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The Adoption of Liquefied Natural Gas (LNG) as a Ship Fuel: a Systematic Review of Perspectives and Challenges

Siyuan WANG*

Institute of Transport & Maritime Management Antwerp (ITMMA),
University of Antwerp
Kipdorp 59, B-2000 Antwerp, Belgium
siyuan.wang@uantwerpen.be

Theo NOTTEBOOM

Transportation Management College
Dalian Maritime University
1, Linghai Road, Dalian, PRC

&

Antwerp Maritime Academy, Belgium

&

Institute of Transport & Maritime Management Antwerp (ITMMA),
University of Antwerp
theo.notteboom@gmail.com
Tel: +32 3 2655151

Abstract

The stringent ship emission regulations under IMO's MARPOL Annex VI are a main driver to consider liquefied natural gas (LNG) as a ship fuel. Research into LNG as a marine fuel saw a strong growth in recent years, but no study has analyzed in a systematic way the level of convergence among the findings presented in the wide range of studies. In order to fill this gap, this paper seeks to perform a systematic review to synthesize the findings of 33 published studies on the use of LNG as a ship fuel. The aim is not only to obtain a much broader understanding of the current perspectives and challenges for applying LNG as a bunker for ship propulsion, but also to identify the gaps and weak points in the literature which could suggest future research. Moreover, given the output of the synthesis, the paper presents an extensive decision-making framework for shipowners when deciding on a fuel switch for their fleet from conventional oils to LNG in order to achieve a level of conceptual development beyond that attained in individual studies. In addition, the study also identifies

*Corresponding author

the important role of ports in facilitating and encouraging the large-scale adoption of LNG in the maritime industry.

Keywords: LNG, Ship fuel, ECAs, Air emission, Systematic review, Research synthesis.

1. Introduction

As the schedule for the application of the strict sulphur limits (enacted by IMO from 2015¹) in the emission control areas (ECA) is fast approaching, shipowners and operators are challenged to look for compliance bunker oils for their fleet. Currently, they have two options: either (a) change the fuel quality by using more expensive low sulphur fuel oil (LSFO) such as marine gasoil (MGO) instead of heavy fuel oil (HFO) or (b) clean the exhaust gas to a corresponding emission level by using an exhaust gas cleaning or scrubbing system (EGCS) (Notteboom, 2011). However, this paper deals with another possible compliance solution, i.e. the switch to liquefied natural gas (LNG) as a ship fuel.

LNG is natural gas which becomes liquid at a temperature of -160°C. Liquefied gas occupies a volume corresponding to 1/600 of the product in the gaseous state, which makes it space efficient to be stored onboard ship as a bunker. Compared to conventional fuel oils used by ships, LNG has very low emissions of Sulphur Oxide (SO_x), Nitrogen Oxide (NO_x) and Particle Matter (PM). NO_x emissions are reduced by up to 85-90% compared to heavy fuel oil, SO_x and PM by close to 100% and CO₂ by around 15-20% (Brett, 2006; Pitt, 2010; Bengtsson, 2011).

Research into LNG as a ship fuel saw a strong growth in recent years. However, no study has analysed in a systematic way the level of convergence among the findings presented in the many studies conducted by research centres, classification societies, ship engine manufacturers and consultancy firms. Therefore, In order to fill this gap, this paper seeks to perform a systematic review following a rigorous procedure to analyse and synthesize the findings of a selected and relevant set of published studies on the use of LNG as a ship fuel. The purpose of the paper is to report the results of the selected studies with a reasonable indication of consistency, divergence and complement among them, and also to identify the gaps and weak points which could suggest future research. Moreover, “syntheses” usually involve ‘putting together’ studies that are about similar things, but it should be greater than

¹ IMO MARPOL Annex VI sets stricter standards for the sulphur content of marine bunkers and set stringent limits on NO_x emissions from ship engines, especially in ECAs. The current sulphur standard for ship fuels in ECAs is at 1% and will further be reduced to 0.1% from Jan. 2015. The NO_x emission (Tier III) limits enforced only in ECAs requires 75% NO_x reduction for ships built after 2021.

the sum of the parts (Noblit & Hare, 1988). As such, through a systematic review, the paper not only aims at a much broader understanding of the current perspectives and challenges related to the use of LNG as a ship fuel, but also attempts to achieve a level of conceptual development beyond that attained in individual studies.

The paper is organized in the following way. Section two introduces the applied methodology and describes the research design in more detail. Section three presents the results of the systemic review by sorting and integrating information from separate studies guided by review questions. Section four discusses the results and proposes a framework of factors affecting shipowner's decision-making on the switch to LNG as a bunker fuel. This section also identifies two weak points in the existing literature. Finally, section five addresses some concluding remarks and suggests areas for future research.

2. Methodology and research design

2.1 Systematic review as a research method

A systematic review is not a traditional literature review. A conventional literature review usually features a lot of detailed insights but might be skewed by familiarity and availability bias and the implicit preferences of the reviewer. Therefore it might fail to represent the research relevant to the question at hand in a systemic way (Goodstein and Brazis, 1970; Tranfield et al., 2003). Instead, conducting a systematic review enables to assemble, analyse and interpret a full and comprehensive body of existing/available evidence in a thorough and unbiased manner, which is regarded as a key first step to establishing the conclusions science supports (Rousseau et al., 2008). Although the initial development of a standard approach to systematic review was designed for quantitative research in medical science, some scholars have applied it to a broad range of research fields, incorporating both quantitative and qualitative evidence. The fields cover public policy, education, social care, and management and organization studies (Rousseau et al., 2008; Denyer & Tranfield, 2009).

Systematic reviews have clearly defined procedures which require reviewers to report each step in a transparent and rigorous manner. According to Denyer and Tranfield (2009), there are five steps to complete a systematic review. The first step is to formulate review questions which address the specific questions of initial interest, namely, the things you want to know and synthesize from the review. For the next step, exhaustive literature searches of published and unpublished studies are conducted to ensure that the review results take into account all the available evidence and are based on good quality contributions. Then, the third step is to choose and evaluate the studies by using a set of explicit selection criteria which mainly check whether a study is relevant to the review questions and whether its results are validated and reliable. General quality checklists, such as those produced by the Critical Appraisal Skills Program, or CASP checklist, are usually used to help evaluate studies (Campbell et al.,

2003). After this process, an analysis and synthesis of the selected studies is performed. Rousseau et al. (2008) argue that the efficacy of any use of evidence depends on the availability of carefully conducted systematic research syntheses. Thus, the formulation of syntheses is the most crucial phase of the whole process of systematic review. Finally, the reviewer has to report the results of the synthesis and to conform whether the studies are consistent, divergent or complementary, and also to recognize omissions, limits and untested assumptions in the existing literature. The basis of a good systematic review lies in following the above five steps in a strict manner and in making the process transparent to readers.

Synthesis is at the core of systematic review which involves some degree of conceptual innovation (Strike & Posner, 1983). Many types of syntheses have been established to fit different purposes of research, such as integrative synthesis and interpretive synthesis. These two types of synthesis are represented by two well established methods, i.e. meta-analysis for quantitative research (Hedges & Okin, 1985) and meta-ethnography for qualitative research (Estabrooks et al., 1994; Noblit & Hare, 1988). Considering that most studies on the adoption of LNG as a ship fuel contain numeric findings, qualitative information or primary researcher interpretations which are mainly based on different assumptions or case-by-case analysis, it is deemed impossible to conduct a meta-analysis or meta-ethnography for the concerned research. Therefore, this paper seeks to use an integrative synthesis to aggregate qualitative findings or the qualitative accounts derived from quantitative analysis with a level of general sense from each study. This approach to the integrative synthesis of qualitative data mimics quantitative meta-analysis which has been already examined by Yin (1989).

2.2 Research design

This paper strictly follows the five steps of the systematic review methodology and presents an explicit and transparent research process. The detailed research steps are presented in Figure 1.

<Insert figure 1 about here >

The first step is to frame the review questions. To formulate the structure of review questions (Figure 2) for addressing our initial interests, we incorporate certain concepts from two established frameworks for industry analysis and business strategy development. They are PEST (Political, Economic, Social and Technological) analysis (Ward & Rivani, 2005) and Porter's five forces model² (Porter, 2008). The review questions are divided into two groups.

²Porter's five forces include three forces from 'horizontal' competition: the threat of substitute products or services, the threat of established rivals, and the threat of new entrants; and two forces from 'vertical' competition: the bargaining power of suppliers and the bargaining power of customers.

The first group of questions are derived from the PEST framework which refers to some important general environmental factors for determining the commercial feasibility of the use of LNG as a ship fuel. These factors include the availability of a regulatory framework, the economic viability, the technological and operational feasibility and public-social awareness. The second group of questions relates to Porter's five forces model which covers several competitive environment factors, including competitive alternatives to LNG (i.e. the existing substitute solutions to comply with environmental targets), new clean alternatives (i.e. new entrants), LNG availability (i.e. supply of LNG) and potential customers. These factors could influence the application scale of LNG as a bunker fuel in the maritime industry.

< *Insert figure 2 about here* >

The second step is to conduct an extensive literature search using internet search engines, electronic databases, etc. This literature search is mainly targeted on published studies which provide a rather comprehensive analysis of the adoption of LNG as a ship fuel instead of focusing on a purely technical or engineering propensity. This step of the methodology resulted in 41 relevant studies published in the period 2008-2012, while the number of studies included in the final synthesis was reduced to 33 (eight unqualified studies has been excluded) after evaluating the quality of the studies by CASP checklist (see Appendix 1). The detailed list of the selected 33 studies and their evaluation results can be found in Appendix 2 and 3. These selected studies can be divided into three groups. There are: 12 working or consultancy reports; 10 journal papers or master theses; and 11 conference-related papers or materials. The authors of these studies come from research institutes, maritime authorities, classification societies, consulting firms and engine manufacturers (see the detailed distribution of authors in Appendix 4). Lastly, a crucial step is the synthesis undertaken by extracting relevant information from the above individual studies based on the review questions. The integration of the obtained information allows identifying the current positive and negative factors influencing the application of LNG as a ship fuel. The next section will present the result of the synthesis in more detail.

3. Results of the systematic review

3.1. Presentation of the overall results

The results of the synthesis are composed of integrative accounts extracted and sorted from the 33 selected studies and presented for each review question formulated in Section 2.2. Particularly, the first group of review questions in Figure 2 consists of key determinants for the commercial feasibility of using LNG as a ship fuel. Therefore, in order to obtain a much

broader picture of the current perspectives and challenges linked to the use of LNG, we identify 17 factors from these review questions with reference to the existing literature (see Figure 3), aiming to extract the relevant information from the individual studies in a structured way.

< Insert figure 3 about here >

It is however noted that not every selected study refers to all these 17 factors. We include a table which explicitly indicates how many and which factors are discussed in each study (see the details in Appendix 5). In addition, for each factor discussed in an individual study, we set four criteria (i.e. positive, developing, uncertain and negative) to evaluate whether it is a positive or negative factor in light of the use of LNG as a ship fuel (each criteria marked by different colours in Appendix 5). Since most studies present relatively clear statements and opinions for each factor, it was feasible to make a judgement for the set criteria and to aggregate the appraisal within an index diagram. Figure 4 not only shows the consistency and/or divergence of the existing literature but also provides an overview picture of the current situation on the use of LNG as a bunker in the shipping industry. It is worth noting that since the selected literature covers the time frame from 2008 to 2012, existing divergence between earlier and later studies might be attributed to the ongoing technological innovation and economic and regulatory advances to support LNG as a fuel.

< Insert figure 4 about here >

The following section will elaborate further on Figure 4 through a detailed discussion for each of the factors. However, it is noted that since the next part reports the results which are synthesized by the findings of the 33 selected studies, the specific references are not to be shown in detail to the corresponding text. Instead, the label of the colour in the table of Appendix 5 helps to easily relate to the original literature by using the study number in Appendix 2.

3.2.Availability of a regulatory framework

Many of the studies³ explicitly refer to some existing regulatory gaps regarding the application of LNG as a ship fuel. We identify the gaps in three parts of the regulatory framework: LNG cargo handling and transport, the LNG bunkering operation and the use of LNG fuelled ships (see Figure 5).

< Insert figure 5 about here >

It is widely recognized that the regulatory framework for onshore LNG installations and the maritime transport of LNG cargo have been established at national and international levels in line with the fast growth of the world LNG trade, for example, the SIGTTO and OCIMF guidelines and the IGC code⁴. Although these international regulatory documents mainly deal with the transport and transfer of large quantities of LNG cargo and handled by an experienced crew on board of ships and at terminals, these standards may be adapted to LNG feeder distribution later (e.g. LNG feeder carriers or bunker barges) for supplying small amounts of LNG to ships for propulsion purposes.

So far, there is no international rule recognizing that LNG can be used as a marine fuel, only except for the IGC code which allows LNG carriers to use BOG (boil of gas) as a part of the ship's propulsion. However, many of the reviewed studies (L.g. Col.2.⁵) state that regulations on gas-fuelled ships are under development. IMO has started to draft the IGF code (the international code of safety for ships using gases or other low flashpoint fuels) which will cover safety and operational issues for gas-fuelled seagoing vessels. Before the IGF code is finalized by 2014, the current IMO interim guidelines on safety for natural gas fuelled engine installations in ships (ratified in 2009) has been temporarily adopted. Also, some classification societies (e.g. DNV, LR, GL and ABS⁶) have developed their own rules on the construction of LNG fuelled-ships and related safety operations, but most of them largely mirror the IMO interim guidelines.

³ 24 of the 33 selected studies refer to this issue. Through checking the studies marked with colors (no matter what colors is) in Column No.1-3 in the table of App.5, it is known which 24 studies discuss this factor.

⁴ SIGTTO: Society of International Gas Tanker and Terminal operators. OCIMF: Oil Companies International Marine Forum. IGC code: International code for the construction and equipment of ships carrying liquefied gases in bulk.

⁵ It means the studies marked the color of light green (L.g) in Column No.2 (Col.2) in the table of Appendix 5 (App.5) are the referred literature. The same notice way is adopted in the rest part of the paper in order to link the synthesis to the original literature. Please note that the four colors are noted as D.g (Duck green), L.g (Light green), R (Red) and O (Orange).

⁶ DNV: Det Norske Veritas; LR: Lloyd's Register; GL; Germanischer Lloyd; ABS: American Bureau of Shipping

In terms of the LNG bunkering process, most of studies (R. Col.3.) stress that the lack of a set of comprehensive bunkering regulations is one of the key barriers to the use of LNG as a ship fuel. To date, no international standards have been established which incorporate 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. However, some of the latest studies (L.g. Col.3.) indicate that, to close this regulatory gap, ISO established a working group in 2011 (ISO TC 67/WG 10) to develop international guidelines for LNG bunkering operations. The so-called “Guidelines for systems and installations for supply of LNG as a fuel to ships” focus on requirements for the LNG transfer system of all types of bunkering modes, the personnel involved and the related risk of the whole LNG bunkering process (DNV, 2012). The document will be finalized and published as an ISO document by 2014.

Another regulatory barrier is related to the use of LNG on inland vessels in Europe. Within the European Agreement concerning the international carriage of dangerous goods by inland waterways (ADN) and the Rhine vessel inspection regulations (RVIR), the transport of LNG by inland vessels is not allowed. Also, both regimes prohibit the installation on inland ships of combustion engines that use a fuel with a flashpoint below 55°C. This means LNG is restricted to be used as a fuel since its flashpoint is -180°C. Therefore, it is really necessary to develop appendices under the framework of ADN and RVIR to include LNG handling both as shipping cargo and a ship fuel for inland vessels (Feenstra, 2012).

3.3.Economic viability

Sophisticated LNG engines and the cryogenic double-walled fuel tanks require significant capital investments, certainly when compared to oil fuelled ships. The different reviewed studies present a wide variety of construction costs for LNG fuelled vessels, or conversion costs for existing vessels. The observed cost range is partly linked to the ship design, the engine type (dual-fuel or single LNG engine), and the size of fuel tank (i.e. dependent on the frequency of refilling), etc. Overall, the estimated cost for an LNG fuelled ship is between 20 to 25% higher compared to an oil equivalent vessel. Baumgart and Olsen (2010) point 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 the exact reduction in costs is impossible to predict. It all depends on the shipowners’ view on whether higher building costs can be justified by lower operating and voyage costs by using LNG. In addition, some studies (R. Col. 4) indicate that the cost for a newly-built LNG fuelled vessel is less than the cost to convert a similar existing vessel. LNG is therefore more feasible for new ships.

The LNG price lies at the core of the economic discussion on the use of LNG as a ship fuel. It is widely recognized that the current low LNG price compared to the conventional oil fuel is a main economic driver for this new application. At present, LNG costs about half as much as

fuel oil in the US and also remains very competitive in the European market (Ashworth, 2012). With the prediction of a high distillate fuel price in the coming years due to increasing demand and the cost of the desulphurization process (this was proven by spikes in the price of marine diesel oil in US after the North America ECA came into effect in August 2012 (FC Business Intelligence, 2013)), the current relative stable LNG price might yield significant cost savings for shipowners who face a high pressure of low freight rates. 24 of the 33 selected studies describe different scenarios on the future LNG price. Most of these studies (D.g.Col.5) keep a positive attitude: LNG is projected to retain a large price advantage. However, other studies (O. Col.5) present a different picture that, with the rapidly increasing global LNG demand and a relative tough supply in the next few years, uncertainty on the price levels will remain more significant with even higher prices possible especially on the spot market. TEN-T (2012) argues that the market prices for LNG are much less uniform and less transparent than the oil market. A single global LNG market does not exist at the moment as the LNG price is fragmented across the world with large differences between locations and contracts. Hence, it seems that the various estimates of the future LNG price presented in the different studies make it hard to bring widely supported forecasts on the future energy prices.

Some studies (O.Col.6) observe that the current positive LNG wholesale price (the price sold at the larger import terminals) is not the final bunker price for end-users. The LNG fuel price includes the costs of supply logistics for making LNG available to be used as bunker. These costs include the infrastructure cost of the LNG refuelling terminals, the distribution cost of LNG to the bunkering terminal and the cost of the bunkering operation (MAGALOG, 2008). The current lack of LNG bunkering infrastructure and supply chain networks presents a far more uncertain picture for the LNG fuel price. This may lead to a slow-down in the development of this new application, as shipowners do not have a clear picture on the future evolution of the LNG fuel price. It therefore remains highly uncertain whether shipowners could benefit from the offset between fuel cost savings and large capital investments and at meantime could enjoy a more desirable payback time.

Most studies (D.g. Col.7) highlight the lower maintenance cost of the LNG engine in contrast with the oil engine due to a more clean and efficient system and a long lifetime of the machinery. Furthermore, some studies (L.g. Col.8) expect that the possible environmental cost (e.g. taxation or emission trading scheme) charged to shipping by governments will make the LNG cost savings more attractive than other options. To date, there is only a NO_x taxation system in Norway, but it is believed that the environmental cost regime for marine transport will develop in many countries in the coming years.

3.4.Technological feasibility

Using LNG as a ship fuel is not new. The technology is well-established as LNG carrier operators can look back on 40-year experience in powering their ships using LNG. To date, around 360 LNG carriers sailing all over the world are using boil of gas (BOG) as a part of ship propulsion. Moreover, LNG enjoys an excellent safety record without any serious incidents. Up to January 2013, the technology has also been tested on 34 non-LNG carrier gas-fuelled vessels mostly sailing in Northern Europe. There are 31 confirmed orders for delivery in 2013-2014 (Ashworth, 2012).

The current biggest technological challenge relates to the space-consuming LNG fuel tanks. The space loss will affect ship productivity and freight 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 onboard, the space is even around 3 to 4 times larger than the conventional oil system. A few of the reviewed studies (L.g. Col.11) state that, in addition to putting a smaller fuel tank onboard by refuelling frequently on regular sailing routes, a type of hull-integrated tank is under development that may mitigate the problem of capacity loss in the near future.

The location of the bigger LNG fuel tanks onboard ships still remains problematic, in particular when considering retrofitting projects. Many studies argue (R. Col.10) that LNG is more likely to be the fuel for new ships than for existing ships that would need conversion. Some other studies (O. Col.10) include feasibility research for conversions of the existing vessels. A good example is the successful retrofitting project of a Swedish product tanker “Bit Viking” in 2011 which was converted from the conventional diesel engine to dual fuel LNG engine with two on-deck fuel tanks. But these studies (O. Col.10) also claim that the possibility of conversion largely depends on ship age and configuration on a case-by-case basis.

Another technical challenge is the unburned methane (CH_4) emitted from LNG or dual-fuel engines. Methane (CH_4) is one of the main greenhouse gases (GHG) (i.e. CO_2 , CH_4 and N_2O) which cause even higher global warming potential than CO_2 . Therefore, if this problem of the LNG engine cannot be solved, it will reduce the overall environmental performance of LNG-fuelled ships.

When it comes to safety risks associated with the operation of LNG-powered vessels, many studies (D.g. Col.13) show a rather positive attitude that LNG as a fuel on board has the same safety level compared to a conventional design with traditional bunkers on board. This has been well demonstrated by 12 years of safe operations of LNG fuelled ships in Norway after the first LNG fuelled ferry, *Glutra*, entered into operation in 2000. In addition, some classification societies (e.g. DNV) conducted safety hazard studies which show that it is feasible to have passengers on board and to load or unload passengers or cargo whilst refuelling, but this idea is not yet widely accepted. Some studies (O. Col.13) argue that since there are no common safety risk assessment approaches and risk acceptance criteria for LNG

fuelled ships and bunkering procedures to date, some particular safety concerns like cryogenic temperature and gas explosions still need to be further evaluated by additional studies in order to ensure both efficient and safe handling of LNG onboard ships.

3.5. Infrastructure availability

Almost all reviewed studies (R. Col. 14 & 15) show a 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. This significant barrier currently represents a “chicken-and-egg” problem. Bunker suppliers are unwilling to invest in the infrastructure necessary until there is sufficient demand to supply commercial shipping with LNG fuel. On the other hand, shipowners are unwilling to invest in LNG-fuelled ships if supplies of LNG bunkers are difficult to obtain. As TEN-T (2012) observes, an infrastructure of marine LNG bunkering stations has two dimensions: a “soft” dimension focusing on regulations and industry standards, and a “hard” dimension focusing on the physical system consisting of bunkering terminals, bunker vessels and tank trucks or LNG portable tanks. Both of these two dimensions are not well developed on a global scale at the moment.

The types of bunkering infrastructure are defined by four LNG bunkering modes. First, transportation by road and direct filling at port from a LNG truck, which is relatively easy to establish for small amounts of LNG, but it is not practical or cost effective for larger quantities. The second solution is the transfer of LNG from a terminal to a ship via a pipeline and loading arm. The third option is ship-to-ship bunkering by using an LNG bunker vessel. This option is considered as the most practicable long term option due to its flexible operation in terms of bunkering place and time (e.g. bunkering during cargo handling at berth), but it requires a sufficient volume of LNG traffic. The final option is to use portable LNG tanks loaded on board and used as fuel, which is regarded as a viable solution especially for inland waterway transport. The first two supply modes are typically found in Norway now. The third option is already in a testing phase which is expected to be a popular bunkering solution in the near future, while the last innovative design has not yet reached the implementation stage.

In order to realize the LNG bunkering operations using the above options, it is very important to quickly establish a minimal bunkering infrastructure to kick-start the market development now. As the EU co-financed study TEN-T (2012) project indicated, the build-up of a sufficient infrastructure network for LNG is a necessary condition to achieve the take-up of the LNG-fuelled vessels. Therefore, to show its ambitious targets on the development of LNG bunkering facilities and infrastructure, the European Commission proposed that LNG refuelling stations should be installed in all maritime and inland ports of the trans-European core network by 2020 (2025 for inland ports). This aim includes a total of 139 ports which account for about 10% of all EU ports in number (AMEC, 2013).

3.6.Public-social awareness

Many of the reviewed studies (R. & L.g in Col.16) agree that in order to speed up the use of LNG as a ship fuel, the “chicken-and-egg” dilemma can best be mitigated by government involvement. Therefore, public interventions play an important role in promoting and developing the necessary infrastructure so that LNG can become a commercial option for ship operators. The approach for such involvement can be subsidies, funding or reduced taxes, etc. However, some studies (R. in Col.16) argue that so far there is very limited public financial support from local governments to lay the ground for initial fuelling infrastructure development, except the NO_x tax and funds scheme established in Norway. A few of the latest studies (L.g in Col.16) state that the public awareness for using 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. In addition, port incentives would be another important approach to encourage this new application. For instance, some leading port authorities in Europe, like Rotterdam and Antwerp, have already established port-specific emission regulations that give a discount in port dues to shipowners who use clean fuels for their vessels (i.e. the Environmental Ship Index program).

Another concern of public-social awareness is the public acceptance of the use of LNG as a ship fuel. Despite its excellent safety record so far, LNG transport is seen as a dangerous technology. Some studies (R. Col. 17) point out that a major reason for the perceived negative public perception of the dangers of LNG is the poor communication with the general public on the advantages of LNG as a cleaner fuel for shipping. Also, the local and regional authorities and the media show a low awareness. In order to increase public acceptance, a better communication between the project developers, the authorities and the general public needs to be established. In addition, it is important to perform an adequate safety analysis and communicate the results with the general public and the neighbours of LNG bunkering areas. TEN-T (2012) claims that the establishment of “gas acceptance” by the general public would shorten the permit process and accelerate the development of LNG bunkering infrastructure.

3.7.Availability of LNG

The broader application of LNG is supported by the abundant global natural gas reserves and the fast growth of world LNG trade. In 2011, the total LNG trade was nearly five times larger than the 1990 level. So far, there are 18 exporting countries and 25 importing countries trading LNG worldwide, with many more countries aspiring to enter the market (Wang and Notteboom, 2012). Therefore, a network of large LNG infrastructure is well established all over the world. Although the growth of these large terminals is driven by the increasing land-based demand, particularly for power generation and residential usage, these facilities will

play a key role in the future as distribution hubs to support the introduction of LNG bunkers for ships.

The systematic review of existing studies reveals that LNG bunkers can be supplied from two sources. The first source is regarded as the main source for providing LNG to ships, namely, obtaining LNG from the nearby large import terminals as mentioned above. For this supply option, some facilities must be established to create a feeder distribution system, like small-medium storage terminals, feeder and bunker ships, trunks and on-shore filling stations, etc. The second source comes from piped gas which is chilled to LNG through a liquefaction process. The establishment and operation of small scale LNG liquefaction plants is quite costly compared to the first option. However, this option 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. With such cheap gas even plus the high LNG production and delivery cost to ships, the final LNG bunker price may still remain competitive compared to distillate fuel oils.

3.8. Potential shipping sectors using LNG as s ship fuel

The 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. Putting together all findings from each study, it can be concluded that 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 triggered by the stricter environmental standards, e.g. ECAs and inland waterways; (3) The LNG fuel system is suited in relation to storage of gas and other onboard processes; (4) A rather high fuel consumption per ship. So far there are three existing ECAs which are located in North-western Europe and North America. Therefore, the short sea shipping sector with dense regular liner traffic in these regions seems the obvious start for a large-scale adoption of LNG as a fuel for ships. The ship segments, like car/passenger ferries, offshore supply vessels, RoRo ships and patrol vessels, etc. are the most attractive for the use of LNG. In addition, the inland waterway segment is another potential market for the use of LNG bunkers. In the longer term, perhaps after 2020 (when global SOx limits are applicable) LNG bunkering may eventually cascade into deep sea ships facilitated by the stringent global emission targets and an established supply chain and infrastructure network all over the world.

3.9. New clean alternatives

Apart from LNG, there are some other possible clean ship fuels discussed in the reviewed studies. They include bio-fuels (like bio-diesel and bio-gas), hydrogen, methanol and nuclear energy. All these potential clean alternatives have attractive merits to be ship fuels, more in

particular in view of largely reducing CO₂ emissions. However, due to some technical, economic, logistic and safety challenges, these options are not expected to become commercially feasible in the shipping industry on a large scale within a short period of time. In addition, political and social concern on using nuclear energy for ship propulsion is a crucial obstacle for this application. Therefore, given the short timescales between now and 2015 (when the first strict SO_x limit comes into enforce in the ECAs), LNG seems to be the most feasible clean fuel to comply with the upcoming environmental standards (Danish Ministry of the Environment, 2010).

3.10. *Competitive solutions to LNG*

In order to comply with strict NO_x Tier III standards in ECAs after 2021, the alternatives of using low sulphur fuels like MGO or opting for scrubbers are only sufficient when an additional abatement technology is installed such as Selective Catalytic Reduction (SCR) to reduce NO_x emissions. LNG as a clear fuel can meet all tougher upcoming SO_x and NO_x emission targets without any abatement technology. Therefore, using LNG as a marine fuel is regarded as an attractive technological solution to cope with the environmental challenges facing the shipping industry in the years to come. Through the extensive literature review, Figure 6 shows the current advantages of and challenges for each of the three alternatives.

< Insert figure 6 about here >

It can be concluded that using low sulphur fuels is the most immediate compliant solution, due to minor modifications to ships with limited up-front costs and the established supply chain and bunkering facilities. Nevertheless, the growing demand for distillate oils would cause the fuel price to rise, and these increased operational costs to shipowners are more likely to be passed on in the form of increased freight rates. It is believed that such increased rates would lead to a “modal back-shift” from short sea shipping to road haulage, which consequently would erode the competitiveness of shipping compared to other transport modes as well as increase congestion on the roads and local environmental problems (Entec, 2009; Notteboom, 2011; SKEMA, 2010). Therefore, this option is not regarded as a desirable strategy for a sustainable long-term development of shipping.

Operating scrubbers is considered as a viable method for removing sulphur and particulate matter from exhaust gas emissions. However, at present, shipowners lack confidence about this solution due to high uncertainty over its technical performance, e.g. system reliability, the risk of non-compliance, etc. Also, in order to remove NO_x to meet Tier III standards, the

scrubber must be operated in conjunction with SCR, but the combination of these two technologies remains problematic at the moment. Although the cost of installing scrubbers onboard is less than that of an LNG system, the higher maintenance costs together with more fuel consumption in the long-term make this option uncertain on economic feasibility grounds. In addition, scrubber waste handling might pose extra time in port and bring special charges. Hence, scrubbers are considered to be an immature technology, but clearly it is continuing to develop and remains a likely mid-term solution for ship owners to meet the required emission levels.

Successfully using LNG as a marine fuel would enable a sustainable development of the shipping industry in the future. However, the current lack of bunkering infrastructure and operation standards imply that it might take a long time before LNG bunkers become main stream at a global scale. In order to fill the gap, one popular solution in Europe consists of using dual-fuelled ships which can burn HFO, distillate fuels and LNG. This development demonstrates shipowners seek to hedge against possible challenges during this transition period.

4. Discussion

After synthesizing the data from the individual studies, we analyse and identify the factors that may affect shipowners' decisions on the adoption of LNG as a fuel for their ships, and finally develop an extensive framework to support the decision-making in this regard. The framework depicted in Figure 7 can be regarded as a conceptual development beyond that attained in individual studies. It concerns a complex but systematic decision system. When deciding on whether to shift fuel to LNG, shipowners have to review the candidate ship's operating profile in terms of:

- The sailing pattern; e.g. does the ship have a regular sailing schedule with a fixed refuelling pattern (due to the current limited availability of LNG bunkering facilities);
- The rate of ECA exposure (due to the strict ECA emission regulations). It is presumed that ships with a high degree of ECA operations will benefit in multiply ways from LNG as a marine fuel;
- Fuel consumption (to estimate fuel cost savings). The more fuel consumed by the ship, the more economic benefit it will gain when using LNG. This is a crucial element to decide a payback time of the capital investment;
- The lifecycle of the vessel. The estimated remaining operational years of the ship need to be taken into account when evaluating the economic feasibility for retrofitting.

< Insert figure 7 about here >

The shipowner's decision is based on a complex interaction between several factors. Cost factors decide whether the shipowner could benefit from the price advantage of LNG over conventional oils and a lower operational cost of the LNG fuel system, and enjoy a desirable payback time by offsetting the large capital investment. Although cost considerations are a crucial part of a shipowner's decision, they are not the only factor at play. Shipowners also need to consider technological and operational factors when considering opting for LNG fuelled ships. In addition, public incentives would allow shipowners to benefit from first mover advantages in terms of financial support for the costly capital investment. Most of these factors identified by the existing literature have been discussed in detail in Section 3.

However, few studies consider the earning factors which may also influence the overall economic performance of LNG fuelled ships. We therefore include these factors into the decision-making framework. The first parameter taken into account is the reduction of ship revenue due to "commercial capacity loss". According to GL (2011), large LNG fuel tanks are estimated to consume 3% of the total available TEU slots on medium-sized container ships (4600-8500TEU). The second factor refers to the possible off-hire days for retrofitting the existing ship to LNG. It takes a longer time to convert to the LNG fuel system than installing scrubbers, which would also cause some loss of ship earnings. These two factors may affect the overall LNG fuelled ship's revenue in a negative way. However, we see great interest in the competitiveness of the ships powered by LNG in the freight market and the possible asset value development in the second-hand market. These aspects are rarely discussed by the existing literature. For instance, as mentioned before, once the strict emissions limits come into enforce, most of ships would use low sulphur fuel which may cause the fuel price to go up and finally lead to an increase in freight rates. The cheaper LNG would keep the owners of LNG fuelled ships away from low margins and is hoped to help provide competitive rates to freight hauliers. Moreover, in cases when the ship is time-chartered to charterers who will pay voyage costs for bunker use and port dues, LNG-fuelled ships may be the most favourable choice thanks to the cost effectiveness. In addition, the preference of charterers who want to 'green' their supply chain would also strengthen the competitiveness of LNG fuelled ships. In this sense, it seems that LNG fuelled ships might be competitive compared to other compliant vessels in the freight market when the supply chain and bunkering facilities would be well established in a global context after 2020.

Another valuable discussion point emanating from the present systematic review relates to the "chicken-and-egg" problem in kicking-start the development of the LNG bunkering market. As many studies indicate, public authorities (governments, regional regulatory bodies, e.g. EU) should promote this new application by using several tools, like enacting strict environmental regulations and establishing financial support schemes. It goes without saying that the

involvement of such public sectors is very important, while we observe that ports, namely port authorities, also play a crucial role in facilitating the adoption of LNG as a marine fuel. This issue is rarely discussed in existing literature. We argue that port authorities should play a proactive role in promoting and encouraging the use of LNG as a ship fuel for the following reasons:

- Port authorities to some extent represent the public interest in terms of maritime safety, security and environmental issues. The promotion and support of LNG as a ship fuel adds value to this role;
- Port authorities are more and more evolving from passive ‘landlords’ and ‘regulators’ to ‘facilitators’ and even ‘entrepreneurs’ (Verhoeven, 2010). The LNG discussion offers port authorities a window of opportunity to give an additional content to their emerging roles of facilitators and entrepreneurs;
- The emergence of clear sustainability strategies of ports and the concept of green port show ports are eager to ‘green’ their image. Port authorities are increasingly realising that good environmental performance is not only a necessary requirement to maintain good relations with local communities, but can also become a source of competitive advantage (Notteboom and Winkelmans, 2003; Adams et al., 2009). An active policy to support the adoption of LNG as a ship fuel fits nicely in this green philosophy.

How do port authorities currently facilitate LNG bunkering in its perimeter? As existing literature pays little attention to this issue, it can be considered as a valuable avenue for future research. Establishing a set of best practices for the development of LNG bunkering is quite useful in view of spreading this application among the world’s major ports. Such best practices could be established based on the following three dimensions. First of all, port authorities can assist in realizing some basic but essential steps to make LNG bunkering feasible. These steps include the investment in LNG bunkering infrastructure, the assessment of the safety risks of the use of LNG in the port environment and the development of a set of bunkering standards and guidelines. Second, facilitating port authorities can take initiatives to cooperate with other stakeholders, such as bunkering operators and shipowners to develop a financially-viable business model to establish a LNG bunkering supply network. It is believed that close partnerships could reduce the uncertainties over availability of infrastructure, LNG demand and price, etc. and help to solve the “chicken-and -egg” dilemma. Finally, port authorities can design incentive schemes to encourage ship owners and bunkering operators to invest in this new emerging business. Figure 8 illustrates the possible proactive roles of port authorities in the development of LNG bunkering.

< *Insert figure 8 about here* >

So far, the port authorities of the world's major seaports are increasingly aware of the benefits that LNG could bring to improve air quality within the port and the surrounding areas. Rotterdam, Antwerp and Singapore are just some of the major ports exploring, studying and developing LNG bunkering infrastructure as part of their strategic plans. Most of these ports plan to have such facilities in operation by 2015 (DNV, 2013).

5. Conclusions

The upcoming stringent environmental regulations enacted by IMO, particularly at the level of the ECAs, serves as a catalyst for exploring the use of LNG as a marine fuel. The use of LNG promises environmental performance and economic viability. The systematic literature review in this paper presented perspectives of and challenges for the adoption of LNG as a ship fuel. The analysis of the legal, economic, technological and public-social factors determining the feasibility of this new application showed a picture far from optimistic. Several crucial barriers, such as the lack of bunkering infrastructure and operational standards, are slowing down the development. However, rising environmental concerns gave a strong incentive to the public sector to provide policy support in removing any remaining obstacles. The widespread application of LNG as a ship fuel is supported by the competitive environment: global LNG supply chains are already in place and other clean fuel options are expected to face even larger obstacles than LNG. In a start-up phase the use of LNG is likely to be limited to some specific shipping sectors due to the confined ECAs and the lack of a large-scale bunkering infrastructure network. Moreover, in the short term, low sulphur fuel oils remain a very strong competitive solution, especially for the existing vessel fleet. Thus, the use of LNG as a ship fuel is expected to first gain momentum in niche markets, like small ferry routes and regular liner traffic. In the longer run (perhaps from 2020) the adoption of LNG as a ship fuel on a global scale rests on three main factors: (1) the price difference between LNG and low sulphur fuel oil; (2) the global emission regulations (e.g. the global SO_x limits enforced in 2020 or 2025); (3) the availability of LNG bunkering facilities in a global context.

Using a systematic review, two weak points or gaps in the existing literature could be identified opening avenues for future research. First, the economic viability discussion on using LNG is focussed on operating costs. The competitiveness of LNG fuelled ships compared with other compliant vessels in the freight market is not being discussed in existing literature. We believe that further research on this topic is needed to provide a more comprehensive picture on the economic performance of LNG fuelled ships. Second, the role of specific public entities, such as public port authorities, in enhancing the widespread

adoption of LNG as a fuel receives only little attention. In this paper, it was argued that port authority can play an important facilitating role in this matter. Future research could focus on identifying best practices for port authorities in this respect.

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Appendix 1: The modified CASP checklist for evaluating studies (10 questions)

A: Screening questions: Does this study address a clear question?

#1. Does the study address a clearly focused issue? ➤ A clear statement of the aims of the research? ➤ Have an appropriate study design?	Yes ☐	Can't tell ☐	No ☐
#2. Is the study relevant to the synthesis topic? ➤ Address the formulated review questions?	Yes ☐	Can't tell ☐	No ☐

B: Are the results of this study valid?

3. Does the study clearly explain the research method which fits for authors' stated aims?	Yes ☐	Can't tell ☐	No ☐
*4. Does the study describe explicitly about the data collection? ➤ How and why the data collected?	Yes ☐	Can't tell ☐	No ☐
5. Does the study explain clearly how the data analysis is done?	Yes ☐	Can't tell ☐	No ☐
*6. Is the data analysis sufficiently rigorous to address the aims? ➤ Links between data and interpretations?	Yes ☐	Can't tell ☐	No ☐

C: How are the results?

7. Are the findings of the study explicit and easy to understand?	Yes ☐	Can't tell ☐	No ☐
*8. Are data collection and analysis sufficiently presented to support the descriptive findings?	Yes ☐	Can't tell ☐	No ☐
9. Does the study add to knowledge or theory in the field?	Yes ☐	Can't tell ☐	No ☐
10. Are these findings important to practice?	Yes ☐	Can't tell ☐	No ☐

Overall assessment of study <u>This study will be included in the synthesis or not?</u> Two requirements are considered of the inclusion of studies: ● Two screening questions with # must be 'Yes' ● Not all answers to the three key questions with * are 'No'	Yes ☐	No ☐
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Source: Own elaboration based on CASP checklist

Appendix 2: List of the selected studies

Study NO.	Title of Study	Author	Authority of Authors	Publication time (2008-2012)
Reports (working reports, consultancy reports and other practitioner materials)				
RE-01	Environmental and economic aspects of using LNG as a fuel for shipping in the Netherlands	Ruud Verbeek et al.	TNO Netherlands	2011
RE-02	LNG markets perspective	James Ashworth	TRI-ZEN International	2012
RE-03	LNG fuelled deep-sea shipping: outlook for LNG bunker and LNG fuelled new building demand up to 2025	Jesper Aagesen et al.	Lloyd's Register(LR)	2012
RE-04	Modalities for the provisioning of LNG as shipping fuel in Flemish ports	Det Norske Veritas (DNV)	Det Norske Veritas (DNV)	2012
RE-05	Greener shipping in the Baltic Sea	Det Norske Veritas (DNV)	Det Norske Veritas (DNV)	2010
RE-06	Natural gas for marine vessels: U.S. market opportunities	Thomas et al.	American Clean Skies Foundation	2012
RE-07	Costs and benefits of LNG as ship fuel for container vessels	Pierre C. Sames	Germanischer Lloyd (GL)	2011
RE-08	LNG fuelled inland vessels and the Port of Rotterdam	Liam Feenstra	Port of Rotterdam	2012
RE-09	Natural gas for ship propulsion in Denmark: possibilities for using LNG and CNG on ferry and cargo routes	Frank Stuer-Lauridsen et al.	Danish Ministry of the environment	2010
RE-10	North European LNG Infrastructure Project: a feasibility study for an LNG filling station infrastructure and test of recommendations	The Danish Maritime Authority	Danish maritime Authority(EU Ten-T Program)	2012
RE-11	Developing LNG as a clean fuel for ships in the Baltic and North Seas	MAGALOG Project	EU funded study	2008
RE-12	Car Ferry LNG Fuel Conversion feasibility Study: life cycle cost analysis	The Glosten associates	The Glosten associates	2011
Papers(Master theses, papers and articles)				
PA-01	The LNG use as a maritime fuel: environmental challenges and perspectives	Basdani E.I, and Lignou M.N.	Maritime Administration in Piraeus, Greece	2011
PA-02	Potential and conditions for LNG fueled short sea shipping in East Asia	Henrik Andersson and Kasper Winroth	Chalmers University of Technology, Sweden	2010
PA-03	Potential market for LNG fueled marine vessels in the United States	Bridget C. Brett	Massachusetts Institute of Technology	2008

PA-04	LNG-fueled vessels in the Norwegian short-sea market: a cost-effective response to environmental regulation	Meike Baumgart and Jon Halvard Bolstad Olsen	Norges Handelshøyskole	2010
PA-05	The introduction of LNG as marine fuel in the Dutch shipping industry	Royal Haskoning	TU Delft: Transport Infrastructure & Logistics	2012
PA-06	LNG as a vessel and general transportation fuel	G. W. Van Tassel	Society of Naval Architects and Marine Engineers	2010
PA-07	Sailing for cleaner skies: Study of LNG fuel for sea vessels in Rotterdam	A.H. de Ruiter	TU Delft: Transport Infrastructure & Logistics	2010
PA-08	The future potential of LNG as a bunker fuel	Gaute Dag Løset and Rolf Erik Tveten	Norwegian University of Science and Technology	2011
PA-09	Tighten emission regulations in Northern Europe	Torstein R. Alvestad	Norges Handelshøyskole	2011
PA-10	The development of a supply chain for a liquefied natural gas bunkering procedure at Stena Danica	Jimmy Dahlstrom and Rasmus Lundh	Chalmers University of Technology, Sweden	2011
Conference materials (conference reports and presentations)				
CN-01	The use of LNG as fuel for propulsion on board merchant ships	Marco Andreola	Rolls-Royce	2011
CN-02	LNG as a transportation fuel	Gazprom	Gazprom	2012
CN-03	Gas-fuelled ships: LNG fuelled engines and fuel systems for medium-speed engines in maritime applications	Dag Stenersen	MARINTEK	2011
CN-04	Vessel emission study: comparison of various abatement technologies to meet emission levels for ECA's	Danish Ministry of Economics	Danish Ministry of Economics	2012
CN-05	LNG as a marine fuel	Det Norske Veritas (DNV)	Det Norske Veritas (DNV)	2012
CN-06	The risks of marine transportation of LNG and LNG-fuelled ships	Mauri Lindholm	Aker Arctic	2012
CN-07	LNG as ships' fuel-the EMSA perspective	Henrik Ringbom	EMSA	2011
CN-08	Approval of ships using LNG as fuel	Lasse Karlsen	Norwegian Maritime Authority	2012
CN-09	The potential conversion of the U.S great lakes steam bulk carriers to LNG propulsion	Michael G. Parsons et al.	Great Lakes Maritime Research Institute	2012
CN-10	LNG fuel systems: certification and approval	Steve Gumpel	ABS	2012
CN-11	Foreword: LNG from concept to reality	Giulio Tirelli	Wartsila	2012

Appendix 3: Results of the evaluation of the selected studies

The modified CAPS checklist 10 questions {Yes = Y; Not = N; Can't tell = CT}

Study NO.	*(Q1)Address a clearly focused issue	*(Q2)Relevance to the synthesis	(Q3)Clear research methods	*(Q4)Explicit data collection	(Q5)Clear data analysis	*(Q6)Data analysis rigorous	(Q7)Explicit and understandable findings	*(Q8)Data analysis sufficiently support findings	(Q9)Adding knowledge or theory	(Q10)findings important to practice	Included in the Synthesis?
Reports (working reports, consultancy reports and other practitioner materials)											
RE-01	Y	Y	Y	CT	Y	Y	Y	Y	CT	CT	Y
RE-02	Y	Y	N	N	CT	CT	Y	CT	CT	CT	Y
RE-03	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
RE-04	Y	Y	CT	CT	CT	Y	Y	Y	Y	Y	Y
RE-05	Y	Y	N	N	CT	CT	Y	CT	CT	CT	Y
RE-06	Y	Y	CT	CT	CT	CT	Y	CT	CT	CT	Y
RE-07	Y	Y	Y	CT	Y	Y	Y	Y	Y	Y	Y
RE-08	Y	Y	Y	CT	Y	Y	Y	Y	Y	Y	Y
RE-09	Y	Y	CT	CT	Y	Y	Y	Y	CT	Y	Y
RE-10	Y	Y	Y	CT	Y	Y	Y	Y	Y	Y	Y
RE-11	Y	Y	CT	CT	Y	Y	Y	Y	Y	Y	Y
RE-12	Y	Y	CT	CT	Y	Y	Y	Y	Y	Y	Y
Papers(Master theses, papers and articles)											
PA-01	Y	Y	CT	CT	CT	CT	Y	CT	CT	CT	Y
PA-02	Y	Y	CT	Y	CT	CT	CT	CT	CT	CT	Y
PA-03	Y	Y	CT	N	CT	CT	CT	CT	CT	CT	Y
PA-04	Y	Y	Y	Y	CT	CT	Y	Y	CT	CT	Y
PA-05	Y	Y	Y	Y	Y	Y	Y	Y	Y	CT	Y
PA-06	Y	Y	N	CT	CT	CT	Y	CT	CT	CT	Y
PA-07	Y	Y	Y	Y	CT	CT	Y	CT	CT	CT	Y
PA-08	Y	Y	Y	Y	CT	CT	Y	Y	Y	CT	Y
PA-09	Y	Y	Y	Y	Y	Y	Y	Y	CT	CT	Y
PA-10	Y	Y	Y	CT	CT	CT	Y	CT	CT	CT	Y

Conference materials (conference reports and presentations)											
CN-01	Y	Y	N	N	CT	N	Y	CT	CT	Y	Y
CN-02	Y	Y	N	N	CT	CT	CT	CT	CT	CT	Y
CN-03	Y	Y	N	N	CT	CT	Y	CT	CT	CT	Y
CN-04	Y	Y	Y	CT	Y	Y	Y	Y	Y	Y	Y
CN-05	Y	Y	N	N	CT	CT	Y	CT	CT	CT	Y
CN-06	Y	Y	N	N	CT	CT	CT	Y	CT	CT	Y
CN-07	Y	Y	CT	N	CT	CT	Y	CT	CT	CT	Y
CN-08	Y	Y	N	N	CT	CT	Y	CT	Y	Y	Y
CN-09	Y	Y	CT	CT	CT	CT	Y	CT	CT	Y	Y
CN-10	Y	Y	CT	CT	CT	CT	CT	CT	Y	Y	Y
CN-11	Y	Y	N	N	CT	CT	CT	CT	CT	CT	Y

Appendix 4: Distribution of authors and publication time

Appendix 5: Identification of positive and negative factors affecting the use of LNG as a ship fuel (from selected 33 studies)

Positive factors Developing factors Uncertain factors Negative factors

[illegible]

FIGURES

Figure 1. Design of the procedure for a systematic review (Source: Authors)

Figure 2. A framework for the review questions (Source: Authors)

Figure 3. The factors identified from the first group of review questions (*Source: Authors*)

Notes: * the number in parenthesis means the number of studies where the relevant issue is discussed

Environmental cost is not yet established now except in Norway, but some studies expect that environmental cost will be developed in the future which can make LNG fuel more attractive

Figure 4. Positive and negative factors in light of the adoption of LNG as a ship fuel (Source: Authors)

Figure 5. Regulatory gaps for the use of LNG as a ship fuel (Source: Own elaboration based on EMSA (2013))

Figure 6. Comparison between three alternative solutions to meet IMO/ECA regulations (Source: Authors)

Figure 7. Factors affecting the shipowner's decision on the application of LNG as a ship fuel (Source: Authors)

Figure 8. The role of port authorities in solving the 'chicken-and-egg' problem in the development of LNG bunkering (Source: Authors)