level of coverage at the development stage with the aid of public infrastructure funding.

The implementation of the alternative fuels infrastructure directive (AFID) in the context of the harmonised national strategy frameworks of the EU Member States is an important element of this. Other national LNG platforms and EU projects, such as Blue Corridors or BioLNG EuroNet could also contribute to LNG infrastructure build-up.

ESTABLISHING AND USING LNG NETWORK EFFECTS

The demand for LNG fuel is still low, and individual transport sectors have often not yet reached a critical mass. That is particularly true of inland shipping, but also of some other users of LNG as an end product. That is why, when establishing the infrastructure, it is important to create network effects, for example by considering and developing the potential LNG demand from heavy-duty vehicles, inland navigation and coastal shipping as a whole. Particular attention should be paid to inland navigation here, since the slow establishment of an LNG fleet will prevent it from developing more than a moderate LNG demand of its own.

EFFICIENT APPROVALS AND STANDARDS

As LNG is a new type of final energy, there is often too little experience when implementing LNG retail projects. Efficient and, as far as possible, unified approval procedures must be set up to speed up market penetration. Sufficient recognition of LNG standards and norms for the construction of LNG infrastructure facilities such as service stations and bunkering stations, for the construction and operation of ships, vehicles and machinery, for the transport, storage and handling of LNG as a final product, is also required.

LARGER NUMBERS OF LNG ENGINES

Electrification of ships and long-distance heavy-duty vehicles with battery electric vehicles does not seem to be an option at present. LNG engine technology, on the other hand, is already available for heavy-duty vehicles and ships. However, LNG engines both for ships and heavy-duty vehicles are still much more expensive than standard diesel engines. To generate further economies of scale for production, the production numbers of LNG engines must be increased significantly.

There may be a case for introducing subsidies for LNG-applications in small- and medium-sized enterprises, which do not have the budget for purchasing LNG engines; this applies to both hauliers and inland navigation companies, but particularly the latter, as these fleets have a long service life and hence do not need to be replaced as often.

MAKE FULL USE OF THE ENVIRONMENTAL BENEFITS OF LNG ENGINES

There are two available engine designs for heavy-duty LNG vehicles (SI-petrol/gas and HPDI) with different environmental benefits in terms of fuel consumption and air pollutant, greenhouse gas and noise emissions. The methane slip problem is regulated by Euro VI, so users can choose the solution that is best for them.

Methane slip in ships has not yet been adequately addressed. Here too, methane slip should be reduced as far as possible by technical measures, for example by developing catalyst systems. Regulatory incentives could also be introduced.

SUPPORTING FISCAL MEASURES

For the introductory phase, energy tax measures can support LNG as a fuel for road transport. This can also be justified by the fact that LNG, like other gas fuels, generally produces fewer emissions than diesel fuels from combustion.

If greenhouse gas emissions are to be priced in the long term, low-emission fuels, particularly from renewable sources, would be more competitive, as they produce lower CO_2 emissions. Fossil LNG would also benefit from this because of its low energy source-specific greenhouse gas emissions.

Fiscal measures do not affect shipping. In the first place, most EU Member States grant shipping a reduction or exemption from energy tax, and in the second place, bunker fuel for international shipping is not subject to energy tax. One long-term option for the fuel consumption of shipping would be to include it in a global emissions trading system; as this would take a considerable lead-time to prepare, it is not expected to have any impact on the development of marine LNG in the short- or medium term.

LOW-EMISSION AND RENEWABLE LNG

To ensure that low-emission LNG can be used economically, it is essential to create long-term, reliable basic conditions for fuel producers and marketers.

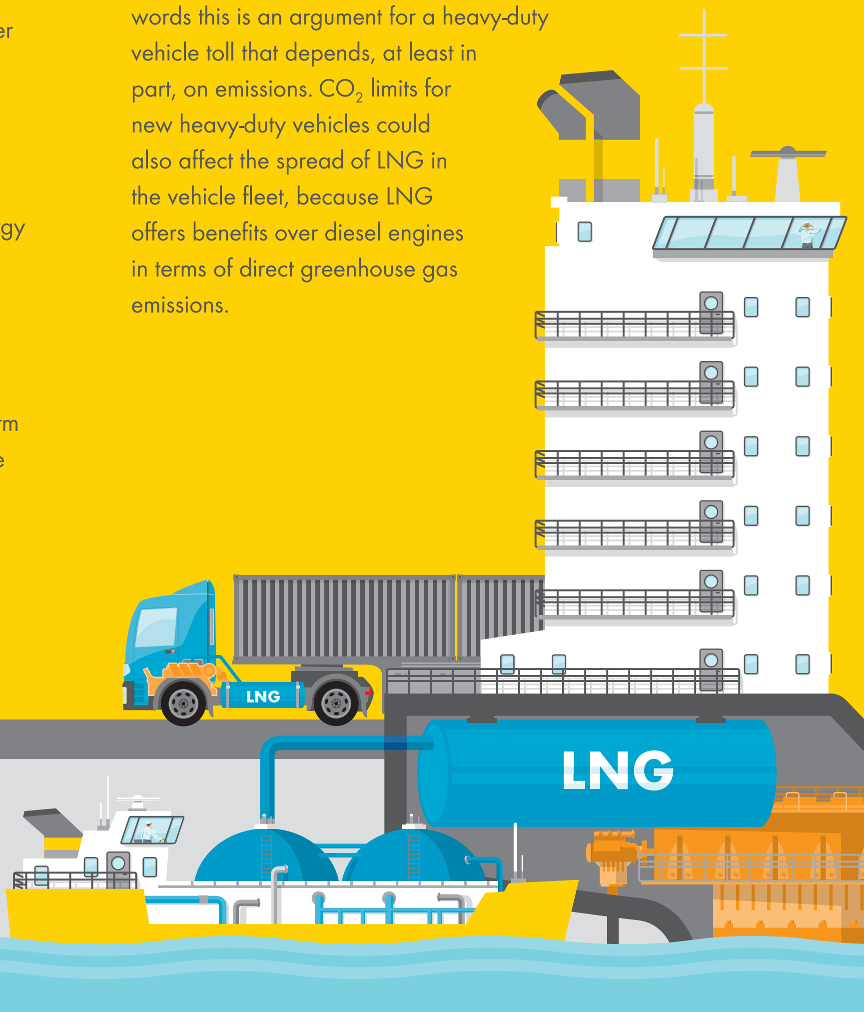
These could include regulatory incentives for different technologies, such as setting increasing quotas for the content of renewable fuels (such as Bio-LNG) or fuel-specific greenhouse gas quotas (as specified in the EU Renewable Energies Directive), because these provide incentives to invest in facilities for the production and supply of LNG produced from renewable sources.

USER BENEFITS AND ACCEPTANCE

For the development of LNG in the mobility sector it is essential to ensure that it offers users more benefits than the standard powertrain. User benefits can be created primarily by economic or regulatory incentives. For LNG, these also include environmental regulation.

For LNG in the shipping industry, regulatory incentives could include more extensive ECAs and basing port fees on emissions. Environmental zones and port fees are also a possible incentive for promoting the use of LNG in inland navigation.

For heavy-duty vehicles environmental zones are only a moderate measure of promoting LNG, as they mainly operate on the national motorways. However, experience has shown that motorway tolls have a significant impact on the choice of engine technology for long haul heavy-duty vehicles; in other words this is an argument for a heavy-duty vehicle toll that depends, at least in part, on emissions. CO_2 limits for new heavy-duty vehicles could also affect the spread of LNG in the vehicle fleet, because LNG offers benefits over diesel engines in terms of direct greenhouse gas emissions.



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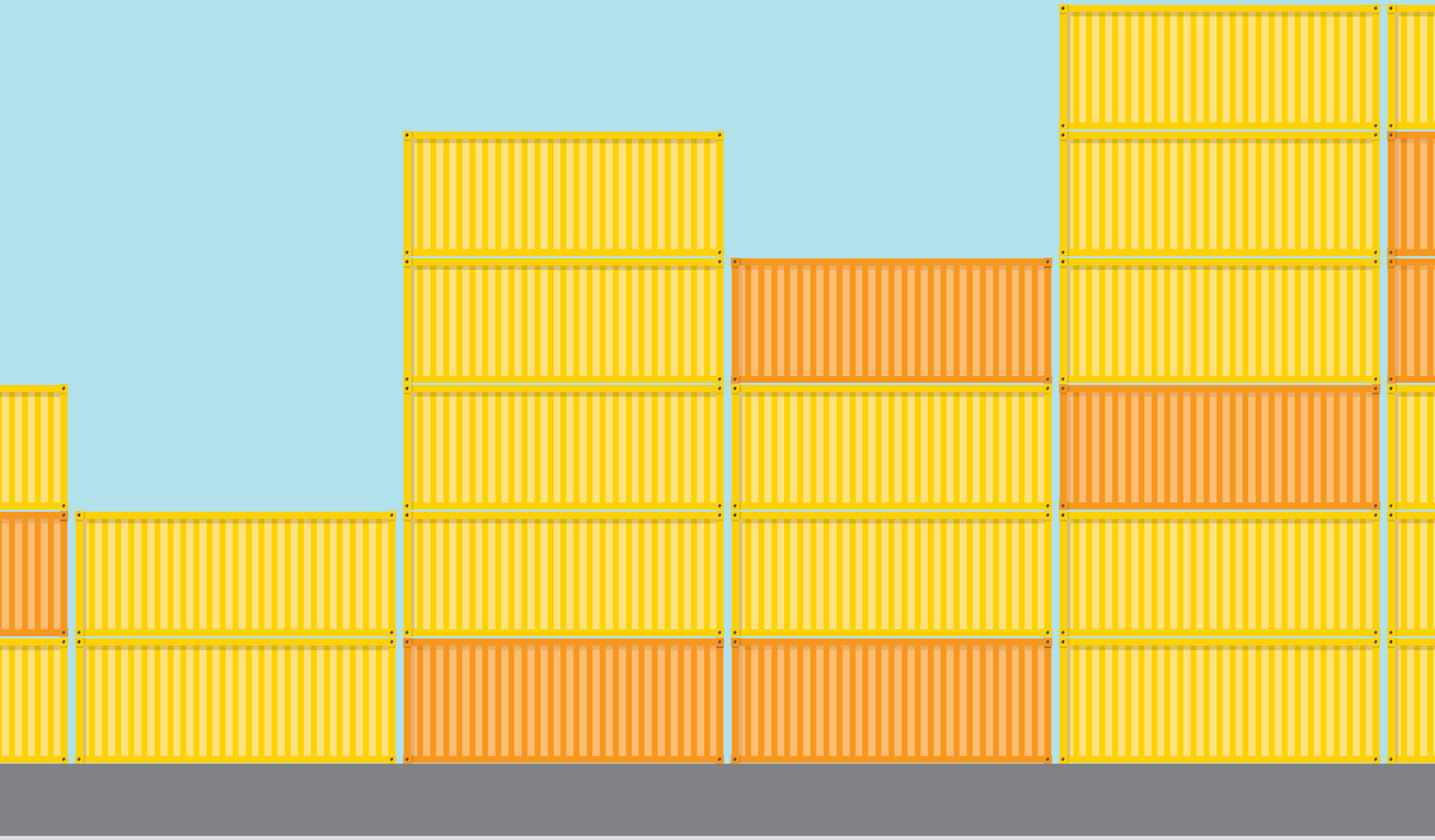

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