Gasification of the commercial fleet

Challenges and perspectives of LNG as fuel

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LNG is a promising fuel to reduce marine emissions (SO\textsubscript{x}, NO\textsubscript{x}, particulate matter and GHG). This report addresses the areas where potential bottlenecks could arise. Adverse LNG market conditions and costs, and LNG emissions are identified as possible threats to the further development of this resource as marine fuel.
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Authors

Luca Gandossi and Hugo Calisto.
Executive summary

The necessity of a more environmentally friendly maritime transport and the progressive introduction of international legislation to limit emissions are challenging the global shipping industry. Liquefied Natural Gas (LNG) is a potential solution to meet this challenge by replacing conventional, more-polluting oil-based fuels, as it can offer the near complete removal of SO\textsubscript{X} and particulate emissions and a substantial reduction of NO\textsubscript{X} emission.

LNG is not only cleaner when combusted, but it may also offer economic advantages to ship owners. These are difficult to quantify, especially given the uncertainties associated with several important parameters such as the future cost (and availability at the relevant locations) of LNG, but studies seem to indicate that it may indeed be a commercially advantageous fuel, especially for new built (Schinas and Butler 2016).

Whereas LNG carriers have used LNG as fuel for decades, other types of vessels have started to used LNG as fuel only fairly recently, since around 2000. Hence, this technology can be considered mature for a segment of the fleet, but very much less so for all others. It was thus of great interest to investigate potential technology needs, bottlenecks and other related issues, problems and opportunities associated to potential transition and gasification of the merchant fleet. This report discusses such issues.

Policy context

The EC white paper (28 March 2011) 'Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System' called for a reduction of the dependence of transport on oil. The results from consultations with EU experts, different stakeholders and EC were reflected in documents such as the Communication (24 January 2013) on 'Clean Power for Transport: A European alternative fuels strategy' and helped identifying natural gas (and LNG as natural gas in liquid form), among other fuels, as a serious alternative for long term oil substitution.

Directive 2014/94/EU establishes a common framework for the deployment of alternative fuels infrastructure in the European Union to minimise dependence on oil and to mitigate the environmental impact of transport. It establishes minimum requirements for deployment of a continued network of alternative fuels infrastructure, and in particular refuelling points for natural gas (CNG and LNG) within a TEN-T Core Network. It also specifies the need to standardise technical specifications for interoperability of recharging and refuelling points. Moreover, Directive (EU) 2016/802 establishes limits on the maximum sulphur content of, among other fuels, marine fuels (LNG included). This directive in fact codes International Marine Organisation (IMO) initiatives into EU law.

The attention paid to LNG by experts and the referred pieces of EU legislation have lead JRC to carry out this review study on the situation, perspectives and challenges of LNG as a marine fuel.

Key conclusions

LNG as fuel for maritime vessels is already a proven and available solution. LNG carriers have used LNG as fuel for decades. Since around 2000 the technology has also been tested on a substantial amount of non-LNG carrier gas-fuelled vessels, with the in-service and on-order fleet of LNG-powered seagoing ships reaching the 200 mark in March 2017.

A considerable amount of regulatory and technical progress has taken place in the last few years. This led us to conclude that no major technological bottlenecks appear to hinder the potential adoption of LNG as marine fuel.

We recommend that further research is carried on two main areas: the issue of methane emissions and the development of LNG markets.

LNG as fuel seems to offer considerable environmental benefits because of the reduced emissions of pollutants such as NO\textsubscript{X}, CO\textsubscript{X} and particulates, but better estimates of the
amount of methane released (both because of leaks during handling and methane slip) are needed.

Further investigation on the issue of LNG markets is needed for a more complete understanding of the potential of this commodity as marine fuel.

**Main findings**

Whilst attempting to obtain a broad understanding of the ongoing perspectives and challenges concerning the application of LNG as a fuel for maritime propulsion, we identified and discussed the main areas of:

- Availability of a regulatory framework;
- Economic viability;
- Technological feasibility;
- Availability of bunkering infrastructure;
- Availability of LNG;
- Public-social awareness.

Concerning the availability of a regulatory framework, we discussed the progress achieved so far in three main areas: regulation for the use of LNG as marine fuel, regulation for LNG bunkering and regulation for inland waterways vessels. Our analysis showed that whereas as recently as 2014 a fairly large regulatory gap regarding the application of LNG as a ship fuel existed, considerable progress has been achieved in the last four years. Such regulatory gap can be considered filled to a large extent, as discussed at length in Section 3.1.

A detailed discussion on the economic viability of LNG as marine fuel was beyond the purpose of this study. Our brief analysis concluded that many factors will affect such viability: international regulatory frameworks and regional initiatives, commercial and operational attributes determining the competitiveness of LNG-fuelled ships and potential challenges preventing the adoption of LNG, with the price of LNG (against the price of conventional fuels and other energy carriers) possibly the fundamental parameter defining the economic discussion on the use of LNG as a marine fuel. Further investigation on the issue of LNG markets will therefore be essential for a more complete understanding of the potential of this commodity as marine fuel.

Four main technical issues were identified as having a particular interest. These were:

1. Emission assessment and monitoring;
2. LNG engines and the issue of methane slip;
3. On board fuel tanks and storage infrastructure;
4. Retrofitting of existing vessels.

A critical fifth aspect was identified as the availability of infrastructure:

5. Bunkering infrastructure.

Concerning availability of LNG as energy source, and although the growth of the global LNG market is foreseen to be driven by the increasing demand for power generation and residential usage, we concluded that LNG import facilities will play a key role in the future as distribution hubs to support the introduction of LNG bunkers for ships. Considering their growing number, we inferred that LNG availability should not be a major bottleneck for the introduction of LNG as a ship fuel.

Given its direct and indirect effects on the public and workers, we included a sixth critical aspect for further discussion:

6. Safety issues associated with handling LNG.
Finally, we considered the issue of public acceptance as a potential bottleneck for the use of LNG as a ship fuel:

7. Public acceptance of LNG.

1. Emission assessment and monitoring

Many thorough assessments of full life-cycle air emissions of alternative marine fuels have been carried out, and a considerable amount of work has been completed or is currently under way to develop improved monitoring methods. We conclude that the issue of emissions monitoring does not appear to represent a potential technology bottleneck for the transition to a more widespread usage of LNG as marine fuel. The issue of emission assessment is more delicate. Assessment studies are based on models that make several assumptions subject to vast uncertainties. We recommend that further research is carried out to determine whether LNG systems will lead to greenhouse gas (GHG) emissions reduction or increases compared to conventional fuels in maritime applications.

2. LNG engines and the issue of methane slip

The analysis and review carried out in the section dedicated to LNG engines lead us to conclude that a large array of technological solutions have already been developed and deployed in real case applications. Steam turbines have been the preferred propulsion systems on LNG carriers until the beginning of the 2000s, offering several advantages such as ease of use, intrinsic reliability, reduced maintenance costs, uncomplicated control of Boiled-Off Gas (BOG), etc. Gas turbines solutions exist in many varieties and configurations. Internal combustion engines are the predominant propulsion system in all sectors of marine transport, but until recently they could not burn different fuels simultaneously. From the early 2000s, dual fuel internal combustion engines (both two strokes and four strokes) have been developed, capable of using methane as well as marine diesel.

Methane slip (the release of methane, unburned through the engine), until recently considered a real drawback, can be managed by improved engine designs and the current consensus among industry experts is that methane slip during combustion has been practically eliminated in modern two-stroke engines (with further reductions expected from four-stroke engines). We therefore concluded that the issue of LNG engines does not appear to represent a potential technology bottleneck for the transition to a more widespread usage of LNG as marine fuel.

3. On board fuel tanks and storage infrastructure

Several options of LNG fuel tanks and fuel gas supply systems are available depending on the vessel size and type of engine. In conclusion, the technology to develop LNG fuel tanks, fuel systems and BOG systems seems to be very well developed. The main challenge is rather economical, relating to the need of installing larger tanks affecting in turn ship productivity.

4. Retrofitting of existing vessels

Retrofitting projects recently concluded or planned for the near future have demonstrated the feasibility of such operation. The technical challenges are very diverse, differing on a case-to-case basis according to the ship type, but do not seem to present particular difficulties. For the operator, the decision whether to retrofit is often an economical one. Typically, for retrofitting no funding is available, whereas it is for building a new ship.

5. Bunkering infrastructure

LNG bunkering infrastructure is expanding on a global scale. Today, there are 60 supply locations worldwide, including Singapore, the Middle East, the Caribbean as well as Europe. A further 28 facilities have been decided and at least 36 are under discussion. By the beginning of 2018, six LNG bunker vessels are already in operation globally, and four more projects are confirmed.
6. Safety issues associated with handling LNG

The appropriate safety culture required to handle and operate LNG vessels seem to be in place, both mandated by national and international regulations. Operators need to maintain a high level of attention in this regard, but this particular aspect does not seem to represent a particularly difficult challenge that may hamper the adoption of LNG as marine fuel.

7. Public acceptance of LNG

Public perception of LNG is overall positive and improving, but lack of knowledge regarding this particular fuel is still reported, both regarding potential advantages and disadvantages of alternative fuels. In any case, we conclude that this aspect does not seem to represent a particular bottleneck. The safety of LNG handling has been demonstrated in decades of experience and the matter rests on properly informing the concerned public, for instance locally when a harbour decides to begin operating with LNG bunkering facilities.

Related and future JRC work

Two issues have been identified in this report as potential threats to the further development of LNG as marine fuel: LNG market adverse conditions (in terms of price of other fuels) and LNG emissions. Natural gas emissions in the entire EU natural gas transmission network and particularly LNG emissions will be addressed in a report to be delivered as part of JRC institutional work during 2019. Additionally, JRC will follow the evolution of the LNG market(s), including LNG transport costs and cost of refuelling in order study the impact of these factors in the development of the LNG commercial propelled fleet.

Quick guide

Chapter 1 is dedicated to setting the scene for this study and to review the main policy initiatives concerning emission control legislation for international shipping.

Chapter 2 is dedicated to reviewing the many different strategies that have been proposed to reduce emissions from ships.

In Chapter 3 we attempt to obtain a broad understanding of the ongoing perspectives and challenges concerning the application of LNG as a fuel for maritime propulsion. In particular, we discuss the availability of a regulatory framework, the economic viability, the technological feasibility, the availability of infrastructure and of the primary resource itself (LNG) and public-social awareness issues.

Technical aspects of particular interest will be identified and further analysed and discussed in Chapter 4. More in details:

- The issue of emission assessment and monitoring is covered in Section 4.1.
- LNG engines and the issue of methane slip are discussed in Section 4.2.
- On board fuel tanks and storage infrastructure are explored in Section 4.3.
- The challenges associated with retrofitting are covered in Section 4.4.
- Bunkering infrastructure is discussed in Section 4.5.
- Safety (both on board and on shore) is covered in Section 4.6.
- Public acceptance of LNG is explored in Section 4.7.

Finally, conclusions will be drawn in Chapter 5.
1 Introduction

The necessity of a more environmentally friendly maritime transport and the progressive introduction of international legislation by institutions such as the International Maritime Organization (IMO) and the European Union are challenging the global shipping industry. Indeed, as for 2015, legislation has been introduced to significantly limit emissions from ships, beginning in northern Europe and North America (IMO 2011; European Parliament and Council of the European Union 2016; IMO 2018).

Liquefied Natural Gas (LNG) is a potential solution to meet these requirements by replacing conventional, more-polluting oil-based fuels (heavy fuel oil, marine gas oil, or distillate fuels). This ranges from emissions of SOX and NOX to CO2, particulates and black carbon. LNG can offer the near complete removal of SOX and particulate emissions and a substantial reduction of NOX emission and hence, as a fuelling option, it offers multiple advantages to both human health and the environment (DNV GL 2015b).

LNG is not only cleaner when combusted, but it may also offer economic advantages to ship owners. These are difficult to quantify, especially given the uncertainties associated with several important parameters such as the future cost (and availability at the relevant locations) of LNG, but studies seem to indicate that it may indeed be a commercially advantageous fuel, especially for new built (Schinas and Butler 2016). Finally, the recent decrease by roughly 20% in EU gas demand between 2010 peak year and 2014 provide room for allocating gas to other areas of demand. All these factors may foster the gasification of the merchant fleet.

The scope for displacement of bunker fuel oil by LNG is potentially huge (Adamchak and Adede 2013). Excluding LNG carriers, the LNG-fuelled vessels in operation represent a very small percentage of the total commercial marine fleet. However, LNG as a bunker fuel faces a number of challenges, most notably the investment required in ships propulsion and fuel handling systems and in onshore bunkering facilities, the development of new international safety regulations, and LNG availability (Adamchak and Adede 2013; Buades 2017).

If emission reductions can be expected in the future with LNG, it is important to mention that a recent study on a cruise ferry powered by four dual-fuel engines and operating in the Baltic Sea hinted at the possibility that emissions of total hydrocarbons and carbon monoxide were higher for LNG compared to present marine fuel oils (Anderson, Salo et al. 2015).

Whereas LNG carriers have used LNG as fuel for decades, other types of vessels have started to use LNG as fuel only fairly recently, since around 2000. Hence, this technology can be considered mature for a segment of the fleet, but very much less so for all others. It is thus of great interest to investigate potential technology needs, bottlenecks and other related issues, problems and opportunities associated to potential transition and gasification of the merchant fleet. This report discusses such issues.

The remainder of Chapter 1 is dedicated to setting the scene for the study and review the main initiatives concerning emission control legislation for international shipping. Chapter 2 is dedicated to reviewing the many different strategies that have been proposed to reduce emissions from ships. In Chapter 3 we attempt to obtain a broad understanding of the ongoing perspectives and challenges concerning the application of LNG as a fuel for maritime propulsion. We will discuss the availability of a regulatory framework, the economic viability, the technological feasibility, the availability of infrastructure and of the primary resource itself (LNG) and public-social awareness issues. Technical aspects of particular interest will be identified and further analysed and discussed in Chapter 4. Finally, conclusions will be drawn in Chapter 5.
### 1.1 Setting the scene

Conventional marine fuel is processed from crude oil in refineries and before being used it is usually stored at bunker stations located in port areas. More in detail, there are five types of marine fuels which are categorized based on their blends and viscosity, namely:

1. **Marine Gas Oil (MGO).** It is identical to the automotive diesel fuel which is used in land vehicles.
2. **Marine Diesel Oil (MDO).** It contains a mixture of heavy fuel oil and marine gas oil, has low viscosity and does not require preheating before use.
3. **Intermediate Fuel Oil (IFO).** Almost similar to marine diesel oil, a mixture of residual oil or HFO with MGO.
4. **Marine Fuel Oil (MFO).** Almost similar to HFO. It is a mixture of HFO with MGO but contains less gas oil than IFO.
5. **Heavy Fuel Oil (HFO).** The lowest grade of marine fuel. It is a residual oil, having a high-viscosity residual oil and requires preheating before use.

In today’s shipping industry, heavy fuel oil is mostly used to power the main engine during voyage while marine diesel oil and marine gas oil are normally used for auxiliary engines and operation in harbours (Mohd Noor, Noor et al. 2018), but ever growing emissions standards are making the primary use of conventional marine diesels more expensive and less practical.

Natural gas offers some significant environmental advantages over traditional petroleum products. This is most notable in the use of LNG as a marine fuel rather than heavy fuel oil or marine diesel. LNG typically produces lower emissions of carbon dioxide ($\text{CO}_2$) and virtually no nitrogen oxides ($\text{NO}_x$), particulate matter (PM), or sulphur oxides ($\text{SO}_x$). A comparison of the emission factors for marine fuels is shown in Table 1 (IMO 2015; Le Fevre 2018). Using LNG as a ship fuel is not new. The technology is well-established, with the first experiences carried out towards the end of the 1950s. At the end of 2016, the (International Gas Union 2017) reports that there are a total of 439 LNG tankers in the global LNG fleet, either actively trading or available for work. These vessels use boil-off gas (BOG) as a part of ship propulsion. LNG as fuel enjoys an excellent safety record without any serious incidents (Wang and Notteboom 2014).

<table>
<thead>
<tr>
<th>Emission</th>
<th>Heavy Fuel Oil</th>
<th>Marine Diesel Oil</th>
<th>LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SO}_x$</td>
<td>0.049</td>
<td>0.003</td>
<td>trace</td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>3.114</td>
<td>3.206</td>
<td>2.750</td>
</tr>
<tr>
<td>$\text{CH}_4$</td>
<td>trace</td>
<td>trace</td>
<td>0.051</td>
</tr>
<tr>
<td>$\text{NO}_x$</td>
<td>0.053</td>
<td>0.087</td>
<td>0.008</td>
</tr>
<tr>
<td>PM</td>
<td>0.007</td>
<td>0.001</td>
<td>trace</td>
</tr>
</tbody>
</table>

Source: (IMO 2015; Le Fevre 2018).

Moreover, the technology has also been tested on a substantial amount of non-LNG carrier gas-fuelled vessels, mostly sailing in Northern Europe (e.g. Norway). The in-service and on-order fleet of LNG-powered seagoing ships has reached the 200 mark in March 2017: 103 ships in service and 97 on order (Corkhill 2017a; Corkhill 2017b). One year earlier, in March 2016, there were 74 LNG-fuelled vessels in service and 88 on order (hence 2017 saw an increase year on year of 23 per cent).

The progressive introduction of LNG as a marine fuel is likely to target particular shipping segments and ports that can be particularly suited to early development of this concept. (Wang and Notteboom 2014) noted that the shipping segments especially suited for early adoption of LNG powered propulsion share the following characteristics: (1) a regular
sailing pattern; (2) operations in specified regions with stricter environmental standards (such as ECAs); (3) the LNG fuel system is suited in relation to storage of gas and other on-board processes; (4) a relatively higher fuel consumption per ship. Therefore, the short sea shipping sector with dense regular traffic in regions such as North-western Europe and North America seems the most promising for a large-scale adoption of LNG as a fuel for ships. Ship segments such as car and passenger ferries, offshore supply vessels, RoRo\(^1\) ships and patrol vessels, etc. are the most attractive for the use of LNG. The inland waterway segment is also very promising (Wang and Notteboom 2014).

1.2 Emission control legislation for international shipping

In general we can identify two main branches regarding emission legislation in international shipping, namely (1) the initiatives if the International Maritime Organization (IMO); and (2) the legislation of the European Commission.

More in detail, the relevant IMO initiatives are the adoption of the MARPOL convention and its ANNEX VI and the development of the Energy-Efficient Design Index (EEDI) and the Ship Energy Efficient Management Plan (SEEMP) (Perera and Mo 2016) and (Stevens, Sys et al. 2015). These are described in the next two sub-Sections.

1.2.1 IMO initiatives

1.2.1.1 MARPOL Convention and Annex VI

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from both operational and accidental causes. The MARPOL Convention was adopted on 2 November 1973 by IMO.

Annex VI contains the regulations regarding sulphur emissions by ships and is the newest addition to the MARPOL convention. In particular, it contains provisions for two sets of emission and fuel quality requirements regarding SO\(_x\), particulate matter and NO\(_x\). The first is a global requirement and the second is a more stringent control in special Emission Control Areas (ECAs). It came into force in May 2005, with a more stringent revision adopted as of July 2010, specifying significantly lowered emission limits in the Emission Control Areas (IMO 2011).

There are currently four existing ECAs: the Baltic Sea, the North Sea, the North American ECA, including most of US and Canadian coast and the US Caribbean ECA. The International Maritime Organization (IMO) has started a study to investigate the possibility for a new 0.1% low sulphur emission control area that would cover part (or all) the Mediterranean Sea (IMO 2018).

In particular, Regulation 14 of MARPOL Annex VI states that the sulphur content of any fuel used on board a ship must be reduced to 0.5% from 1 January 2020. Inside an Environmental Control Area (ECA), however, the limits for SO\(_x\) and particulate matter must be further reduced from 1% (since 1 July 2010) to 0.10%, effective from 1 January 2015 (IMO 2011).

1.2.1.2 Energy-Efficient Design Index (EEDI)

The EEDI is a non-prescriptive, performance-based index that leaves the choice of technologies to be used in a specific ship design to the industry (IMO 2018). It requires a minimum energy efficiency level per capacity mile for different ship type and size segments. EEDI is based on a formula for calculating the mass of CO\(_2\) emitted per transport work (metric ton per nautical mile) at a specific power plant operating point. The actual EEDI is calculated based on formulas and guidelines published by the IMO,\(^1\)

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\(^1\) Roll-on/roll-off (RoRo) ships are vessels designed to carry wheeled cargo, such as cars, trucks, semi-trailer trucks, trailers, and railroad cars, that are driven on and off the ship on their own wheels.
and the attained index value must be below a prescribed baseline value (Ekanem Attah and Bucknall 2015).

The EEDI for new ships is the most important technical measure and it aims at promoting the use of more energy efficient (less polluting) equipment and engines. As long as the required energy efficiency level is attained, ship designers and builders are free to use the most cost-efficient solutions for the ship to comply with the regulations. EEDI was made mandatory for new ships with the adoption of amendments to MARPOL Annex VI (IMO 2011). From 1 January 2013, following an initial two year phase zero when new ship design will need to meet the reference level for their ship type, the level is to be tightened incrementally every five years, and so the EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase.

1.2.1.3 Ship Energy Efficiency Management Plan (SEEMP)

The SEEMP is an operational measure that helps the shipping company improve the energy efficiency of its operations in existing vessels (IMO 2018). It is meant to show how energy savings can be made in four steps: planning, implementation, monitoring and self-evaluation (MEPC, 2011).

In the SEEMP, the current performance of the ship has to be determined. Also a plan for improvement must be developed. This improvement can be reached through a large list of possible options (such as speed optimization, weather routing, etc.) which all should be examined (Stevens, Sys et al. 2015).

The planning phase in the SEEMP relates to vessel/shipping company specific operation requirements. Therefore, the goals for improving energy efficiency in each vessel initiate at this step. The implementation phase initiates by establishing an implementation mechanism to achieve the respective energy efficiency goals. The monitoring phase consists of developing a real-time monitoring mechanism with on-board sensors. These collect vessel navigation and performance parameters to be analysed for the evaluation of the vessel's energy efficiency under the SEEMP. The final step, the self-evaluation, consists of a voluntary reporting and review process. In this phase lessons learned and future improvements are identified (Perera and Mo 2016).

1.2.2 European legislation

In 2011, the European Commission (EC) published a White Paper on transport, affirming the will of the European Union to diminish its greenhouse gas emissions to limit climate change to 2°C. To this end, the European Commission estimated that a reduction in greenhouse gas emission levels by 80–95% below1990 levels must attained by 2050. For the transport sector in particular, the greenhouse gas emissions must be reduced by 20% by 2030 and by 40% by 2050 compared to their level in 2005 (European Commission 2011).

The IMO initiatives were coded into EU law with Directive (EU) 2016/802, regulating SOx emissions from ships (European Parliament and Council of the European Union 2012). This Directive establishes limits on the maximum sulphur content of gas oils, heavy fuel oil in land-based applications as well as marine fuels. It also contains some additional fuel-specific requirements for ships calling at EU ports, obligations related to the use of fuels covered by the Directive and the placing on the market of certain fuels (e.g. marine gas oils). In addition to MARPOL requirements, a 0.1% maximum sulphur requirement for fuels used by ships at berth in EU ports was introduced (fuel with higher sulphur content can be used if the ship is equipped with abatement systems on-board). Furthermore, passenger ships operating on regular services to or from any EU port are forbidden to use marine fuels if their sulphur content exceeds 1.50% in sea areas outside the ECAs.

The 2014 EC Directive (2014/94/EU) has established a common framework of measures for the deployment of alternative fuels infrastructure in the European Union in order to
minimise dependence on oil and to mitigate the environmental impact of transport (European Parliament and Council of the European Union 2014). The directive does not specifically dictate regarding ships or vessels, but is about infrastructure and refuelling points, so it addresses the operation in/of harbours.

In particular, at paragraph 42, it identifies LNG as an attractive fuel alternative for vessels to meet the requirements for decreasing the sulphur content in marine fuels in the SO\textsubscript{x} Emission Control Areas as dictated by Directive 2012/33/EU regarding the sulphur content of marine fuels. To this end, it dictates that a core network of refuelling points for LNG at maritime and inland ports should be available at least by the end of 2025 and 2030, respectively. Refuelling points for LNG should include LNG terminals, tanks, mobile containers, bunker vessels and barges. At paragraph 43 the Directive calls on the Commission and the Member States to work towards modifying existing regulations to allow large-scale carriage of LNG on inland waterways and to allow the efficient and safe use of LNG for propulsion of vessels on inland waterways.

On 16 June 2016 the European Council formally adopted a revised Directive, (EU) 2016/1629, which sets out how technical requirements for inland waterway vessels are applied in Europe (General Secretariat of the Council 2016). This directive does not explicitly mention LNG as fuel but is intended to improve legal certainty, avoid differing safety levels and reduce administrative burdens for the sector (European Parliament and Council of the European Union 2016). Inland waterway vessels will have to comply with technical standards developed by the European Committee for drawing up Standards in Inland Navigation, see 3.1.3.

It is also of interest to mention Regulation (EU) 2015/757 on the monitoring, reporting and verification of CO\textsubscript{2} emissions from maritime transport that applies to ships above 5000 gross tonnage, regardless of their flag, calling at EU ports, valid as of 1st of January 2018.

A recent overview of the latest developments in the field of alternative fuels and the market uptake of alternative fuel transport systems and related infrastructure in the EU is given by (European Commission - DG MOVE - Expert group on future transport fuels 2015).
2 Strategies for reducing maritime emissions

There are many different strategies to reduce emissions from a sailing vessel. A broad categorisation can be made by dividing the strategies into (Yang, Zhang et al. 2012; Seddiek and Elgohary 2014; Stevens, Sys et al. 2015):

(1) those based on applying reduction technologies on-board;
(2) those based on using of alternative fuels;
(3) those based on fuel saving.

In the remainder of this chapter we give a brief overview of such strategies.

2.1 Ship emissions reduction strategies based on applying reduction technologies on-board

Technologies for emissions reduction based on applying reduction technologies on-board can be further subdivided into three general areas: in-engine, fuel-related and exhaust cleaning technologies. The most emissions reductions technologies are concerned with nitrogen oxides and sulphur oxides emissions, but other pollutants are considered as well.

2.1.1 NOx emissions

There are several technical strategies to NOx emissions from a ship engine (Seddiek and Elgohary 2014; Marine Insight 2017).

Selective catalytic reduction. In this method, low sulphur fuel oil is used and exhaust temperature is maintained above 300°C. The exhaust gas is mixed with a water solution of urea and then it is passed through catalytic reactor. It is currently considered the best efficient method of NOx reduction and is already used on board many ships. Its only disadvantage is probably its higher installation and operating cost (Seddiek and Elgohary 2014).

Water injection and emulsification. In this method, water is added to the combustion chamber to reduce peak combustion temperature, reducing NOx formation. See for instance (Hountalas, Mavropoulos et al. 2006).

Humid air. In this method, water vapour is injected into the intake air supplied to the engine cylinders. The process reduces the local temperature in the cylinder and raises the specific heat of the air-fuel mixture which also contributes to the elimination of the hot spots in the engine cylinder. With decreased temperature, NOx reduction is achieved (Rahai, Shamloo et al. 2011). This method can achieve reduction of NOx by 70 to 80%.

Engine tuning. Tuning the combustion process can be an effective method. Options include modifying the spray pattern, the injection timing, the intensity of injection and injection rate profile, compression ratio, the scavenge air pressure and scavenge air cooling. Delayed injection timing is very effective in reducing NOx but increases fuel consumption and smoke (Goldsworthy 2002).

Exhaust Gas Recirculation. In this method, the engine exhaust gases are send back to the scavenge space to mix up with the air to be supplied to cylinder for combustion. This reduces the oxygen content of the air and hence reduces formation of NOx. See for instance (Hansen, Kaltoft et al. 2014).

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2 Scavenging is the process of removing exhaust gases from the cylinder after combustion and replenishing the cylinder with fresh air. Efficient scavenging is essential to achieve a good combustion of the fuel inside the engine cylinder (see for instance https://marineengineeringonline.com/scavenging-in-diesel-engines).
Two Stage Turbocharger. By cooling the combustion process using a Miller cycle\(^3\), NO\(_x\) emissions can be efficiently reduced. This requires high boost pressures, achieved by using a two-stage turbo charging system (Wik and Hallbäck 2008).

Engine Component Modification. In this strategy, engine properties to reduce NO\(_x\) formation during combustion are introduced at the design phase, rather than retrofitting secondary measures. One such measure is for instance the integration of specific fuel injectors to eliminate fuel dripping and after-burning.

2.1.2 SOx emissions

We identify three specific strategies to reduce SO\(_x\) emissions from a ship engine (Marine Insight 2017).

Sulphur oxides are formed during combustion process in the engine because of presence of sulphur content in the fuel, and hence the most commonly used method to abate these emissions is to use low sulphur fuel oil. This fuel is more expensive but it allows to comply with Annex VI of MARPOL while entering ECAs.

Exhaust Gas Scrubber Technology. In this method, the exhaust gasses from the engine are passed through a gas cleaning system (usually called scrubber) where there are mixed with a liquid, normally based on either seawater or freshwater. For instance, fresh water blended with caustic soda can be used to achieve SO\(_x\) reductions up to 95%. The system also include a treatment plant where pollutants are removed from the water after the scrubbing process and sludge handling facilities (the sludge removed by the treatment must be disposed properly).

Cylinder Lubrication. Good quality cylinder lubrication can contribute to neutralise the sulphur in the fuel and hence reduce SO\(_x\) emissions.

2.1.3 Other emissions

In addition to the technologies used to reduce both NO\(_x\) and SO\(_x\), other can be applied for other pollutants such as carbon dioxide and particulate matter.

Particulate matter (PM) is the combination of soot and other liquid- or solid-phase materials. If not minimized, it causes adverse effects both for human beings and the environment. A very thorough review of the works carried out to control diesel particulate matter in the last few decades is carried out by (Mohankumar and Senthilkumar 2017).

Methods for addressing PM can be classified as pre-combustion and post-combustion control technologies. Among pre-combustion control techniques there are fuel modifications (for instance the use of biodiesel or the employment of oxygenated fuel additives) and in-cylinder modifications (e.g. injection and pressure, multiple injections, auxiliary air injection and water emulsified fuel). Among post-combustion control technologies are the use of diesel particulate filter and various types of regeneration. Post-combustion technologies seem to be the best-suited methods to meet the current stringent emission regulations, with diesel particulate filter been the currently most deployed technology to minimize this type of emissions (Mohankumar and Senthilkumar 2017).

According to the IMO, the shipping sector is a modest contributor to overall CO\(_2\) emissions. It is estimated that the sector is responsible for emitting about a tenth of the emissions compared to the trucking industry and a thousandth of that from aviation, in terms of carbon emissions per ton per mile (Childs 2014). Fuel switch to lower carbon fuels for propulsion is probably the best technical option. Other options include operational measures based on energy management, for instance slow steaming (ships operate at slow speeds, reducing their fuel consumption considerably) and route optimisation. Incremental measures include improving hull design, propeller optimisation

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3 In a Miller cycle, the intake valve is left open longer than it would be in an Otto-cycle engine.
and waste heat recovery. Renewable energy could be harnessed to reduce CO₂ emissions, for instance in the form of wind-assist for propulsion (e.g. kite systems). Finally, energy storage (batteries) and a more widespread use of cold ironing (see Section 2.2.5) could enable the sector to decarbonise by allowing it to run off electricity produced via a low carbon grid (Gilbert 2018).

### 2.1.4 Summary

Table 2 summarizes the average emissions reduction percentages as a result of deploying some of the emissions reduction technologies discussed in the preceding Sections, as estimated by (Seddiek and Elgohary 2014). See also (Armellini, Daniotti et al. 2018) for a very recent analysis and comparison of different emission abatement strategies applied to a real case (a cruise ship, chosen because of its more variable cruise operational profile than a cargo ship).

#### Table 2. Methods for reducing ship emissions.

<table>
<thead>
<tr>
<th>Reduction method</th>
<th>Potential reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOₓ</td>
<td></td>
</tr>
<tr>
<td>Selective catalytic reduction</td>
<td>95%</td>
</tr>
<tr>
<td>Emulsification</td>
<td>20-25%</td>
</tr>
<tr>
<td>Humid air</td>
<td>70%</td>
</tr>
<tr>
<td>Engine tuning</td>
<td>50-60%</td>
</tr>
<tr>
<td>Exhaust gas recirculation</td>
<td>10-30%</td>
</tr>
<tr>
<td>SOₓ</td>
<td></td>
</tr>
<tr>
<td>Fuel switching (from residual fuel to distillate fuel) process</td>
<td>60-90%</td>
</tr>
<tr>
<td>Sea water scrubbing, exhaust below water line</td>
<td>Up to 95%</td>
</tr>
<tr>
<td>Particulate matter</td>
<td></td>
</tr>
<tr>
<td>Electrostatic filters</td>
<td>Up to 85%</td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
</tr>
<tr>
<td>Energy management</td>
<td>1-10%</td>
</tr>
</tbody>
</table>

*Source:* (Seddiek and Elgohary 2014).

### 2.2 Ship emission reduction based on using of alternative fuels

Fuels that have the potential to reduce emissions can play a significant role as substitutes for the conventional ones, provided that these fuels and the necessary technology are offered at competitive price levels (Moirangthem and Baxter 2016). Whilst not the only ones, the more promising alternative fuels commonly considered today are LNG, hydrogen, methanol, bio-diesels and electrical power. In this chapter we review these in more details. We also discuss the potential use of nuclear energy in Section 2.2.6, even if this does not appear a viable solution for the short to medium term, mostly given the issue of public acceptance.

A very interesting environmental and economical assessment of alternative marine fuels is given by (Deniz and Zincir 2016). Hydrogen was found to be the safest alternative fuel for use onboard. LNG and hydrogen were found to be the most effective alternative fuels on engine performance because of increases of brake thermal efficiency and decreases in brake specific fuel consumption. LNG was considered to be the most effective alternative fuel when considering engine emissions. Interestingly, hydrogen was placed in front of other alternative fuels in terms of the adaptability to existing ships, due to less system components, simpler system structure, no need of large space, and no special tank need for its storage. Commercial considerations were associated with cargo loading capacity, fuel quantity needed for a given voyage and bunker capability. Hydrogen does not need storage tank, because it is produced on demand. Hydrogen was found to have the least investment costs, due to less and simple system components. On the other hand, LNG has the least operating costs related to lubricating oil, spare parts and additional costs. At the total costs, LNG and hydrogen were found to be the best alternative fuels.
2.2.1 LNG

Liquefied natural gas as a potential marine fuel is the main topic of this report and is extensively discussed in Chapters 3 and 4.

LNG is a colourless and odourless mixture of light hydrocarbons, whose main component is methane (CH$_4$) with a ratio of between 85–96% in volume, with minor proportions of ethane (C$_2$H$_6$), propane (C$_3$H$_8$), butane (C$_4$H$_{10}$), pentane (C$_5$H$_{12}$), and nitrogen (N2) as inert component (Fernández, Gómez et al. 2017). The boiling point is -161.5°C at normal conditions. The flash point is -187.8°C. The specific gravity as liquid is 0.45 and 0.6 as gas. Compressed natural gas (CNG) at 25 MPa has density 185 kg/m$^3$. Liquefaction makes possible to increase density to 460 kg/m$^3$ (Herdzik 2011). LNG can be classified into three groups, according to its density: heavy, medium or light.

Table 3. LNG classification based on density and composition.

<table>
<thead>
<tr>
<th>Molar Composition (%)</th>
<th>Light LNG</th>
<th>Medium LNG</th>
<th>Heavy LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH$_4$)</td>
<td>98.60</td>
<td>92.30</td>
<td>85.87</td>
</tr>
<tr>
<td>Ethane (C$_2$H$_6$)</td>
<td>1.18</td>
<td>5.00</td>
<td>8.40</td>
</tr>
<tr>
<td>Propane (C$_3$H$_8$)</td>
<td>0.10</td>
<td>1.50</td>
<td>3.00</td>
</tr>
<tr>
<td>Butane (C$<em>4$H$</em>{10}$)</td>
<td>0.02</td>
<td>0.60</td>
<td>1.20</td>
</tr>
<tr>
<td>Pentane (C$<em>5$H$</em>{12}$)</td>
<td>–</td>
<td>0.10</td>
<td>0.23</td>
</tr>
<tr>
<td>Nitrogen (N$_2$)</td>
<td>0.10</td>
<td>0.50</td>
<td>1.30</td>
</tr>
<tr>
<td>Density (at −162°C/1.3 bar) (kg/m$^3$)</td>
<td>427.58</td>
<td>451.58</td>
<td>474.87</td>
</tr>
</tbody>
</table>

Source (Fernández, Gómez et al. 2017).

Heat transfer from the environment to the LNG in the holding tanks inevitably results in some partial boiling of the liquid, with the consequent formation of boil-off gas (BOG). The main reasons for this heat transfer is due to the difference in temperature between the ambient and the cargo being carried and the energy dissipated from the slogging between the walls and the fluid, caused by the load being shaken by the movement of the vessel (Fernández, Gómez et al. 2017). It is on journeys in bad weather conditions that the BOG produced is increased considerably (Dobrota, Lalić et al. 2013).

The BOG produced in the tanks of LNG carriers must be removed in order to maintain the design pressure within the tanks, either by using it as fuel in the propulsion system or (in vessels fitted with re-liquefaction facilities) re-liquefied and returned to its tank in a liquid state. The latter option requires a high consumption of energy and for this reason BOG has been used since a long time to help power LNG carriers.

2.2.2 Hydrogen

Hydrogen is an energy carrier which is normally in gas state. It is attractive due to the clean exhaust of its reaction with oxygen in to water. Hydrogen has several very interesting properties, such as a wide flammability range, a high flame speed, high diffusibility, low minimum ignition energy, and zero carbon. On the other hand, it has a high self-ignition temperature (858K), meaning that it cannot be used in a compression ignition engine without a spark plug (Deniz and Zincir 2016), even if it can be combusted in engines and turbines, pure or in a mix with natural gas.

Given its characteristics, it is an ideal fuel to combine with other fuels, see for instance (Dimitriou, Kumar et al. 2018) for a recent study on a heavy-duty hydrogen-diesel dual-fuel engine. Hydrogen can otherwise be used on-board in fuel cells that convert its chemical energy into electricity. Fuel cells could have a higher efficiency than combustion engines.
Despite its many positives, hydrogen as fuel can be costly to produce, transport, and store. Compressed hydrogen has a very low energy density by volume requiring six to seven times more space than heavy fuel oil. Liquid hydrogen requires cryogenic storage at very low temperatures, associated with large energy losses (when insulation is not of high standard), and very well insulated fuel tanks. (Christos 2014; DNV GL 2015b).

(Deniz and Zincir 2016) have recently compared the environmental and economic performance of methanol, ethanol, liquefied natural gas, and hydrogen as alternative fuels. They found that hydrogen scored the highest in terms of safety, bunker capability, durability, and adaptability, proving that it could be a viable alternative to LNG. To ensure safe operations, special care must be given to the storage of hydrogen on board vessels (Christos 2014; DNV GL 2015b).

A very relevant and recent study is the doctoral thesis of (Raucci 2017). The author present a very thorough literature review of the main studies concerning the use of hydrogen as a fuel in shipping and uses modelling to investigate hydrogen uptake in the shipping sector, the main economic and environmental implications and its potential to compete with LNG and current marine fuels.

The European Maritime Safety Agency provided in 2017 an overview of different fuel cell technologies with reference to applications in shipping and a safety assessment of some technologies which were deployed in real applications. It also included a mapping of the regulatory framework, including an overview of standards, regulations and guidelines applicable for fuel cells in shipping as well as for bunkering of novel fuels such as hydrogen (European Maritime Safety Agency 2017a).

2.2.3 Methanol

A number of other liquid fuels, such as methanol, can be used in dual-fuel engines. Typically, a small quantity of marine fuel oil is used as pilot fuel, to initiate the ignition process, followed by combustion of the selected alternative fuel. Methanol does not require cryogenic temperatures for storage (as opposed to LNG) and therefore the fuel storage tanks and related equipment are simpler and less expensive. Methanol is an excellent replacement for gasoline and is used in mixed fuels, and it may also achieve a good level of performance in diesel engines. Its use in diesel engines requires an ignition enhancer, which may be a small amount of diesel oil. Methanol shows good combustion properties and energy efficiency as well as low emissions from combustion (Andersson and Salazar 2015).

On the other hand, it has a relatively low flashpoint, is toxic and its vapour is denser than air. As a result of these properties, additional safety measures are required (DNV GL 2015b). Another drawback of methanol is that its energy content is lower than that of traditional fuels. Given equivalent energy density, the space needed for storing methanol in a tank is approximately twice that of traditional diesel fuels (whereas methanol and LNG are similar in terms of energy density) (Andersson and Salazar 2015).

Methanol has been given attention as a low carbon alternative fuel because it can be synthesized from a number of feedstocks, including renewable ones such as municipal waste, industrial waste and biomass. Even if methanol is not produced from renewable resources, it remains an environmentally interesting fuel for ships due to its low NOx and particulate emissions (IMO 2016b).

The report published by IMO in 2016 present a comprehensive analysis of the environmental benefits, the technology readiness and the economic feasibility of methanol as marine fuel (IMO 2016b). Other relevant studies are the report commissioned by the Methanol Institute (Andersson and Salazar 2015) and the EMSA study (European Maritime Safety Agency 2015) on methyl and ethyl alcohol fuels.

(Svanberg, Ellis et al. 2018) carry out a synthesis of literature to provide an overview of main challenges and opportunities along potential supply chains of renewable methanol for maritime shipping. These authors show that renewable methanol is a technically
viable option to reduce emissions from shipping and there are no major challenges with potential supply chains. They also conclude that relatively minor economic barriers do exist but these can be overcome if environmental targets are strengthened or if fuel oil prices revert to past higher levels.

The Swedish operator Stena Line has successfully retrofitted one of its vessels for using methanol as a solution to low sulphur fuel requirements. According to (IMO 2016b), this is the first and only vessel in the world running on methanol (as of 2016). Additionally, a number of chemical carriers are also being designed to be able to run on methanol, so that they can use their own methanol cargo as fuel. In general, due to the relatively limited availability of methanol (compared to oil and gas at current levels), it is not expected that it will penetrate deep sea shipping sectors in the near to medium term future but it can become an important part of the fuel mix in local markets or specialised segments, such as local ferries or chemical tankers (DNV GL 2015b).

As recently as 5 June 2018 the Maritime Safety Committee of the IMO invited ISO to develop (1) a standard for methyl/ethyl alcohol as a marine fuel and (2) a standard for methyl/ethyl alcohol fuel couplings. More in detail, the request was formulated during a discussion regarding amendments to the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels. In this regard, ISO expressed the willingness to develop such standards, but pointed out that there was a lack of sufficient experience in the industry for the use of such fuel (Maritime Safety Committee of the IMO 2018).

### 2.2.4 Bio-diesels

Biodeisel consist of monoalkyl esters of long chain fatty acids oils derived from renewable lipid sources such as vegetable oil or animal fat. Sources can be classified into four main groups:

1. Edible vegetable oil, such as those derived from soybean, sunflower, palm, etc.,
2. Non-edible vegetable oil, such as those derived from algae, cotton seed, etc.
3. Recycle and waste oil.

Biodeisel offers some very good features as marine fuel. It is a renewable source of energy and is very versatile, as it can be obtained from a wide range of feedstocks depending on the geographical location. It can be applied in diesel engines as pure or blended with other petroleum diesels without engine modification. It is biodegradable and non-toxic and it contains virtually no sulphur. The flash point is higher than petroleum diesel, making it less flammable and hence safer to handle and easier to store (DNV GL 2015b).

Biodeisel also has some drawbacks as well. It has slightly less energy content than petroleum diesel. It has a higher viscosity and density, sometimes creating problems to the fuel injection system. Because of its higher pour point, solidification of biodiesel can happen in cold weather, causing clogged filter and damage to the fuel lines. Its NOx emissions fuel are about 10% higher than petroleum diesel. Biodeisel also tends to deteriorate natural rubber materials such as hoses and seals. End quality can vary because of the many different types of feedstock used. Finally, it has currently a higher cost than petroleum diesel (Mohd Noor, Noor et al. 2018).

Biofuels derived from waste have many benefits, but securing the necessary production volume can be a challenge. The logistics of collecting and transporting biomass to a processing facility contribute significantly to cost (DNV GL 2015b). In this sense, algal biofuels seem to be very promising. The work carried out by (Doshi, Pascoe et al. 2016) presents an excellent review of the economic and policy issues in the production of algae-based biofuels. This study highlighted key limitations of first and second-generation biofuels, and found that microalgae could alleviate much of the shortcomings affecting its predecessors, but that high production and energy costs still represent a major
limitation. The authors also highlighted that policy intervention still has a major influence over the development and use of biofuels.

An excellent review of biodiesel as alternative fuel for marine diesel engine applications is provided by (Mohd Noor, Noor et al. 2018). The technical report published by JRC is also a very good reference source (Moirangthem and Baxter 2016). A very thorough technical assessment of biofuels for marine engines that takes into account the entire supply chain from field to ship has been carried out by (Hsieh and Felby 2017).

### 2.2.5 Electrical power

Recent developments in ship electrification hold significant promise for more efficient use of energy. Low-carbon power production could be exploited to produce electricity in order to power moored ships (the so-called "cold ironing") and to charge batteries for fully electric and hybrid ships (European Parliament and Council of the European Union 2014; DNV GL 2015b).

Electrical motors have been used on ships for a very long time, but traditionally the power was supplied by diesel generators. The need for more efficient and versatile ships has increased the variety in hybrid propulsion and power supply architectures. These are thoroughly reviewed by (Geertsma, Negenborn et al. 2017). This paper classifies marine propulsion topologies into mechanical, electrical and hybrid propulsion, and power supply topologies into combustion, electrochemical, stored and hybrid power supply. Combustion power supply is the traditional way to produce work, using diesel engines, gas turbines or steam turbines. Electrochemical power supply is derived from the electrochemical energy stored in a chemical substance (for instance hydrogen in fuel cells). Stored power supply is derived from energy storage systems such as batteries, flywheels or super capacitors. A hybrid system uses some combination of the above. Table 4 summarises the benefits and drawbacks of the power and propulsion technologies so classified.

The initial development of power electronics took place in the 1990s and has led to extensive application of electrical propulsion. This was done with the purpose to overcome the poor part load efficiency (i.e. the efficiency of the engine outside its design, 100% load) and the robustness of mechanical propulsion. This type of propulsion was first introduced in cruise ships, and other applications (large warship, offshore vessels, etc.) which have a significant hotel load\(^4\). Hybrid propulsion was later introduced for vessels both operating a large proportion of time at design speed, and operating significant periods at low power, below 40% of their top speed. Ships that have increasingly utilised hybrid propulsion are for example warships, patrol vessels, tugs and offshore vessels (Geertsma, Negenborn et al. 2017).

More recently, the development of high power batteries in other industries has enabled their use in shipping. Batteries can provide benefits such as load levelling\(^5\), efficient back-up power and a propulsion mode with no noise nor emissions (Geertsma, Negenborn et al. 2017). The main drawback is an increase in the purchase and replacement cost, and because of the low energy/power density, the use of purely stored power supply from batteries is limited to vessels that require a very short range. Batteries have been increasingly applied vessels such as tugs, yachts, offshore vessels and ferries.

Whilst several hybrid ships have been built and are being used for testing batteries in shipping, ships relying exclusively on electrical power have started to be developed only very recently. The first fully electric ferry, the *Ampere*, entered service in Norway’s Sognefjord during 2015. The ferry has a capacity of 360 passengers and 120 cars, and uses two 450 kW electric motors which emit no direct emissions over the 6 km crossing. Each crossing uses approximately 150 kWh from lithium-ion batteries that are recharged between crossings using power from the shore-based grid (Moirangthem and Baxter

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\(^4\) The electrical load relating to the human occupancy aspects of a vessel (air conditioning and lighting, etc.) is analogous to the power requirements of a hotel.

\(^5\) Load levelling is a measure for reducing the effects of large fluctuations in power demand.
A second ferry, the *Elektra*, has been in operation in Finland since 2017. According to the latest reports, 53 similar ferries have been ordered (Kane 2018). The master thesis of (Kullmann 2016) carried out a comparative life cycle assessment all-electric Ampere and the diesel-driven vessel *MF Oppedal* (a ferry operating on the same route across the Sognefjord between the towns of Lavik and Oppedal).

An interesting technical possibility envisage the recharging of batteries during the voyage, while the ship is operating on a different type of engine/fuel. This option is to be analysed in a CEF programme project⁶.

**Table 4.** Benefits and drawbacks of propulsion and power supply (PS) technologies.

<table>
<thead>
<tr>
<th>Propulsion</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Low loss at design speed, Low CO₂ and NOₓ emissions at design speed, Low conversion losses</td>
<td>Poor part load efficiency and emissions, High NOₓ at reduced speed, Low redundancy, Mechanical transmission path of noise, Engine loading</td>
</tr>
<tr>
<td>Electrical</td>
<td>Robustness, Matching load with generators, High availability, Reduced NOₓ emission at low speed, Potentially low noise</td>
<td>Constant generator speed, Losses at design speed, Risk of constant power load instability</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Low loss at design speed, Robustness, Matching load &amp; engines at low speed, Potentially low noise on electric drive</td>
<td>Constant generator speed, System complexity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Supply</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-chemical</td>
<td>Air independent, No harmful emissions, High efficiency and low noise</td>
<td>Limited range, Safety, Complex with reforming</td>
</tr>
<tr>
<td>Stored</td>
<td>Air independent, No harmful emissions and noise</td>
<td>Very limited range, Safety</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Load levelling, Zero noise and emission mode, Storing regenerated energy, Efficient back-up power, Enabling pulsed power, Reduced fuel consumption &amp; emissions, No NOx increase during acceleration</td>
<td>Constant generator speed, System Complexity, Safety due to battery, Battery cost</td>
</tr>
</tbody>
</table>

*Source: Extract from Table 1 of (Geertsma, Negenborn et al. 2017).*

An interesting issue to discuss is that of cold ironing, i.e. the process of providing shore-side electrical power to a ship at berth while its main and auxiliary engines are turned off. This is also called alternative maritime power, onshore power supply or shore-side electricity. According to (Innes and Monios 2018), as of 2017 there were only 28 ports in the world with cold ironing installed. The technology still has many operational challenges, especially for ports with several small berths and a wide variety of vessel types which may be reluctant to install the required connections on their vessels. Cold ironing could even offer have financial advantages for ship operators, contingent on the cost of required on-board equipment, local electricity prices, and the fuel quality requirements at port. Standardization of the systems and equipment required is important to ensure compatibility between different port installations, so that a ship can use this opportunity at all ports without additional requirements (DNV GL 2015b).

(Innes and Monios 2018) examine the practical challenges of cold ironing system design, total energy demand, system costs and emission savings with a particular focus on small and medium ports. It also presents a thorough literature review regarding policy and regulation. A comprehensive review of the technical aspects, practices, existing

⁶ https://ec.europa.eu/inea/node/11824
standards and the key challenges in designing a harbour grid for shore to ship power supply is given by (Kumar, Kumpulainen et al. 2019).

2.2.6 Nuclear power

Nuclear power is particularly suitable for vessels which need to be at sea for long periods without refuelling. The use of a nuclear power plant to power the motion of a marine vessel has been quite widespread for military purposes since the 1950s. Over 140 vessels are powered by more than 180 small nuclear reactors and more than 12,000 reactor years of marine operation has been accumulated, according to the World Nuclear Association, mostly submarines but also icebreakers, aircraft carriers and merchant ships (World Nuclear Association 2018).

Development of nuclear merchant ships began in the 1950s but on the whole has not been commercially successful. A limited number of examples include: (1) the US-built NS Savannah (commissioned in 1962 and decommissioned eight years later), was a technical success, but not economically viable; (2) the German Otto Hahn cargo ship and research facility, that sailed for 10 years without any technical problems but proved too expensive to operate and was converted to diesel in 1982; (3) the Japanese Mutsu, put into service in 1970, was dogged by technical and political problems.

On the other hand, nuclear propulsion has proven technically and economically essential in the Russian Arctic, where operating conditions (capability to break ice up to 3 metres thick, refuelling difficulties, etc.) beyond the capability of conventional icebreakers are significant factors. The Russian nuclear fleet includes six nuclear icebreakers and a nuclear freighter, with operations totalling approximately 365 reactor-years to 2015 (World Nuclear Association 2018).

With increasing attention being given to emissions arising from burning fossil fuels for international air and marine transport and the excellent safety record of nuclear powered ships, it is conceivable that renewed attention could be given to marine nuclear powered ships. Indeed, some recent concept studies have been carried out.

In 2010 Babcock International's marine division completed a study on developing a nuclear-powered LNG tanker. The study concluded that particular routes lent themselves well to the nuclear propulsion option and that technological advances in reactor design and manufacture had made the option more appealing (Babcock International Group's Marine Division 2010). In 2009 Lloyd's Register Group investigated the benefits of applying marine nuclear propulsion using proven technology. Their study confirmed the safe and efficient application of pressurised water reactors for the propulsion of ocean-going merchant ships on the basis that political, regulatory barriers and market dynamics would remain favourable (Carlton, Smart et al. 2011). In 2014 two papers on commercial nuclear marine propulsion were published arising from this international industry project led by Lloyd's Register (Hirdaris, Cheng et al. 2014a; Hirdaris, F. Cheng et al. 2014b). The authors reviewed past and recent work in the area of marine nuclear propulsion, described a preliminary concept design study for a tanker based on a conventional hull with special arrangements for accommodating a nuclear propulsion plant and concluded that the concept is feasible.

In general, the nuclear power option seems most immediately promising for large bulk carriers that shuttle back and forth on few fixed routes between dedicated ports and cruise liners with their very high energy demand. From a regulatory perspective, frameworks do exist, even if probably in need of updating. For instance, IMO adopted a code of safety for nuclear merchant ships, Resolution A.491(XII), in 1981, still valid (IMO 1981). Lloyd's Register has developed and maintained a set of provisional rules for nuclear-propelled merchant ships, but the authors could readily not find an online version of this document. The general conclusion is that further maturity of nuclear technology and in particular the development and harmonisation of the regulatory framework are necessary factors before the concept becomes truly viable.
2.3 Ships emissions reduction based on fuel saving strategies

Good reviews of the main strategies which may be applicable on vessels in order to achieve fuel savings (and hence reduce emissions) are given by (Royal Academy of Engineering 2013) and (Seddiek and Elgohary 2014). A study on energy efficiency technologies for ships was carried out on behalf of the European Commission, listing and discussing fourteen energy efficiency measures (Winkel, Bos et al. 2015).

We identify and discuss the following five main categories of fuel saving strategies: ship resistance reduction; propulsion improving devices, wind-assisted propulsion, energy conservation management, speed reduction and shore side power connection.

2.3.1 Ship resistance reduction

Various technologies and optimisation techniques exist to reduce the resistance on the hull of a ship, in turn reducing the fuel consumption. Some are applied in practice whereas others are at the conceptual stage (Sinha 2017).

The *air lubrication method* is an idea based on the creation of a layer of air bubbles in the turbulent boundary layer developing downstream on the hull in the water flow. The bubbles reduce the wetted surface area of the hull and thus decrease hydrodynamic resistance. The same principle is employed in hydrofoils and fast planing craft but these are not practical options for heavy cargo vessels where lifting the main mass of the hull out of the water is out of the question. The efficiency of this method has been mainly determined numerically, using computer models, and by carrying out a limited number of practical tests with very positive results, suggesting that the method could be adopted on a larger scale. Silverstream Technologies and Shell applied this technology on the tanker Amalienborg and showed net energy efficiency savings approaching 5% (ShipInsight 2015).

A proven method to reduce resistance is *hull form optimisation*. Different options exist. We distinguish the following: fore body optimisation, aft body optimisation and appendage resistance. Fore body optimisation includes development in the design of the forward region of the ship which includes consideration of the bulb design, forward shoulder, and waterline entrance. For instance, the bulbous bow is designed in such a way as to reduce the wave making resistance by producing its own wave out of phase with the incoming wave system to create a destructive interference with the incoming waves. Aft body optimisation works by improving the flow around the stern of the ship. Flow improving devices such as stern flaps can also be considered for addition. Appendage resistance is created by ships' keels and rudder. This can be minimised by adopting particular designs (Sinha 2017).

2.3.2 Propulsion Improving Devices

Propeller efficiency can be improved by employing pre-swirl or post-swirl devices and high-efficiency propellers (Legovic and Dejhalla 2016).

Pre-swirl devices such as fins and stators are hydrodynamic appendages attached to the hull. Their purpose is to redirect the wake flow in order to impose a rotation opposite to the propeller rotation. In this manner the angle of attack of the flow on the propeller blades over the entire disk can be improved. The most applied types are the pre-swirl.

Post-swirl devices are intended for conditioning the flow at the aft end of the hub. The rotational components of the flow created by the propeller are converted to useful axial flow. In some cases the propeller hub vortex is suppressed to improve rudder efficiency, so a smaller rudder can be used.

Among high-efficiency propellers, options include fixed-pitch screw propellers with optimized geometry, controllable pitch propellers, ducted, contra-rotating and overlapping propellers, as well as several other designs.
2.3.3 Wind-assisted propulsion

Sails or other devices can be installed on new vessels or retrofitted on older ones to help achieving fuel reductions (Moirangthem and Baxter 2016).

Lloyd’s Register defines wind-assisted propulsion as the use of a device, such as a wingsail, soft sail, kite or Flettner rotor, to capture the energy of the wind and generate forward thrust (Lloyd’s Register Marine 2015) or recharge batteries. The thrust required to propel the ship comes from combining such devices with the ship’s engine. This process, also known as motorsailing, the amount of effective propulsion power needed to achieve a given speed.

Wingsails (or rigid sails) work in the same way as aircraft wings, deployed as single or multiple foils attached to a single base. Square rig sail systems are freestanding, rotating spars that carry canvas sails similar to those used by the traditional sailing vessels, but are fully automated and have no rigging on the deck or mast. See for instance the DynaRig system (Magma Structures 2014). Towing kites can be deployed at high altitude at sea (and recovered when close to land and to structures such as bridges). Flettner rotors are cylindrical structures mounted on the deck and spun mechanically by electrical motors. The cylinders spin (powered) to use the Magnus effect to generate forward thrust.

2.3.4 Energy conservation management

Energy conservation management mostly refers to measures aimed at recovering some of the energy from exhaust gases that would otherwise be wasted (Seddiek and Elgohary 2014).

Waste heat recovery methods entail passing exhaust gases from a ship’s engines through a heat exchanger to generate steam for a turbine-driven generator. The heat energy from the exhaust gas is taken and transformed into electrical energy to reduce direct engine-fuel consumption for the propulsion system or reduce auxiliary engine needs (Winkel, Bos et al. 2015). Another application was proposed by (Seddiek, Mosleh et al. 2012), who discussed the possibility of using exhaust gases to operate an absorption air condition unit. (Singh and Pedersen 2016) review the most suitable heat recovery technologies for maritime use and discuss their features and achievable recovery efficiencies.

2.3.5 Speed reduction

The relation between speed and power for a ship is not linear. Usually a speed reduction (“slow steaming”) of a given magnitude will result in a greater relative reduction of power demand. Hence, moderating a ship's speed can have beneficial result from the point of view of reducing fuel consumption.

(CE Delft 2012) investigated legal, technical and economic aspects of speed reduction, concluding that slow steaming would offer significant environmental benefits. A more recent study observed that there are no legal impediments to speed regulation. It could either be set globally, unilaterally (e.g. as a condition of entry into a port) or bilaterally between ports in two states (CE Delft 2017). The policy dimension of this measure is indeed the most relevant one, as it is not always in the best interest of the operator. For instance speed regulations should best be differentiated to ship type and size in order not to disturb the competition between operators.

2.3.6 Shore side power connection

Shore side power connection, also called cold ironing, is discussed in Section 2.2.5 (page 17).
3 The adoption of LNG as a ship fuel

We begin our considerations by building on the excellent study by (Wang and Notteboom 2014). These authors performed a systematic literature review, synthesizing the findings of 33 published studies on the use of LNG as a ship fuel with a double purpose: (1) to obtain a broad understanding of the ongoing perspectives and challenges concerning the application of LNG as a fuel for maritime propulsion and (2) to identify the gaps and weak points in the literature to suggest future research. The authors identify 17 factors for determining the commercial feasibility of the use of LNG as a ship fuel, grouped under 5 main categories. These are:

- **Availability of a regulatory framework**
  1. LNG onshore facilities and maritime transport;
  2. Gas-fuelled ships;
  3. LNG bunkering operation.

- **Economic viability**
  4. Capital costs for LNG system;
  5. LNG price;
  6. LNG fuel price;
  7. Maintenance costs;
  8. Environmental costs.

- **Technological feasibility**
  9. LNG fuel technology;
  10. Fuel tank space;
  11. Retrofitting tendency;
  12. Methane slip;

- **Infrastructure availability**
  14. LNG fuel distribution network;
  15. Bunkering facilities.

- **Public-social awareness**
  16. Public incentive;
  17. Public perception.

We discuss each category in the following Sections, and use the discussion to identify the factors for further analysis, which will be covered in the next Chapter.

3.1 Availability of a regulatory framework

3.1.1 Regulation for the use of LNG as ship fuel

Many of the studies analysed in 2014 by (Wang and Notteboom 2014) highlighted existing regulatory gaps regarding the application of LNG as a ship fuel, in particular LNG cargo handling and transport, the LNG bunkering operation and the use of LNG fuelled ships. A regulatory framework for onshore LNG installations and the maritime transport of LNG cargo have been established at both national and international levels, for example, the SIGTTO (SIGTTO 2000), the IGC code (IMO 2016a) and the guidelines of the Oil Companies International Marine Forum (OCIMF) guidelines, but these regulatory
documents mainly dealt with the transport and transfer of large quantities of LNG cargo. As of 2015 – noted (Wang and Notteboom 2014) – there was no international rule specifying that LNG could be used as a marine fuel, except for the IGC code allowing LNG carriers to use BOG (boil-off gas) as a part of the ship’s propulsion (Wang and Notteboom 2014). These authors noted that an even more glaring gap existed in terms of comprehensive bunkering regulations. This issue is discussed in detail in next Section (3.1.2).

Our analysis shows that this regulatory gap has been very recently filled to a large extent, with the IMO and classification societies developing different standards and rules aimed to minimise risks related with building gas-fuelled vessels (Buades 2017).

**Table 5.** Rules and standards related to the use of LNG as ship fuel, developed by classification societies.

<table>
<thead>
<tr>
<th>Name of classification society</th>
<th>Title of publication</th>
<th>Date of first publication</th>
<th>Reference (with year of most recent issue)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germanischer Lloyd</td>
<td>Guidelines for Gas as Ship Fuel</td>
<td>May 2010</td>
<td>(Germanischer Lloyd AG 2010)</td>
</tr>
<tr>
<td>DNV</td>
<td>DNV GL rules for gas as ship fuel</td>
<td>October 2010</td>
<td>(DNV GL 2018b)</td>
</tr>
<tr>
<td>Bureau Veritas</td>
<td>Safety Rules for Gas-Fuelled Ships</td>
<td>May 2011</td>
<td>(Bureau Veritas 2017)</td>
</tr>
<tr>
<td>Italian Register</td>
<td>Rules for the classification of ships, Amendments to part C, Chapter 1: New Appendix 7 - Gas-fuelled ships</td>
<td>June 2011</td>
<td>(Registro Italiano Navale 2012)</td>
</tr>
<tr>
<td>Nippon Kaiji Kyokai</td>
<td>Guidelines for Gas fuelled ships</td>
<td>February 2012</td>
<td>(Nippon Kaiji Kyokai 2016)</td>
</tr>
<tr>
<td>Korean Register of Shipping</td>
<td>Guidance for LNG Fuel Ready Ships</td>
<td>July 2012</td>
<td>(Korean Register of Shipping 2017)</td>
</tr>
<tr>
<td>Lloyds Register</td>
<td>Rules and regulations for the classification of Natural Gas-fuelled ships</td>
<td>July 2012</td>
<td>(Lloyds Register 2016)</td>
</tr>
<tr>
<td>Polish Register of Shipping</td>
<td>Guidelines on safety for Natural Gas-fuelled engine installations in ships; publication No. 88/P</td>
<td>July 2012</td>
<td>(Polski Rejestr Statków 2012)</td>
</tr>
<tr>
<td>China Classification Society</td>
<td>Rules for Natural Gas Fuelled Ships</td>
<td>September 2013</td>
<td>(China Classification Society 2018)</td>
</tr>
<tr>
<td>Indian Register of Shipping</td>
<td>Natural Gas Fueled Vessels for Coastal and Inland Waters</td>
<td>July 2017</td>
<td>(Indian Register of Shipping 2017)</td>
</tr>
<tr>
<td>Russian Maritime Register of Shipping</td>
<td>Under development</td>
<td>-</td>
<td>(Russian Maritime Register of Shipping 2017)</td>
</tr>
</tbody>
</table>

*Source: Own research and (LNG for Shipping 2015).*

The most relevant regulation for the safe application and handling of LNG as ship fuel is IMO’s *International Code of Safety for Ships using Gases or other Low-flashpoint Fuels* (IGF Code), in force since 2017-01-01 (IMO 2017). In particular, its principal aim is to address all areas that require special attention for the usage of natural gas or other low-flashpoint fuels, such as gas fuel storage tanks or machinery spaces. The code provides compulsory standards for the arrangement and installation of engines, equipment and
systems for gas or low-flashpoint fuelled vessels with the aim to reduce risks for the vessel, its crew and environment.

In addition, several classification societies have also developed a framework and rules for minimising risks of gas-fuelled vessels. These are listed in Table 5. Among these, we mention for instance DNV GL rules for gas as ship fuel (DNV GL 2018b), covering propulsion, power generation and auxiliary systems (Part 6, Chapter 2) and equipment and design features (Part 6, Chapter 5).

3.1.2 Regulation for LNG bunkering

As discussed above, (Wang and Notteboom 2014) concluded that if the regulatory framework concerning the use of LNG as fuel was somewhat lacking, an even more glaring gap existed in terms of comprehensive bunkering regulations. As of 2014 no international standards have been established incorporating minimum requirements for the bunkering procedures, training and equipment necessary to ensure safe LNG handling for gas-fuelled ships via both shore-based and ship-to-ship bunkering operations. This was indeed identified as one of the key barriers to the use of LNG as a ship fuel (Wang and Notteboom 2014).

Already in 2015, DNV had developed its Recommended Practice (RP G105) on the development and operation of LNG bunkering facilities (DNV GL 2015a), but the recent years have witnessed considerable developments in this area. In the following we list the most notable regulatory initiatives.

- The International Organization for Standardization (ISO) issued in 2015 the "Guidelines for systems and installations for supply of LNG as fuel to ships (ISO 18683:2015)" (ISO 2015) and "Specification for bunkering of gas fuelled ships (ISO 20519:2017)" (ISO 2017). The latter contains requirements that are not covered by the IGC Code, including the following items: hardware (liquid and vapour transfer systems); operational procedures; training and qualifications of personnel involved and requirements for LNG facilities to meet applicable ISO standards and local codes.
- The Society for Gas as a Marine Fuel published in 2015 their LNG Bunkering Safety Guidelines with contributions from industry stakeholders aimed at providing the LNG bunkering industry with the best practices to ensure high levels of safety, integrity and reliability. In 2017 a second issue was published, augmented by combining the first issue with IACS Recommendation 142 (described in the next bullet point) and including chapters on risk assessment, the definition of hazardous areas and safety zones, responsibilities, technical requirements and procedures (Society for Gas as a Marine Fuel 2017).
- The International Association of Classification Societies (IACS) published in June 2016 the IACS Recommendation on LNG bunkering (Rec.142) (International Association of Classification Societies 2016).
- The International Association of Ports and Harbours (IAPH) developed specific LNG bunker checklists (IAPH LNG Bunker Check-Lists) for known LNG bunkering scenarios such as ship-to-ship, shore-to-ship and truck-to-ship, including specific requirements relevant for all parties involved in bunkering operations. It was recently announced that the IAPH Working Group on LNG fuelled vessels has completed the development of an Audit Tool for LNG Bunker Operations to be made available as of September 2018 for ports to help meeting the growing demand for license applications (Cruise Industry News 2018).

The above international standards and guidelines are complemented by a significant set of national requirements and local port regulations.
3.1.3 Regulation for inland waterways vessels

Another regulatory barrier identified by (Wang and Notteboom 2014) was related to the use of LNG on inland vessels in Europe. At that time, two regulatory regimes forbade the transport of LNG by inland vessels: the European Agreement concerning the international carriage of dangerous goods by inland waterways (adopted in Geneva on 26 May 2000 and amended in 2008, (United Nations Economic Commission for Europe 2008)) and the Rhine vessel inspection regulations (Central Commission for the Navigation of the Rhine 2017). Both regimes also prohibited the installation on inland ships of combustion engines using a fuel whose flashpoint is below 55°C. Because the flashpoint for LNG is -181°C, its use as a fuel is therefore restricted.

Indeed, as mentioned in Section 1.2.2, the EC and its member states endeavoured to modify the European Agreement, (United Nations Economic Commission for Europe 2008), to allow large-scale carriage of LNG on inland waterways, and a considerable amount of regulatory work has been carried out in the last few years (Simmer, Pfoser et al. 2016).

The United Nations Economic Commission for Europe ADN Safety Committee adopted regulations for the transport of LNG in tank vessels at its 12th session in Geneva (United Nations Economic Commission for Europe 2014). This decision resulted in an updated version of the European Agreement concerning the international carriage of dangerous goods by inland waterways, which is currently valid as of 1 January 2017 (United Nations Economic Commission for Europe 2017). This regulation is meant to ensure a high level of safety for the transport of large quantities of LNG.

On the 16th of June 2016 the European Council formally adopted a revised directive which sets out how technical requirements for inland waterway vessels are applied in Europe (General Secretariat of the Council 2016). The new rules (Directive (EU) 2016/1629) do not explicitly mention LNG but are intended to improve legal certainty, avoid differing safety levels and reduce administrative burdens for the sector (European Parliament and Council of the European Union 2016). Inland waterway vessels that want to navigate on Europe's inland waterways will have to comply with technical standards developed by the European Committee for drawing up Standards in Inland Navigation (CESNI).

CESNI was set up under the auspices of the Central Commission for Navigation of the Rhine (CCNR) in June 2015. The most recent edition of the relevant CESNI standard is ES-TRIN 2017 (CESNI 2017). In particular, Annex 8 specifies "Supplementary provisions applicable to craft operating fuels with a flashpoint equal to or lower than 55°C" and is currently wholly dedicated to LNG.

Two initiatives worth mentioning are the T-ENT programme and the LNG Masterplan.

The TEN-T programme is a very ambitious initiative of the EC, consisting of hundreds of projects whose ultimate purpose is to ensure the cohesion, interconnection and interoperability of the trans-European transport network, as well as access to it. These projects take place in every EU Member State and include all modes of transport from road to rail, air and maritime (INEA 2018a). Of relevance is Priority Project number 18 ("Waterway axis Rhine/Meuse-Main-Danube"), a corridor of the main European waterways from the North Sea to the Black Sea (INEA 2018b).

The LNG Masterplan project was launched in 2013 to addresses Priority Project #18 "Waterway axis Rhine/Meuse/Danube" of the TEN-T network, with the goal of facilitating the deployment of LNG as an eco-friendly alternative fuel and a new commodity for inland navigation sector. Thirty-three partners from 12 EU Member States and one associated partner from Switzerland collaborated on various tasks with a view to realise the first LNG artery in Europe and to develop a roadmap for the future (LNG Masterplan 2018). Many interesting activities in ports along the waterway axis were carried out. The first LNG terminal on the Danube was built in Ruse (Bulgaria). The port of Antwerp drafted a technical concept leading to the construction and operation of a dedicated LNG bunker station (expected to be operational in January 2019). Steps towards provision of
alternative fuel infrastructure were done in Galati (Danube) and Constanta (Black Sea) in Romania and Komarno (Danube) in Slovakia.

3.2 Economic viability

A detailed discussion on the economic viability of LNG as marine fuel is beyond the purpose of this study, and we simply review some basic concepts and ideas. Broadly, such viability will be dictated by factors that can be grouped under three categories: (1) international regulatory frameworks and regional initiatives supporting the use of LNG as a marine fuel; (2) commercial and operational attributes determining the competitiveness of LNG-fuelled ships; and (3) challenges preventing the adoption of LNG as a marine fuel (Schinas and Butler 2016).

LNG engines, membrane tanks/vessels and the sophisticated cryogenic fuel tanks require significant capital investments, certainly when compared to oil fuelled ships. (Wang and Notteboom 2014) estimated that the cost for an LNG fuelled ship is between 20 to 25% higher compared to an oil equivalent vessel, but many factors influence the economic viability of LNG as a bunker fuel.

A wide variety of construction costs for LNG fuelled vessels, or conversion costs for existing vessels, mainly linked to the ship design, the engine type and the size of fuel tank. (Baumgart and Olsen 2010) pointed out that the costly LNG system will be sold at a lower price as soon as the technology is applied on a large scale, but were unable to quantify such reduction in costs. Some of the studies reviewed by (Wang and Notteboom 2014) indicated that the cost for a newly-built LNG fuelled vessel should be less than the cost to convert a similar existing vessel and therefore concluded that LNG should be more feasible for new ships.

The LNG price is the fundamental parameter that defines the economic discussion on the use of LNG as a ship fuel. At the time of the (Wang and Notteboom 2014) study, LNG price was about half as much as that of fuel oil in the US and was very competitive in the European market as well. The reviewed modelling studies at that time pointed in different directions, with the majority projecting LNG to retain a large price advantage but with some presenting a slightly different picture, based on scenarios where a rapidly increasing global LNG demand and a relative tough supply in the next few years lead to higher prices.

(Schinas and Butler 2016) recently investigated the feasibility and commercial considerations of LNG-fuelled ships, filling the gaps in the literature about the cost of LNG as bunker, as well as the potential benefit to operators and a methodology that enables policy-makers to promote these ships. These authors concluded that air emissions regulations will continue to demand that ships reduce emission and increase operational efficiency. Hence, policy and technology evolution and market initiatives are expected, which is a promising set of conditions for the market acceptance of LNG-fuelled ships. Based on their analysis of the cost of energy, they clearly identified the benefit of using LNG. The energy-price discount is sufficient to warrant the acquisition premium for LNG-fuelled vessels.

3.3 Technological feasibility

As discussed in Section 1.1, using LNG as a ship fuel is not a new technological development. For instance, LNG carrier operators have been using boil of gas (BOG) as a part of ship propulsion for several decades. Several relevant factors, such as those as identified above (beginning of Chapter 2) are nonetheless technically challenging, in particular the fuel tank and storage system, challenges related to retrofitting existing vessels, the problem of methane slip and the safety risks associated with transporting and using LNG.
LNG-fuelled engines will be discussed in Section 4.2. In particular we discuss the technical challenge constituted by the unburned methane emitted from LNG or dual-fuel engines (the so-called "methane slip").

According to (Wang and Notteboom 2014), the biggest technological challenge relates to the space-consuming LNG fuel tanks as the space sacrificed will affect ship productivity and hence earnings. LNG has a 1.8 times larger volume than diesel oil, and coupling with the whole system of LNG engine and cylindrical-shaped fuel tank on-board, the space is even around 3 to 4 times larger than a conventional oil system. This issue will be discussed more in detail in Section 4.3.

The location of the bigger LNG fuel tanks on-board ships still remains problematic, in particular when considering retrofitting projects. Issues related to retrofitting will be discussed in Section 4.4.

Whereas experience seems to indicate that LNG as a fuel on board has the same safety level compared to a conventional design and safety hazard studies carried out by classification societies such as DNV show that it is feasible to have passengers on board and to load or unload passengers or cargo whilst refuelling, particular safety concerns like cryogenic temperatures and gas explosions need particular attention. This issue is explored in Section 4.6.

### 3.4 Infrastructure availability

Almost all of the studies reviewed by (Wang and Notteboom 2014) pointed to the consensus that a critical challenge to the development of LNG as a ship fuel is the current lack of established bunkering infrastructure and distribution networks for delivering LNG to the ships. On one side there is an unwillingness to invest in the infrastructure necessary until the LNG demand is sufficient. On the other side, operators are unwilling to invest in LNG-fuelled ships if necessary bunkering infrastructure is not there.

According to a report produced by the Danish Maritime Authority as a deliverable of the TEN-T programme Motorways of the Seas, "An infrastructure of marine LNG filling stations has two dimensions: a 'soft' dimension concerning regulations, technical and safety standards: and a 'hard' dimension comprising the physical system of terminals, storage, bunker ships, tank trucks, etc., essentially the same elements as those of the oil-based fuel infrastructure system." (Danish Maritime Authority 2012). As of 2014, both these two dimensions were judged to be not well developed on a global scale (Wang and Notteboom 2014). We discuss in detail this issue and its most recent developments in Section 4.5.

### 3.5 Availability of LNG

The broader use of LNG is supported by the abundant global natural gas reverses and the fast growth of world LNG trade. In 2011, the total LNG trade was nearly five times larger than the 1990 level (Wang and Notteboom 2012). As of 2017, there were 40 countries importing LNG and 19 countries that were LNG exporters. Global LNG trade accounted for 289.8 Mt, a 9.9% increase compared with 2016 (GIIGNL 2017). Therefore, a network of large LNG infrastructure is well established all over the world.

The review of existing studies carried out by (Wang and Notteboom 2014) revealed that LNG bunkers can be supplied from two sources. The first and probably main source would be obtaining LNG from the nearby large import terminals. This supply option would require the establishment of a feeder distribution system (small to medium storage terminals, feeder and bunker ships, trunks, etc.). The second source would be provided by piped methane chilled to LNG through a liquefaction process. This option would be quite costly compared to the first but might be suitable for locations where there is abundant cheap gas transferred by a fine-established grid network, particularly in US where shale gas is being explored on a large scale.
Although the growth of the market is (and will be) driven by the increasing demand for power generation and residential usage, the LNG import facilities will play a key role in the future as distribution hubs to support the introduction of LNG bunkers for ships. Considering their growing number, it does not appear that LNG availability would be a major bottleneck for the introduction of LNG as a ship fuel.

3.6 Social awareness & public acceptance

Public awareness for the use LNG as a ship fuel is rising. For example, the EU has started to develop several financial instruments to support the introduction of LNG bunkering infrastructure, such as the funding from the Trans-European Transport Network (TEN-T) project (Wang and Notteboom 2014). Despite this, a more recent study showed that there is an acute lack of knowledge of LNG in all sectors of society, not just among the general public, but also in the port areas themselves and among the energy experts (Folia Consultores 2017).

Despite its excellent safety record so far, LNG transport is still seen by some as dangerous. Environmental groups do not always regard LNG as a clean fuel because of its non-renewable nature, unwanted methane leaks and venting and the unconventional methods used to extract it (e.g. hydraulic fracturing). Emission monitoring and public acceptance are therefore two potential bottlenecks for the use LNG as a ship fuel. The first issue is discussed in Section 4.1 and the second (even if somewhat beyond the scope of this report) is further explored in Section 4.6.

3.7 Summary

Based on the discussion above, we explicitly identify the factors of interest for the purposes of this study:

- The issue of **emission assessment and monitoring** is covered in Section 4.1.
- **LNG engines** and the issue of methane slip are discussed in Section 4.2.
- On board **fuel tanks** and **storage infrastructure** are explored in Section 4.3.
- The challenges associated with **retrofitting** are covered in Section 4.4.
- **Bunkering infrastructure** is discussed in Section 4.5.
- **Safety** (both on board and on shore) is covered in Section 4.6.
- **Public acceptance** of LNG is explored in Section 4.7.
4 The challenges of LNG as a ship fuel

4.1 Emissions assessment and monitoring

4.1.1 Assessment

Several studies have been carried out recently to assess the emissions associated with the use of LNG for marine transportation. Methods to perform ship emissions inventories can be categorised as fuel-based (top-down) and activity-based (bottom-up) approaches. To assess the effects of particular fuels, such as LNG, the more appropriate methods are, naturally, those top-down. These are based on full life-cycle assessments that identify the possible emission pathways. Figure 1 gives an example of such pathways for selected alternative fuels.

A good review of bottom-up approaches to estimate ship emissions, is given by (Nunes, Alvim-Ferraz et al. 2017). A review of the most up-to-date and available emission inventories regarding ship exhaust emissions in European sea areas is given by (Russo, Leitão et al. 2018). Below, we review some relevant top-down approaches that compare LNG to other fuels.

(Corbett, Thomson et al. 2015) carried out a study that focused in particular on the scope and scale of methane slip and methane leakage during dockside fuel bunkering and use, exploring how LNG vessels perform on a net greenhouse gas basis in comparison with conventional fuels. The study highlighted two findings. The first was that methane slip is an important factor that can determine whether LNG systems will lead to greenhouse gasses (GHG) emissions reduction or increases compared to conventional fuels. The second was that routine bunkering leakages can have a disproportionate impact on overall GHG emissions due to the high volume of natural gas throughput and the high global warming potential of methane.

A similar result was found in a study that considered natural gas vehicles and their fuel supply infrastructures in Denmark (Hagos and Ahlgren 2018). In maritime applications, these authors found that the use of LNG and renewable natural gas instead of low sulphur marine fuels resulted in a 60 to 100% reduction of SOx and 90 to 96% reduction of particulate matter. On the other hand, a 1% methane slip from a dedicated LNG passenger vessel would result, on average, in 8.5% increase in net GHG emissions, hence reducing the beneficial reductions achieved elsewhere.

A very thorough assessment of full life-cycle air emissions of alternative shipping fuels was carried out by (Gilbert, Walsh et al. 2018). A useful conceptual framework for the visualisation and analysis of life-cycle pathways for different fuels is reproduced in Figure 1. The study concluded that presently no readily available fuel option exist to deliver significant savings on local pollutants and greenhouse gas emissions in tandem. LNG is identified as a promising option for meeting existing regulation, but not as a low greenhouse gas emissions fuel.

(Hua, Wu et al. 2017) conducted a total fuel life-cycle inventory calculation for atmospheric emissions for two ships operating between China and Taiwan, comparing the difference resulting from operating on heavy fuel oil and LNG as fuels. Again, whilst total CO2 emissions were reduced, methane emissions increased when LNG was used as alternative fuel. In all cases the use of LNG resulted in a substantial reduction in the emissions of NOx, SO2 and particulates.
Figure 1. Life-cycle pathways of selected alternative fuels.

Source: (Gilbert, Walsh et al. 2018)

4.1.2 Monitoring

Assessment studies are very useful, but it is important to remember that they are usually based on computer models and make several assumptions that are always subject to many uncertainties. In parallel, there are many ways to measure directly the emissions from a particular vessel. The available techniques were for instance reviewed by the European Commission’s JRC and tested in September 2009 during a measurement campaign in the harbour of Rotterdam (Alfoldy, Lööv et al. 2013; Lööv, Alfoldy et al. 2014).

There are two main categories of such techniques. The first groups those methods that rely on optical measurements, such as the LIDAR, Differential Optical Absorption Spectroscopy, UV camera, etc. These are combined with model-based estimates of fuel consumption to determine emissions. Optical methods analyse the variation of the light properties after interaction with the exhaust plume and allow, if the local wind field is known, to determine the emission rate of SO\(_2\).

The second category groups methods based on the so called "sniffer" principle, where SO\(_2\) or NO\(_x\) emission factors are determined from simultaneous measurement of the increase of CO\(_2\) and SO\(_2\) or NO\(_x\) concentrations in the plume of the ship compared to the background. Measurements are performed either directly on the vessel under investigation or remotely (from stations on land, on another boat, on a helicopter or, more recently, on a drone).
A considerable amount of work is under way to develop improved monitoring methods. The Danish Environmental Protection Agency for instance has been working of methods for the fast determination of the sulphur content in fuel (Køcks, Lindholst et al. 2016). The prime focus in the project was to estimate the sulphur content through plume measurements (by remote sensing when ships pass under a bridge). In parallel, methods aimed at the fast analysis of the sulphur content directly in the fuel were investigated, as they could be a supplement to remote sensing. In another very recent project they investigated the development and deployment of a system based on low-cost micro sensors for measuring SO₂, CO₂, NO and NO₂ capable of conducting airborne measurements (from helicopters) of vessel exhaust gasses (Explicit ApS 2018).

4.1.3 Conclusion

Many thorough assessments of full life-cycle air emissions of alternative shipping fuels have been carried out, and a considerable amount of work has been completed or is currently under way to develop improved monitoring methods. We conclude that the issue of emissions monitoring does not appear to represent a potential technology bottleneck for the transition to a more widespread usage of LNG as marine fuel. The issue of emission assessment is more delicate. Assessment studies are based on models that make several assumptions subject to vast uncertainties. We recommend that further research is carried out to determine whether LNG systems will lead to greenhouse gasses (GHG) emissions reduction or increases compared to conventional fuels in marine applications.

4.2 LNG engines

There is extensive experience with LNG use in terms of the use of boil-off gas (BOG) in LNG carriers, and the engines types installed on these can also be used on other types of vessels. We base the discussion in this Section on the review of propulsion systems on LNG carriers carried out by (Fernández, Gómez et al. 2017).

The propulsion system for LNG vessels is closely related with the generation and consumption of the cargo BOG. Propulsion based on steam turbines has been the main system implemented on LNG vessels since the 1960s. This system had the advantage to allow the simultaneous burning of heavy fuel-oil together with the BOG generated during transportation, which in turn feed the propulsion turbines and electric turbo generators. Since 2003, LNG vessel propulsion systems have been at a turning point. Steam turbines are being replaced by internal combustion engines due to improvements in the efficiency of the latter. Such engines are capable of consuming different fuel types and are known by the acronym DF (Dual Fuel). The DF engine is based on the Otto-cycle, with a small amount (1-8%) of diesel as the pilot fuel (used to start the combustion) and gas as the main fuel. DF engines developed since the early 2000s are 4-stroke. However, 2-stroke engines are also beginning to be developed, due to technological advances enabling the use of LNG in this configuration.

(Fernández, Gómez et al. 2017) offer two useful ways to classifying LNG vessel propulsion systems. The first, illustrated in Figure 2, is based on whether the produced BOG is burned off as fuel or recovered. The second is based on the fuel employed and is illustrated in Figure 3. In the following we discuss more in detail these types of engines.
**Figure 2.** Classification of propulsion systems depending on the purpose of the boil-off gas.

- **Boil-off recovered**
  - **Electric**
  - **Steam turbine**

- **Boil-off as fuel**
  - **Simultaneously burnable**
    - **Diesel engine**
  - **Separately burnable**
    - **DFSM**: Dual-fuel steam turbine mechanical propulsion
    - **DFDE**: Dual-fuel (medium speed) diesel electric propulsion
    - **DFDM (LP)**: Dual-fuel (low-speed) diesel mechanical propulsion (low pressure)
    - **DFDM (HP)**: Dual-fuel (low-speed) diesel mechanical propulsion (High pressure)
    - **SFDM+R**: Single-fuel (low speed) diesel mechanical propulsion with reliquefaction
  - **DFGE**: Dual-fuel gas turbine electric propulsion

*Source: (Fernández, Gómez et al. 2017)*

**Figure 3.** Propulsion systems based on fuel used.

- **HFO**
  - **SFDM + R**
  - **SFDE + R**
  - **DFSM**
  - **DFDM (HP) / (LP)**
  - **GAS + HFO**
    - **DFDE**
    - **DFDE + SFDM**
  - **GAS + MDO**
    - **DFDE**
  - **GAS + MGO**
    - **DFGS**
    - **DFGC**

*Source: (Fernández, Gómez et al. 2017)*
4.2.1 Steam turbines

A propulsion plant based on steam turbines comprises a number of boilers, turbines and turbo generators. The natural gas is burned in the boilers to generate superheated steam. The boilers are normally designed to simultaneously consume different fuel (including for instance fuel-oil). The steam is expanded in the turbines and condensed in the main condenser before beginning the cycle again. The turbine generates electric energy by powering a turbo generator. Finally, the electric power so generated is used to propel and power the vessel.

Steam turbines have been the preferred propulsion systems on LNG carriers until the beginning of the 2000s, mainly thanks to their ease of use, intrinsic reliability and reduced maintenance costs. Other advantages offered include the easy control over the use of BOG, low vibrations and reduced consumption of lubricating oil. The main drawback is the poor fuel consumption efficiency, approximately 35% at full cargo, as well as their higher CO₂ emissions and a large engine room when compared with other systems (Sinha and Nik 2012).

4.2.2 Gas turbines

Gas turbines (GT) have been used to propel ships since at least forty years. These systems have been a technological innovation introduced on LNG vessels because of their ability to consume diesel and BOG without any limitations, their high reliability derived from the aeronautical industry and a very high power/weight ratio, meaning a reduced size.

The first vessels to install gas turbine as a main propulsion system were those belonging to the navy and later passenger ships. These combined gas turbines with steam turbines or diesel generators to produce electric power. Normally, LNG vessels with gas turbines do not require other generation system, because all the BOG is used as fuel, thus coping the energy demand of the vessel.

Gas turbines are combined with electric propulsion, in what is called dual-fuel gas-turbine electric propulsion (DFGE) system. There are different combined cycle-based system configurations, which can be subdivided into two groups: power-driven combined cycle and combined gas-turbine electric & steam system (COGES).

The power-driven combined-cycle configuration comprises a gas turbine and a steam turbine. The gas turbine is responsible for supplying, through a reducer, the required torque to rotate the ship’s propeller. The exhaust gases generated in the GT are sent to the recovery boiler where they provide the heat input required to generate steam that is sent to the steam turbine coupled to a generator that supplies power to the vessel during navigation. The plant also includes a number of three auxiliary generators used for power generation at port, when both turbines are stopped. The power driven combined cycle is an unusual configuration on LNG vessels because the advantages of the flexibility provided by the DFGE system are partly negated with the installation of the auxiliary power generators.

The COGES are electric propelled combined cycles. These systems are composed of elements similar to those that form a power driven combined cycle system, but with a difference in the layout of its components and with the main propulsion being electric. Configurations vary according to the manufacturers. In a typical plant, the system relies on two gas turbines with different powers designed in such a way that the exhaust gases of the more powerful gas turbine are exploited in a heat recovery steam generator. The steam generated is used to power a steam turbine which (together with the more powerful gas turbine) provides the electric power and the propulsion requirements during sailing. These turbines provide high system reliability, with the other main advantage being the considerable decrease in engine room size. The main drawback is the high consumption of gas and diesel (Fernández, Gómez et al. 2017).
very recently evaluated gas turbines as alternative energy production systems for large cruise ships. Their analysis showed that employing gas turbines as prime movers leads to both environmental, weight, and volume benefits, but also noted that the lower electric efficiency of gas turbines may cause a decrease in the whole ship energy efficiency.

4.2.3 Internal combustion engines

Internal combustion engines (in particular the two-stroke slow-speed diesel engine) are the predominant propulsion system in all sectors of marine transport. These traditional engines could not burn different fuels simultaneously but recently (from the early 2000s), dual fuel internal combustion engines have been developed. Internal combustion engines, like those installed in cars, work by injecting (and thus igniting) the fuel into hot, high-pressure air in a combustion chamber (the cylinder). The diesel engine operates within a fixed sequence of events, which may be achieved either in four or two strokes. The burning of the air-fuel mixture makes the gases expand, pushing the piston downwards in the chamber and creating the power stroke. A classification is usually made based on the speed of this process: in a low-speed engine the rate is below 400 rpm, in a medium-speed engine the rate is comprised between 400 rpm to 1200 rpm and in a high-speed engine the cycles take place at a rate of 1400 rpm or above.

Two strokes slow speed engines are used as the main propulsion system in merchant shipping because of their low maintenance costs, high efficiency and the option of burning low-quality fuels. This system is indeed also used on some LNG carriers (those with a large cargo and long distance crossings) with the peculiarity of integrating a re-liquefaction plant and a gas combustion unit. The re-liquefaction plant has the task of returning the BOG generated to the cargo tanks in a liquid state, whereas the gas combustion unit is designed to burn the BOG generated in case of emergencies (for instance during a breakdown of the re-liquefaction plant).

Four stroke medium speed diesel engine, capable of dual fuel burning, begun to be developed in 2003, and towards 2008 two-stroke slow-speed diesel engines were introduced (Fernández, Gómez et al. 2017). These types are discussed below.

4.2.3.1 Four stroke medium speed diesel engine (Diesel electric)

A dual fuel engine can work as a conventional single fuel (diesel) engine or in gas mode, by burning mainly natural gas and diesel as pilot fuel. If only diesel is used, the DF engine works under a conventional diesel cycle (diesel mode), with the four strokes being: intake, compression, combustion and exhaust. In gas mode these phases are the same but with some crucial differences. During intake the gas is supplied to each cylinder individually through a valve at the inlet, where it is mixed with air before entry to the combustion chamber. During compression the mixture is compressed by the cylinder. A small quantity of pilot fuel injection then takes place, releasing the energy required to start combustion. The combustion expands the gassed and creates the working stroke of the cylinder. All gasses are then released in the exhaust phase.

A typical configuration of a diesel-electric propulsion system through DF engines consists of several DF engines coupled to electrical generators that supply energy to the entire ship including propulsion, which is done by means of electric engines.

A propulsion system based on dual-fuel engines presents a number of advantages such as high efficiency when compared with steam turbine systems, high redundancy and reduced SOx emissions. The main drawback is the increased amount of required equipment, entailing higher installation and maintenance costs.

4.2.3.2 Two stroke slow speed diesel engine (Diesel electric)

In a two-stroke engine the power cycle is completed with only two strokes (up and down movements) of the piston during a single one shaft revolution. There are two methods for the introduction of the gas into the cylinder. In the first method, low pressure gas is
introduced through a valve in the cylinder head when the exhaust valve has closed and pressure in the cylinder is low. The gas is compressed and mixed with the air and ignited by pilot injection of fuel oil. This system is simple but combustion not always occurs in an ideal way (combustion "knock"). In the second method, the gas is compressed to a high pressure (250-300 bar) and injected into the cylinder through special gas injectors at the same time as the fuel oil.

Two stroke slow speed diesel engines represent the current technological trend, with their most prominent advantage being a high efficiency (Fernández, Gómez et al. 2017). Systems based on this concept have recently been introduced by the German manufacturing company MAN Diesel SE and by the Finnish Wartsila. The MAN Diesel concept is based on a high pressure gas injection principle with pilot fuel ignition, ensuring that the same high thermal efficiency of the diesel combustion process for heavy fuel oil burning can be achieved. The Wartsila concept makes use of gas injection during the compression phase (Ekanem Attah and Bucknall 2015). See (Pariotis and Zannis 2017) for a recent conference paper discussing conceptual ideas, challenges and current market options for two-stroke marine engines.

4.2.4 LNG used in hybrid propulsion systems

Many ideas are under consideration for hybrid propulsion systems using LNG and clean fuels. Hybrid systems can accommodate solar, wind, and hydrogen renewable energy sources. For instance, (DNV GL 2015b) discuss an example of a LNG-fuelled ship with a battery-hybrid propulsion system. This is also discussed by (Jeong, Seo et al. 2018).

4.2.5 Methane slip

Methane slip is the release of methane, unburned through the engine. There are two main reasons for unburned methane emitted form gas engines (Stenersen and Thonstad 2017). The first one is methane hiding away from the combustion, hidden in dead spaces and crevices in the cylinder unit components (such as in the gasket volume between cylinder head and cylinder liner, between piston top land and cylinder liner and behind the anti-polishing ring). During the compression stroke, the gas mixture is compressed into these small volumes and escapes combustion, mainly because the temperature is not high enough in such locations. In the expansion stroke the gas flows out, unburned. The second reason is uncomplete combustion in form of quenching taking place at the coldest part of the combustion chamber. Quenching occur when the mixture is too lean and cooled down along the cylinder liner. On the other hand, a richer mixture will create more NOx so a balance must be achieved between unburned methane and NOx.

(Corbett, Thomson et al. 2015) sent an interesting analysis of the role of methane slip in the investigation of methane emissions from natural gas bunkering operations in the marine sector. Other interesting sources considering this issue are (Brynolf, Magnusson et al. 2014) and (Brynolf, Fridell et al. 2014)

Methane slip can be managed by improving the design of the engine (for instance reducing the cavities where methane can "hide") or with other technical methods such as the use of catalysts (Sandvik 2016). Indeed, the current consensus among industry experts is that methane slip during combustion has been practically eliminated in modern two-stroke engines, and further reductions should be expected from four-stroke engines. (DNV GL 2015b; Stenersen and Thonstad 2017).

4.2.6 Conclusion

The analysis and review carried out in this section lead us to conclude that a large array of technological solutions have already been developed and deployed in real case applications concerning LNG engines. Steam turbines have been the preferred propulsion systems on LNG carriers until the beginning of the 2000s, offering several advantages such as ease of use, intrinsic reliability, reduced maintenance costs, uncomplicated control of BOG, etc. Gas turbines solutions exist in many varieties and configurations.
Internal combustion engines are the predominant propulsion system in all sectors of marine transport, but until recently they could not burn different fuels simultaneously. From the early 2000s, dual fuel internal combustion engines (both two strokes and four strokes) have been developed, capable of using methane as well as marine diesel.

Methane slip (the release of methane, unburned through the engine), until recently considered a real drawback, can be managed by improved engine designs and the current consensus among industry experts is that methane slip during combustion has been practically eliminated in modern two-stroke engines (with further reductions expected from four-stroke engines).

We therefore conclude that the issue of LNG engines does not appear to represent a potential technology bottleneck for the transition to a more widespread usage of LNG as marine fuel.

4.3 LNG tanks and storage infrastructure on board

Despite the fact that LNG carriers have used LNG as fuel for decades, (Wang and Notteboom 2014) assessed in 2014 that the space-consuming LNG fuel tanks as the current biggest technological challenge associated with LNG as marine fuel. These authors argued that LNG has a nearly twice larger volume than diesel oil and that the required systems that include insulation measures and cylindrical-shaped tanks push the space requirements up to 3-4 times larger than conventional diesel systems. Such space loss would undoubtedly affect ship productivity and freight earnings. This is indeed confirmed by the recent work carried out by (Buades 2017).

Storage systems consists of tanks, used to store the LNG on board, and the related process systems necessary for conditioning the LNG (DNV GL 2018c). LNG tanks comprise of a primary barrier, secondary barrier, thermal insulation and supporting structures. There are two types of LNG tanks: integral and independent of the hull structure. In the case of integral tanks, only membrane type tanks are accepted for LNG storage. Such tanks are non-self-supporting tanks and consists of a thin layer (membrane) supported through insulation by the adjacent hull structure (Chorowski, Duda et al. 2015). Independent LNG fuel tanks are designed in accordance with the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO 1993). According to the current IMO Guidelines, these have to be selected from among three types (A, B, or C). These are listed in Table 6 (Karlsson and Sonzio 2010).

Several options of LNG fuel tanks and fuel gas supply systems are available depending on the vessel size and type of engine. Prismatic B-type tanks and C-type tanks seem to be the most feasible option for large vessels. The main advantages of prismatic B-type tanks are that tank design can be adjusted to hull shapes and tanks can have any size. C-type tanks only be partially adjusted to the hull shape and tank maximum capacity is around 20000 m³. Smaller LNG-fuelled vessels can be equipped with prefabricated vacuum insulated cryogenic C-type tanks, available in sizes ranging from 50 to 500 m³ (Buades 2017). (Klein 2016) present an overview of available designs for LNG tanks, with a focus on applicability on cruise ships.

Several types of fuel gas system types exist. Such systems have as main purpose the withdrawal of the liquefied gas from the tank and its heating up to room temperature. This is done in a vaporizer with the use of a glycol-water brine. An additional task of the gas fuel system is the compression of gas to the pressure required by the ship's engines. See for instance (Chorowski, Duda et al. 2015) for a good overview of fuel gas systems.
### Table 6. IMO LNG tank types (International code for the construction and equipment of ships carrying liquefied gases in bulk).

<table>
<thead>
<tr>
<th>Tank type</th>
<th>Description</th>
<th>Pressure</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Prismatic tank adjustable to hull shapes.</td>
<td>&lt; 0.7 bar(g)</td>
<td>Space efficient</td>
<td>• Boil-off gas handling</td>
</tr>
<tr>
<td></td>
<td>Full secondary barrier</td>
<td></td>
<td></td>
<td>• More complex fuel system (compressor required)</td>
</tr>
<tr>
<td>B</td>
<td>Prismatic tank adjustable to hull shapes.</td>
<td>&lt; 0.7 bar(g)</td>
<td>Space efficient</td>
<td>• Boil-off gas handling</td>
</tr>
<tr>
<td></td>
<td>Partial secondary barrier</td>
<td></td>
<td></td>
<td>• More complex fuel system (compressor required)</td>
</tr>
<tr>
<td></td>
<td>Spherical (Moss type). Full secondary barrier</td>
<td>&lt; 0.7 bar(g)</td>
<td>Reliable/proven system</td>
<td>• Boil-off gas handling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• More complex fuel system (compressor required)</td>
</tr>
<tr>
<td>C</td>
<td>Pressure vessel (cylindrical shape with dished ends)</td>
<td>2 &gt; bar</td>
<td>• Allows pressure increase (easy boil-off gas handling)</td>
<td>• Space demand on board the ship</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Very simple fuel system</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Little maintenance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Easy installation</td>
<td></td>
</tr>
</tbody>
</table>

Source: (IMO 1993; Karlsson and Sonzio 2010).

Because of their particular design (LNG tanks provided for marine applications are required to withstand a relatively high collision acceleration and therefore are characterized with fairly developed internal supports which in turns become sources of heat flux to the internal (cryogenic) vessel. Further, IMO regulations indented to reduce greenhouse gases emission require that gas is kept in the tank below the opening pressure of the tank safety valve without venting for a minimum of 15 days when the fuel system is in stand-by mode (no gas is consumed by the engine). These factors make necessary the employment of systems to handle the boil-of-gas (BOG). Such methods are also reviewed by (Chorowski, Duda et al. 2015).

### 4.3.1 Conclusion

Several options of LNG fuel tanks and fuel gas supply systems are available depending on the vessel size and type of engine and the technology to develop LNG fuel tanks, fuel systems and BOG systems seems to be very well developed. The main challenge is rather economical, relating to the need of installing larger tanks affecting in turn ship productivity.

#### 4.4 Retrofitting existing vessels

The main conclusion drawn by (Wang and Notteboom 2014) was that the main challenge associated with retrofitting would be determining the location of the bigger LNG fuel tanks required on board. For this reason, several of the studies reviewed by these authors in 2014 hence argued that LNG would be more likely to be the fuel for new vessels rather than for existing ships requiring conversion. On the other hand, other studies did demonstrate the feasibility for conversions of existing vessels. The example brought by these authors was the successful retrofitting project of the Swedish tanker "Bit Viking", carried out in 2011, which was converted from the conventional diesel engine to a dual fuel LNG engine.
A very interesting project was funded by the European Union and completed in 2005 by a consortium of partners led by the Netherlands Maritime Technology Foundation to develop methods supporting the retrofitting of ships with new technologies for an improved overall environmental footprint (RETROFIT Project 2015). Whilst not specifically focused on LNG retrofitting only, the project investigated the relevant methods and tools. In doing so, it also identified the important technical areas that must be considered. These are:

- The identification of vessel candidates for retrofitting;
- The simulation of the working of the main and auxiliary systems of the vessel;
- The extraction of geometrical data from existing vessels and systems for reverse engineering;
- The development of tools to control ships energy and emission performance;
- The development of design-for-retrofitting methodologies based on standardisation and modularisation principles;
- The development of efficient yard processes to minimise the time the vessel of out-of-business during retrofitting.

Retrofitting with an LNG engine can be carried out simultaneously to add other modernising feature to an older vessel. The German RoRo passenger ferry "MS Ostfriesland" was retrofitted in 2014 with a new gas-electric propulsion system making use of different engine room concepts: a gas safe engine room and two emergency shut down engine rooms. The aft section was completely cut off and a new section welded back to the ship, making the ship over 15 metres longer than before and adding additional space to carry more passengers (DNV GL 2015b).

A 2012 study investigated the conversion of an inland waterway vessel (the "MS Otrate") to LNG fuelled (Bergfast 2012). Besides concluding that a conversion would be technically and economically feasible (at the current LNG prices), the study applied the lessons learnt to discuss the suitability of various ships types for application of LNG propulsion. According to the author tankers would be highly suited, as they already have to fulfil high ignition safety standards and they have availability of a substantial amount of free deck space (enabling the LNG tanks to be located on the ship without loss of cargo space). Dry cargo vessels may be suitable depending on the individual situations, with conversions depending on market expectation. Push boats could also be suitable because of their overall high power demand, although locating the tanks may be problematic. A similar situation would apply to motor vessels. Finally, cruise ships were found to be the vessels with the lowest suitability.

(Koers & Vaart B.V. 2015) analysed both the operational aspects for new built vessels and retrofitting of vessels with LNG. An interesting analysis concerned the potential retrofit of the ferry "Pont Aven", operating in Baltic Sea. This type of vessel, which carries a significant number of passenger cabins, makes retrofitting very challenging, mostly from an economical point of view. The limited space in the technical area below the hotel does not allow the storage of LNG in a conventional tank hold space, but placing the tank in the upper hotel area may require sacrificing many cabins.

The last two years have seen many developments. Technical concepts and solutions are constantly being developed and vessels are being retrofitted. Containment specialist company GTT has developed an exoskeleton tank concept consisting of a structure that can be prebuilt on the dock and then installed as a complete unit in the hull of the vessel, greatly reducing construction times eliminating the necessity to go into dry dock (Marine Log 2017). The company MAN Diesel & Turbo retrofitted in August 2017 the world’s first container ship (the "Wes Amelie") with an LNG engine (LNG World Shipping 2018). In 2018 the "Spirit of British Columbia" was the first passenger vessel in the world to refuel with LNG on a fully enclosed vehicle deck (Ship & Bunker 2018).
An even greater number of conversions have been announced. For instance, the Spanish ferry operator Baleària announced in July 2018 that it will invest €60M to retrofit five of its ferries to LNG in the next two years. The company expects that running these five vessels on LNG will reduce more than 45000 tonnes of CO₂ and 4400 tonnes of NOₓ annually, whilst completely eliminating sulphur and particulate emissions (Moore 2018).

4.4.1 Conclusion

The projects recently concluded or planned for the near future demonstrates the feasibility of retrofitting existing vessels. The technical challenges are very diverse, differing on a case-to-case basis according to the ship type, but do not seem to present particular difficulties. For the operator, the decision whether to retrofit is often an economical one. Typically, for retrofitting no funding is available, whereas it is for building a new ship.

4.5 Onshore bunkering infrastructure

The types of bunkering infrastructure are defined by the difference LNG bunkering modes. The 2012 TEN-T report identified three of such modes (Danish Maritime Authority 2012), and (Wang and Notteboom 2014) added a fourth one (conceptual):

- **Tank truck-to-ship (TTS).** In this mode, transportation takes place by road and the vessel is fuelled at port directly from the LNG truck. This is a mode which is relatively easy to establish for small amounts of LNG (bunker volume requirement of a few m³ up to 200 m³), but is not practical or cost effective for larger quantities.
- **Terminal-to-ship via pipeline (TPS).** In this mode, LNG is transferred from a terminal to a ship via a pipeline and tailor-made systems. It is more suitable for large bunker volumes and for recurrent customers.
- **Ship-to-ship (STS).** In this mode, an LNG bunker vessel brings the fuel to the moored ship. It is considered the most practicable option (for bunker volumes greater than 100 m³) due to its flexible operation in terms of bunkering place and time (for instance allowing bunkering during cargo handling at berth), but its viability requires sufficient volumes of LNG traffic.
- The use of portable LNG tanks loaded on board and used as fuel, regarded as a viable solution especially for inland waterway transport.

A good review of bunkering technology, albeit somewhat dated, is given by (Hodgson and Lee 2012). Our analysis found a paucity of more recent reports or papers in scientific publications discussing the technical aspects of this technology, from which we conclude that it is fairly mature. As discussed in Section 3.4, a real bottleneck as recently as 2014 was the "chicken-and-egg" problem identified by (Wang and Notteboom 2014), i.e. the economical stalemate between bunker suppliers on one side (unwilling to invest in the necessary infrastructure until a sufficient demand is in place) and ship owners on the other (unwilling to invest in LNG-fuelled ships if supplies of LNG bunkers are not available). This problem, mainly due to a notable regulatory drive by the EU, IMO and other international stakeholders, seem to have been largely overcome. As described in the last paragraph of this Section, the LNG bunkering infrastructure is experiencing a burgeoning expansion worldwide.

A comprehensive review of the technical aspects, practices, existing standards and the key challenges in designing a harbour grid for shore to ship (cold-ironing) power supply is given by (Kumar, Kumpulainen et al. 2019). These authors looked at the current and future marine solutions while outlining the key features, challenges and available commercial solutions of cold ironing infrastructure. They concluded that "in spite of many advantages of employing onshore power supply, only a few of the ports are getting benefit from it because of not having any strict regulations and appropriate business models. Shore to ship power technology can advance rapidly if all the stakeholders,
namely ship owners, terminal operators, port administrators, researchers, policymakers and local governments involve simultaneously for making suitable business models for promoting it”.

SEA\LNG (a multi-sector industry coalition aimed at fostering adoption of LNG) launched in January 2018, the Bunker Navigator Tool, an online map-based platform meant to provide easy access to the latest developments in the global LNG bunkering infrastructure. The tool provides an overview of key LNG bunkering infrastructure and how this relates to major global shipping routes and traditional oil bunkering ports. A link to the tool is provided in the footnote.

4.5.1 Conclusion

LNG bunkering infrastructure is expanding on a global scale. Today, there are 60 supply locations worldwide, including Singapore, the Middle East, the Caribbean as well as Europe. A further 28 facilities have been decided and at least 36 are under discussion. By the beginning of 2018, six LNG bunker vessels were already in operation globally, and four more projects are confirmed. Major players including Total, Shell, and Statoil have announced plans for new LNG bunker vessels (DNV GL 2017). (Calderón, Illing et al. 2016) offer a fairly recent review of LNG bunkering facilities with a focus on European ports. (Berti 2018) also reports on the status of development of many important ports worldwide.

4.6 Safety issues

Historically, liquefied natural gas has been considered safe. Since its beginnings, the LNG industry has enjoyed a very high safety record. However, LNG as fuel on ships is still a relatively new and innovative technology. (Semolinos, Olsen et al. 2013) identified one of the main factors in the downsizing and multiplication of the equipment due to a retail network under development and a large number of new users and actors (equipment suppliers, engineering companies, operators, users) with limited experience.

LNG as a liquid is neither flammable nor explosive, but its vapour ignites when the vapour-air mixture is in the 5–15% range (Baalisampa, Abbassi et al. 2018). It is colourless, nearly odourless, non-corrosive, non-toxic but it can act as an asphyxiant in enclosed spaces. It needs to be stored at very low temperature (~160°C) so it presents a cryogenic hazard. Skin contact will result in severe burn injuries, and contact with carbon steel may lead to brittle fractures. Because the large temperature differences between its liquid state and the environment, boil off gas is continuously produced. This must be handled properly (Niotis 2015).

Many risk mitigation strategies and safety measures exist. An operating principle is that LNG safety must be equivalent to operating with diesel fuel. Measures will include: (1) containment and protection; (2) appropriate design and material selection; (3) segregation of spaces; (4) removal of ignition sources; (5) installation of adequate monitoring systems; (6) ventilation; (7) active and passive fire protection; and (8) training and competence (Andersen 2015).

The analysis carried out by (Wang and Notteboom 2014) concluded that as of 2014, despite a positive attitude towards LNG as a fuel on board, particular safety concerns like cryogenic temperature and gas explosions still needed to be further investigated in order to ensure both efficient and safe handling of LNG on-board ships. There have been considerable developments in this area in recent years. As discussed in Section 3.1, the regulatory gap that existed in 2014 seems to have been to a large extent filled. IMO has developed and published its "International Code of Safety for Ships using Gases or other Low-flashpoint Fuels" (IMO 2017). More and more, classification societies have adopted rules and standards aimed at minimising the risks related with operating gas-fuelled vessels (see Section 3.1.1). Considerable work has gone towards developing regulation

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7 https://sea lng.org/bunker-navigator-introduction/
concerning the bunkering of LNG (see Section 3.1.2) and developments proceed apace in the area of inland waterways navigation with LNG (see Section 3.1.3).

(Baalisampang, Abbassi et al. 2018) recently reviewed fire and explosion accident causation and prevention on ships, and included an analysis of the use of alternative fuels for mitigating such risks in maritime transportation. These authors observed that alternative fuels may actually be an effective way to mitigate fire and explosion accidents, even if the differences in chemistry and physical properties lead to different risks associated with transferring, dispensing, and handling such fuels as opposed to traditional ones. Indeed, according to the European Maritime Safety Agency, the typical challenge posed by the adoption of most alternative fuels is the different physical and chemical characteristics associated with lower flashpoints, higher volatilities, and different energy content per unit mass (European Maritime Safety Agency 2017b).

(Baalisampang, Abbassi et al. 2018) concluded that LNG, as well as cryogenic natural gas and methanol have properties more suitable than traditional fuels in mitigating fire risk and appropriate hazard management could even make them a safer option than traditional fuels. However, according to these authors "for commercial use at this stage, there exist several uncertainties due to inadequate studies, and technological immaturity".

(Lv, Zhuang et al. 2017) carried out a formal safety assessment of LNG-fuelled ships along the Chuanjiang River and in Three Gorges Reservoir region. Due to the special geographic position and the pivotal role of Three Gorges ship lock, the lockage of LNG-fuelled ships is not yet allowed to ensure the safety of passengers and that of all ships in transit. The risks of LNG-fuelled ships navigating in four different scenarios (navigation between two dams, lockage, anchorage, and refuelling) were analysed and the conclusion was that such vessels should currently not pass through Three Gorges ship lock. The authors concluded that there is still lack of research on safety assessment and regulations of LNG-fuelled ships under some special navigation conditions, such as fuelling and berthing.

4.6.1 Conclusion

Safety is not only about systems, but also a question of manpower and behaviour. The safety philosophy, or safety culture, of the actors involved is a fundamental factor. Training and knowledge are essential when dealing with LNG as a bunker fuel. (Hines 2015). Training requirements are mandated by the regulations reviewed in this work and we can conclude that this aspect does not represent a particular challenge towards a more widespread adoption of LNG as marine fuel.

4.7 Acceptance of LNG as fuel

An important concern highlighted by (Wang and Notteboom 2014) is that of public acceptance of the use of LNG as a ship fuel. According to these authors, LNG transport was seen in 2014 as a dangerous activity, despite its excellent safety record. Some of the studies reviewed by these authors pointed out that a major reason for the perceived negative public perception of the dangers of LNG was the lack of information of and poor communication with the general public regarding the advantages of LNG as a clean fuel for shipping.

In 2015 the Expert Group on Future Transport Fuels of the European Commission published a study on the development of alternative fuels for transport in the EU. On the issue of public acceptance, the Group recommended that Member States should organise promotional campaigns to encourage citizens to switch to alternative fuel vehicles, promote actions to improve the public perception of safety of hydrogen, LNG and other fuels for transport and ensure appropriate access to information by the consumer on the location of refuelling possibilities for different fuel types (European Commission - DG MOVE - Expert group on future transport fuels 2015).
An important and recent study on the public perception of LNG as a marine fuel was commissioned by CORE LNGas (an initiative mainly focused on the Iberian peninsula, partly funded by the EU) and carried out by Folia Consultores. The analysis results, presented in Table 7, were structured in terms positive and negative perceptions and arranged into a present/future framework to determine weaknesses, strengths, threats and opportunities. A striking results was the acute lack of knowledge of LNG (Folia Consultores 2017).

(Pfoser, Schauer et al. 2018) examined the determinants of stakeholder's LNG acceptance. The main are (1) accessibility and availability of technology and refueling stations, (2) the attitude towards the use of alternative fuels, (3) safety concerns towards LNG, and (4) the expected usefulness of LNG. These authors reviewed existing literature on acceptance studies related to alternative fuels and introduced a conceptual model of LNG acceptance. The proposed model was tested within potential users of LNG and stakeholders along the whole LNG value chain such as energy providers, equipment manufacturers or LNG supplying and distributing companies. In general the results tended to align with previous studies, i.e. stressing the importance of knowledge about the benefits, features and safety issues of LNG to encourage potential users to introduce LNG.

4.7.1 Conclusion

Public perception of a technology may have a profound influence on whether this becomes widely adopted or not. Lack of knowledge regarding LNG among the general public is still reported, and all studies reviewed point to the importance of promotional campaigns to inform citizens about the advantages and disadvantages of alternative fuels.
Table 7. Key aspects of public perception of LNG derived in the CORE LNGas 2017 study.

<table>
<thead>
<tr>
<th>NEGATIVE PERCEPTIONS</th>
<th>PRESENT</th>
<th>FUTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEAKNESSES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acute lack of knowledge of LNG.</td>
<td></td>
<td>LNG is not seen as the only marine fuel currently capable of providing a solution for the improvement of air quality.</td>
</tr>
<tr>
<td>Limited scope to improve CO₂ emissions. Methane is a potent GHG.</td>
<td></td>
<td>LNG carries risks, which easily create the perception of danger and rejection.</td>
</tr>
<tr>
<td>Air quality is not a top priority on the public agenda.</td>
<td></td>
<td>Local authorities’ lack of support for LNG.</td>
</tr>
<tr>
<td>Port authorities do not take a uniform approach to LNG.</td>
<td></td>
<td>The time frame for implementation of LNG could give rise to the need for more immediate alternatives (electricity).</td>
</tr>
<tr>
<td>Stowage and cargo handling companies see the implementation of LNG as a distant possibility.</td>
<td></td>
<td>Messages about the benefits of LNG might be regarded with suspicion if they come from a large energy company, and LNG could be seen as a barrier to renewables.</td>
</tr>
<tr>
<td>The name is seen as technical, vague, confusing and disturbing.</td>
<td></td>
<td></td>
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| POSITIVE PERCEPTIONS | FUTURE |
| STRENGTHS            | |
| LNG benefits air quality because of its role in reducing NOₓ, SOₓ and PM emissions, and the elimination of concentrated marine pollution caused by spillage and discharge. | OPPORTUNITIES |
| We know how to control the risks appropriately. | LNG is seen as an alternative fuel with the potential for widespread use in the transport and maritime sectors. |
| There is no deep-seated fear of LNG among the maritime and port community. | LNG is not yet in the social imagination, which allows space to create a positive image for the product. |
| Implementation of LNG in Northern Europe as an example to follow. | The creation of new and specialised jobs in the services sector and the consolidation of employment in shipbuilding. |
| Port authorities see the extension of LNG from ships to port machinery as a natural and desirable development. | Environmental organisations are not fiercely opposed to the implementation of marine LNG. |
| Spain’s good position in terms of LNG infrastructure. | The likely tightening of air quality policy and regulations may create the right climate for its implementation. |

Source: (Folia Consultores 2017).
5 Conclusions

Whereas LNG carriers have used LNG as fuel for decades, other types of vessels have started to use LNG as fuel only since around 2000. Hence, this technology can be considered mature for a segment of the fleet, but very much less so for all others. It was thus of great interest to investigate potential technology needs, bottlenecks and other related issues, problems and opportunities associated to the gasification of the merchant fleet.

In Chapter 2 we gave an overview of the many different strategies that have been proposed to reduce emissions from ships. These were broadly categorised as those based on applying reduction technologies on-board, those based on using of alternative fuels and those based on fuel saving.

In Chapter 3 we attempted to obtain a broad understanding of the ongoing perspectives and challenges concerning the application of LNG as a fuel for maritime propulsion. We discussed the availability of a regulatory framework, economic viability, technological feasibility, availability of infrastructure and LNG and public-social awareness.

Concerning the availability of a regulatory framework, we discussed the progress achieved so far in three main areas: regulation for the use of LNG as ship fuel, regulation for LNG bunkering and regulation for inland waterways vessels. Our analysis showed that whereas as recently as 2014 a fairly large regulatory gap regarding the application of LNG as a ship fuel existed, considerable progress has been achieved in the last four years. Such regulatory gap can be considered filled to a large extent, with national authorities, the IMO, port authorities and classification societies developing different standards and rules aimed to minimise risks related with building and operating gas-fuelled vessels.

A detailed discussion on the economic viability of LNG as marine fuel was beyond the purpose of this study. We concluded that many factors will affect such viability: international regulatory frameworks and regional initiatives, commercial and operational attributes determining the competitiveness of LNG-fuelled ships and potential challenges preventing the adoption of LNG, with the price of LNG possibly the fundamental parameter defining the economic discussion on the use of LNG as a marine fuel. Further investigation on the issue of LNG markets is therefore essential for a more complete understanding of the potential of this commodity as marine fuel.

Four main technical issues were identified as having a particular interest. These were:

1. Emission assessment and monitoring;
2. LNG engines and the issue of methane slip;
3. On board fuel tanks and storage infrastructure;
4. Retrofitting of existing vessels.

A critical fifth aspect was identified as the availability of infrastructure:

5. Bunkering infrastructure.

Concerning availability of LNG as primary resource, and although the growth of the market is foreseen to be driven by the increasing demand for power generation and residential usage, we concluded that LNG import facilities will play a key role in the future as distribution hubs to support the introduction of LNG bunkers for ships. Considering their growing number, we inferred that LNG availability should not be a major bottleneck for the introduction of LNG as a ship fuel.

Given its direct and indirect effects on the public and workers, we included a sixth critical aspect for further discussion:

6. Safety issues associated with handling LNG.
Finally, we considered the issue of public acceptance as a potential bottleneck for the use of LNG as a ship fuel:

7. Public acceptance of LNG.

These seven main aspects were then discussed in depth in Chapter 4.

Many throughout assessments of full life-cycle air emissions of alternative shipping fuels have been carried out, and a considerable amount of work has been completed or is currently under way to develop improved monitoring methods. We conclude that the issue of emissions monitoring does not appear to represent a potential technology bottleneck for the transition to a more widespread usage of LNG as marine fuel. The issue of emission assessment is more delicate. Assessment studies are based on models that make several assumptions subject to vast uncertainties. We recommend that further research is carried out to determine whether LNG systems will lead to greenhouse gas (GHG) emissions reduction or increases compared to conventional fuels in marine applications.

The analysis and review carried out in the section dedicated to LNG engines lead us to conclude that a large array of technological solutions have already been developed and deployed in real case applications. Steam turbines have been the preferred propulsion systems on LNG carriers until the beginning of the 2000s, offering several advantages such as ease of use, intrinsic reliability, reduced maintenance costs, uncomplicated control of BOG, etc. Gas turbines solutions exist in many varieties and configurations. Internal combustion engines are the predominant propulsion system in all sectors of marine transport, but until recently they could not burn different fuels simultaneously. From the early 2000s, dual fuel internal combustion engines (both two strokes and four strokes) have been developed, capable of using methane as well as marine diesel.

Methane slip (the release of methane, unburned through the engine), until recently considered a real drawback, can be managed by improved engine designs and the current consensus among industry experts is that methane slip during combustion has been practically eliminated in modern two-stroke engines (with further reductions expected from four-stroke engines). We therefore concluded that the issue of LNG engines does not appear to represent a potential technology bottleneck for the transition to a more widespread usage of LNG as marine fuel.

Several options of LNG fuel tanks and fuel gas supply systems are available depending on the vessel size and type of engine. In conclusion, the technology to develop LNG fuel tanks, fuel systems and BOG systems seems to be very well developed. The main challenge is rather economical, relating to the need of installing larger tanks reducing in turn ship productivity.

Retrofitting projects recently concluded or planned for the near future have demonstrated the feasibility of such operation. The technical challenges are very diverse, differing on a case-to-case basis according to the ship type, but do not seem to present particular difficulties. For the operator, the decision whether to retrofit is often an economical one. Typically, for retrofitting no funding is available, whereas it is for building a new ship.

LNG bunkering infrastructure is expanding on a global scale. Today, there are 60 supply locations worldwide, including Singapore, the Middle East, the Caribbean as well as Europe. A further 28 facilities have been decided and at least 36 are under discussion. By the beginning of 2018, six LNG bunker vessels are already in operation globally, and four more projects are confirmed.

The appropriate safety culture required to handle and operate LNG vessels seem to be in place, both mandated by national and international regulations. Operators need to maintain a high level of attention in this regard, but this particular aspect does not seem to represent a particularly difficult challenge that may hamper the adoption of LNG as marine fuel.
Public perception of LNG is overall positive and improving, but lack of knowledge regarding this particular fuel is still reported, both regarding potential advantages and disadvantages of alternative fuels. In any case, we conclude that this aspect does not seem to represent a particular bottleneck. The safety of LNG handling has been demonstrated from decades of experience and the matter rests on properly informing the concerned public, for instance locally when a harbour decides to begin operating with LNG bunkering facilities.

We conclude that no major technological bottlenecks could be identified in this analysis. LNG as fuel for maritime vessels is already a proven and available solution. While conventional oil-based fuels will remain the main fuel option for most existing vessels in the near future, adopting LNG as fuel is already a very interesting solution for many new build and even for the retrofitting of existing vessels.
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List of abbreviations

BOG  Boil Off Gas
CCNR  Central Commission for Navigation of the Rhine
CESNI  Comité Européen pour l’Élaboration de Standards dans le Domaine de Navigation Intérieure
CNG  Compressed Natural Gas
CO₂  Carbon Dioxide
COGES  Combined Gas-Turbine Electric & Steam System
DF  Dual Fuel
DFGE  Dual Fuel Diesel Electric
DNV  Det Norske Veritas
EC  European Commission
ECA  Emission Control Area
EEDI  Energy Efficiency Design Index (for new ships)
EMSA  European Maritime Safety Agency
EU  European Union
GHG  Green House Gases
GT  Gas Turbine
HFO  Heavy Fuel Oil
IACS  International Association of Classification Societies
IAPH  International Association of Ports and Harbours
IFO  Intermediate Fuel Oil
IGC  International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO  International Maritime Organisation
ISO  International Organization for Standardization
JRC  Joint Research Centre
LIDAR  Laser Imaging, Detection And Ranging
LNG  Liquefied Natural Gas
MARPOL  International Convention for the Prevention of Pollution from Ships
MDO  Marine Diesel Oil
MFO  Marine Fuel Oil
MGO  Marine Gas Oil
Mt  Mega tonnes
NOₓ  Nitrogen Oxides
OCIMF  Oil Companies International Marine Forum
PM  Particulate Matter
PS  Power Supply
RP  Recommended Practice
<table>
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<tr>
<td>SEEMP</td>
<td>Ship Energy Efficiency Management Plan</td>
</tr>
<tr>
<td>SIGTTO</td>
<td>Society of International Gas Tanker and Terminal Operators</td>
</tr>
<tr>
<td>SO$_X$</td>
<td>Sulphur Oxides</td>
</tr>
<tr>
<td>STS</td>
<td>Ship-to-ship</td>
</tr>
<tr>
<td>TPS</td>
<td>Terminal-to-ship via Pipeline</td>
</tr>
<tr>
<td>TTS</td>
<td>Tank Truck-to-Ship</td>
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