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Pollutant emissions from LNG fuelled ships

Assessment and recommendations

Susana López-Aparicio and Dag Tønnesen

Scientific report

Preface

This report is part of the project "Developing the programme of measures for the Estonian marine area in compliance with the requirements of the EU Marine Strategy Framework Directive, including feasibility study on using LNG as an alternative ship fuel to reduce pollution" (LNGestland). This report summarises the work carried out by NILU – Norwegian Institute for Air Research regarding the assessment of pollutant emission factors (NO_x, particulate matter, organic compounds) for ships using Liquid Natural Gas (LNG). This evaluation, based on a literature review, will support the selection of scenarios for using LNG along with the information from the feasibility study performed within the project.

The work in this report has been led by Susana López-Aparicio and carried out in close collaboration with Dag Tønnesen. The early version of the report benefited from the internal quality control process at NILU that has been carried out by Claudia Hak. The early version of this report benefited from the comments from Madli Kopti, from the Estonian Maritime Academy of Tallinn University of Technology.

The LNGestland project is supported by the EEA Financial mechanism 2009-2014, within the programme "Integrated Marine and Inland Water Management".

Contents

Page

Summary

This report briefly describes the status of the knowledge regarding liquid natural gas (LNG) as maritime fuel and the emissions associated with LNG fuelled ships.

The project "Developing the programme of measures for the Estonia marine area in compliance with the requirements of the EU Marine Strategy Framework Directive, including feasibility study on using LNG as an alternative ship fuel to reduce pollution" is a project funded within the EEA Financial Mechanism 2009-2014. It is coordinated by the Estonian Environmental Research Centre, and with the Institute of Marine Research (Norway) and Norwegian Institute for Air Research (NILU) as partners.

The project will develop a marine strategy in accordance with the Marine Strategy Framework Directive for managing Estonian marine waters. It consists of a regionally coordinated cost-effective monitoring programme and a programme of measures for managing pressures in marine environment (http://www.klab.ee/merestrateegia/en/). One of the possible measures to be evaluated is the implementation of LNG as ship fuel. Therefore, a technical and economic feasibility study as well as an environmental impact study on using LNG as ship fuel will be carried out.

- The main tasks of NILU in the project as donor project partner are:

- Propose the scenarios for using LNG, based on the feasibility study of using LNG as a ship fuel, which will be carried out in the project;
- Assess and propose emission factors for the relevant pollutants (NO_x, particles, organic compounds) for ships using LNG.

- This report summarizes and evaluates the information published in the literature regarding pollutant emission factors for ships using LNG. We have to point out that the number of studies on emission factors for LNG fuelled vessels is very limited. Therefore, it becomes challenging to select emission factors for different pollutants, different types of vessels and even more for different operational modes (e.g. cruising, manoeuvring, at berth).

LNG fuelled ships

Assessment and Recommendations

1 Introduction

Requirements to comply with strict regulations on sulphur and nitrogen dioxide emissions by the maritime sector (IMO 2013), and in particular in the emission control areas (ECA), there is a need for alternative options for reducing emissions. The use of end of pipe technologies (e.g. scrubbers) or shifting to alternative fuels are among the existing options. This report will focus on the latest one, and in particular on liquid natural gas (LNG) as maritime fuel and the emissions associated with LNG fuelled ships.

The Annex VI "Regulations for the prevention of Air Pollution from ships" of the International Maritime Organization (IMO, 2013) entered into force in May 2005. This mandates to limit the sulphur content of marine fuels on a global basis to:

- 4.5 % m/m[1] prior to 1st January 2012
- 3.5 % m/m on and after 1st January 2012
- 0.5 % m/m on and after 1st January 2020

The Annex VI imposes stricter regulation in ECA (Figure 1), comprising the Baltic Sea (emission control of SO_x); North Sea area (emission control of SO_x); North American area (emission control of SO_x, NO_x and PM); and United States Caribbean Sea area (emission control of SO_x, NO_x and PM). The sulphur content of maritime fuel oil used by ships in the ECA shall not exceed:

- 1.5 % m/m prior to 1st July 2010
- 1.0 % m/m on and after 1st July 2010
- 0.1 % m/m on and after 1st January 2015

[1] % m/m: percent by mass

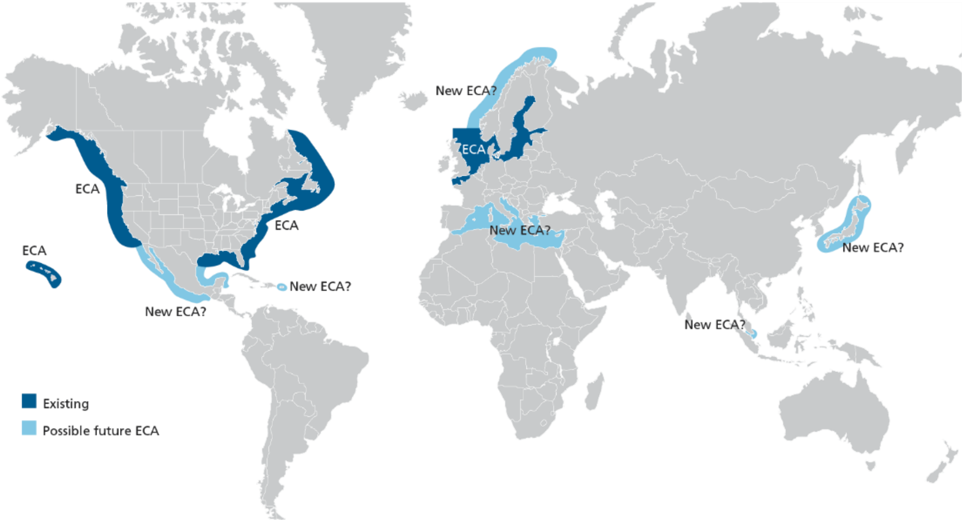

Figure 1: Distribution of existing and possible future Emission Control Areas (ECA).

The regulation number 13 of Annex VI (IMO 2013) concerns NO_x emissions and it contains a 3-tier approach that establishes allowable emissions of total weighted NO_x depending on the engine speed (Figure 2):

- Tier I (current limits) affects diesel engines installed on ships from 1st January 2000 to 1st January 2011.
- Tier II: affects diesel engines installed on ships constructed on or after 1st January 2011.
- Tier III: this limitation affects ships constructed on or after 1st January 2016 and operating in ECA.

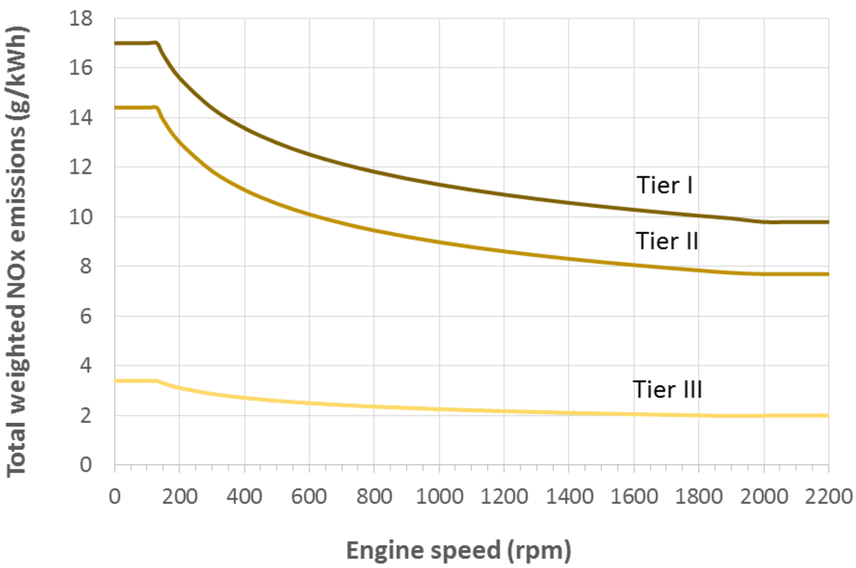

Figure 2: MARPOL Annex VI NO_x emission limit (IMO 2013).

In this report we summarize the information available in the literature regarding emission of different compounds from LNG-fuelled vessels. The purpose is to contribute to the tasks to be performed in the project regarding emissions under different scenarios of implementations of LNG as fuel in vessels operating in Estonian waters. Therefore the work focuses on the main type of vessels operating in Estonian waters and summarized in Table 1. It should, however, be noted that emission factors for combustion of alternative fuels, and in particular LNG, in marine engines are uncertain as the number of emission tests are very limited.

Table 1: Typical ships operating in Estonian waters (Madli Kopti, Estonian Maritime Academy of Tallinn University of Technology - TUT, personal communication). ME: main engine; AE: auxiliary engine. Average time the vessels spend in Estonian waters.

Type of vessels	Gross tonnage (GT)	Engine (kW)	#Calls (2013)	Average time (h)
Passenger Ship	5 000 – 5 999	1400	20 722	13 566
Passenger Ship	30 000 – 39 999	40000 (ME); 2000 (AE)	3 511	10 533
Tankers	10 000 – 19 999	8775 (ME); 1200 (AE)	129	516
Dry Bulk Carrier	2 000 – 2 999	975 (ME); 225 (AE)	356	3 680
Container Ship	10 000 – 19 999	10890 (ME); 1500 (AE)	208	832

2 LNG as fuel for shipping

Liquefied natural gas (LNG) is predominantly natural methane gas (CH_4) which has been converted into liquid to facilitate the transport and storage. It is odourless, colourless, non-toxic and non-corrosive, and among the main hazards is flammability. The interest in LNG as fuel for transportation has grown in the last decades as a consequence of the economic incentives for the use of alternative-fuels and stricter emission standards. LNG is very much used as fuel for heavy-duty vehicles such as buses and trucks, off-road engines, locomotives and as marine fuel.

The number of LNG fuelled vessels is growing globally driven by the stricter emission control and the price advantages of LNG over other marine fuels. Around 48 LNG fuelled vessels were in operation worldwide in 2014 (Figure 3) including car/passenger ferries, general cargo, tug and RoPax[2]. Besides, 53 LNG fuelled new built vessels are confirmed (DNV 2014; Figure 3), including additional vessels categories such as tankers, Ro-Ro, container ships, bulk, icebreakers and car carriers.

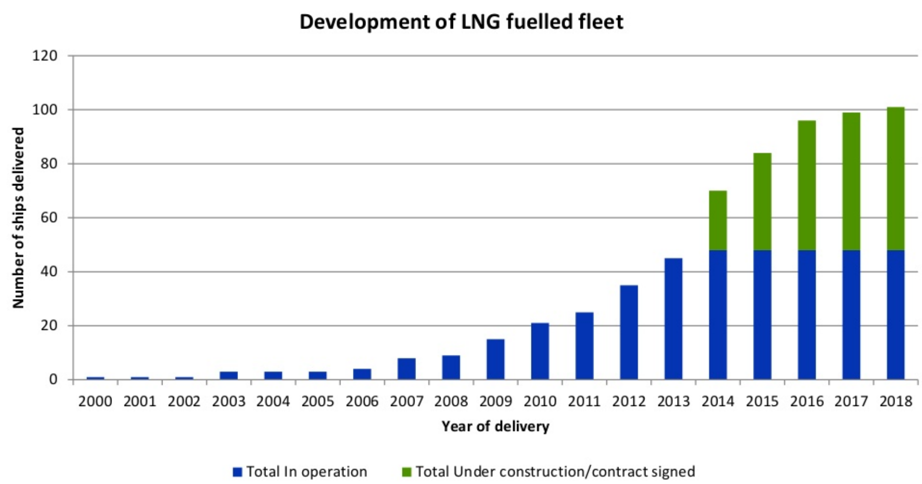

Figure 3: Development of LNG-fuelled ships based on vessels in operation or under construction (After DNV 2014).

Figure 4 shows the breakdown of LNG-fuelled vessels per type, and including under construction. In 2010 the most abundant LNG-fuelled vessels were car/passenger ferries, whereas in 2014 platform supply vessels (PSV) reached similar amount as car/passenger ferries and other types of vessels appeared on the market. For 2018, and based on the confirmed orders of LNG-fuelled vessels, a wide number of vessels types will be in operation. The wide availability of type of vessels on the market, able to operate with LNG fuel, supports the scenarios to be evaluated in the project, which are characterized by implementation of LNG as maritime fuel. As previously indicated, the project focuses on vessels commonly operating in Estonian waters, and this includes passenger vessels, dry bulk carriers, tankers and containers (Table 1), all of them feasible LNG-fuelled vessels.

[2] Roll-on/roll-off passenger vessels

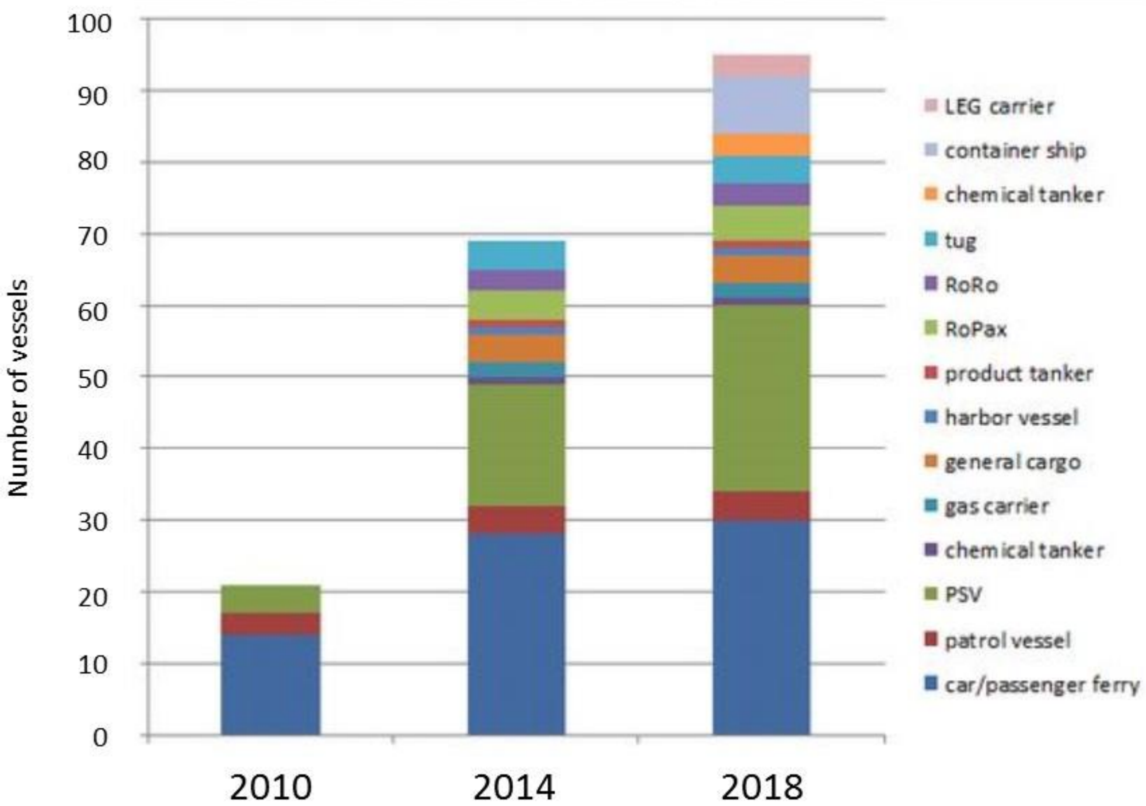

Figure 4: Breakdown of LNG fuelled fleet (world-wide) by vessel type including operating and under construction (After DNV 2014)

3 Literature Review – Source of Information

A literature search was carried out in different phases. In the first phase, the search focussed on peer-reviewed journals. The search was primary performed via search engines such as "ISI Web of Knowledge", "Science Direct" and "Springer Link" and based on combinations of keywords such as; "LNG fuelled ships", "emissions", "emission factors", "LNG shipping emissions" "NOx emissions", among others. As a consequence of the low number of studies published in peer-review journals about emissions from combustion of LNG-fuelled vessels, a second search phase was carried out. In this case, the focus was on the so called grey literature, which includes reports, communications, databases and presentations in conferences and meetings.

Apart from the literature review, communication with the project partners, and the Estonian Maritime Academy of Tallinn University of Technology (TUT), in charge of the feasibility study, have been essential for completing this report. Personal communication was also established with researchers working on emissions from shipping and specifically with LNG-fuelled vessels, such as Selma Brynolf from Chalmers University. However, specific emission factors were not available at the time of writing this report.

Among the most relevant studies and sources of information are:

- Brynolf et al., (2014a) Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transport Research Part D, 28, 6-18.
- Nielsen and Stenersen (2010) Emission factors for CH_4, NO_x, particulates and black carbon for domestic shipping in Norway, revision 1. Norwegian Marine Technology Research Institute, MARINTEK.

4 Emissions factors from LNG-fuelled vessels

Table 2 shows emission factors from LNG-fuelled vessels estimated for typical ships sailing in Estonian waters and calculated by Estonian Maritime Academy of TUT. The emission factors are estimated based on the following assumptions:

- SO_x (as SO_2) emission rate calculated based on emissions from marine gas oil (MGO) with 0.1% sulphur content and pilot fuel consumption for Wärtsilä 4-stroke DF engine.
- NO_x emission rate calculated assuming a reduction of NO_x emission rate of about 80% regarding Tier II (MARPOL 73/78; IMO 2013) due to very homogeneous fuel-air mixture in 4-stroke DF engines working at LNG mode by Otto cycle.
- CO_2 emission rate is calculated as 25% lower emissions than MGO due to higher heating value and lower carbon content in natural gas.
- Particulate matter (PM) emission rate is estimated based on the maximum allowed ash content in the fuel, and for LNG the ash content is very low.

Nielsen and Stenersen (2010) published revised emission factors for CH_4, NO_x, particulates and black carbon for domestic shipping in Norway. The emission factors are based on data collected from measurements carried out in ships with installed NO_x-reducing measures, including LNG as fuel. The information available for LNG fuelled vessels is for only two compounds, NO_x and CH_4 (Table 2).

Nielsen and Stenersen (2010) reported three different emission factors for CH_4, depending on the type of vessels. CH_4 emission factors for offshore supply vessels are higher than emission factors measured for ferries or coast guard vessels. Emission factors for NO_x published by Nielsen and Stenersen (2010) and estimated by TUT are practically the same.

*Table 2: Emission factors from LNG-fuelled vessels estimated in the project (TUT, 2015: Madli Kopti, Estonian Maritime Academy of TUT, personal communication) and reported by Nielsen and Stenersen (2010). *Emission factor for ferries. ¥Emission factor for offshore supply. §Emission factor for coast guard vessels. a Container feeder.*

Emission factors (g/kWh)						
Reference	TUT (2015)	Nielsen and Stenersen (2010)			CNSS 2013	Verbeek et al. (2011)
SO_2	0.004					0.00051
NO_x	1	1.1				1.3 – 3[a]
CO_2	426				421	
PM	0.00036					0.02 – 0.21[a]
CH_4		8.5*	15.6¥	8.5§		

Studies carried out within The Clean North Sea Shipping project (CNSS, 2015) have assessed the potential problems associated with air pollution and greenhouse gases (GHGs) produced by shipping operating along the North Sea coast and within North Sea ports and harbours. Among different issues, the potential impact both at local scale and regarding GHG emissions of LNG-fuelled vessels was addressed (CNSS, 2013). Emissions factors used for the air pollution assessment are those reported by Nielsen and Stenersen (2010) in the case of NO_x and NH_4, whereas emission factors for CO_2 were estimated within the project (Table 2). The comparison between emissions from LNG- and heavy fuel oil (HFO)- fuelled vessels indicates that LNG offers several advantages for the environment. This is due to the NO_x and SO_2 emissions reductions for LNG compared with HFO-fuelled vessels, in addition to an expected decrease in the concentration levels of fine particles and ozone. According to the CNSS (2013) study, switching to LNG would help to reach the emission standards required to operate in the ECAs. However, the study also concludes that reductions of GHGs emissions are uncertain, and especially regarding the leakage of CH_4. The main conclusion from this study, and especially regarding the impact in harbour environment, has to be carefully taken into account, as they only compare emissions from LNG with emissions from HFO, and the latest one is not used in port areas.

There are not many studies that publish specific emission factors for LNG-fuelled vessels, but several studies address emissions from both a local and a life cycle perspective. Some example of these studies are Verbeek et al., 2011, Bengtsson et al., 2012, Brynolf et al., 2014b.

Verbeek et al., (2011) investigate the environmental aspects of using LNG as fuel for three different types of vessels; shore sea ship (i.e. a 800 twenty feet equivalent unit – TEU container), a port ship (i.e. an 80 ton harbour tug) and an inland ship with dimensions around 110 x 11.5 m. Emissions for the container ships are shown in Table 2, as they are the only ones applicable to the type of vessels operating in Estonian waters. Emissions were estimated based on the following assumptions:

- NO_x emissions are estimated based on the “constant NO_x to CO_2 ratio”, which is equivalent to “constant NO_x to fuel consumption ratio”. Different emission factors are considered in the study as different engines with different maximum powers.
- SO_2 emissions are estimated based on the sulphur content of LNG based on information provided by Shell. Based on a sulphur content of around 3.5 ppm by mass, and heating values of 49 MJ/kg, Verbeek et al., (2011) estimated SO_2 emissions of around 143 * 10^{-6} g/MJ, about 0.51 * 10^{-3} g/kWh.
- PM emissions reported by Verbeek et al. (2011) are based on literature review and expert view.

Verbeek et al., (2011) compared emissions from vessels running on LNG and vessels running on diesel marine gas/diesel oil. The results are shown in Figure 5 for different types of engines, representing those produced between 2011 – 2015 and those in 2016 and later. The results obtained for the shore sea ship are the most relevant for our study as container vessels constitute one of the types of vessels operating in Estonian waters (Table 1). Annual emissions, expressed as tank to propeller (TTP), from the container vessels operating with LNG instead of marine diesel oil (MDO) are reduced by 60-75% for both NO_x and PM, and by 99% for SO_x, when evaluating engines produces within the 2011-2015 time frame. The 2016 and later time frame is characterized by diesel engines equipped with selective catalytic reduction (SCR; deNOx catalyst), and therefore complying with MARPOL Tier III (IMO 2013). Emission reductions with LNG fuel are much lower than those obtained by comparing LNG and MDO from older diesel engines, and for NO_x there is almost no emission reduction (Figure 5).

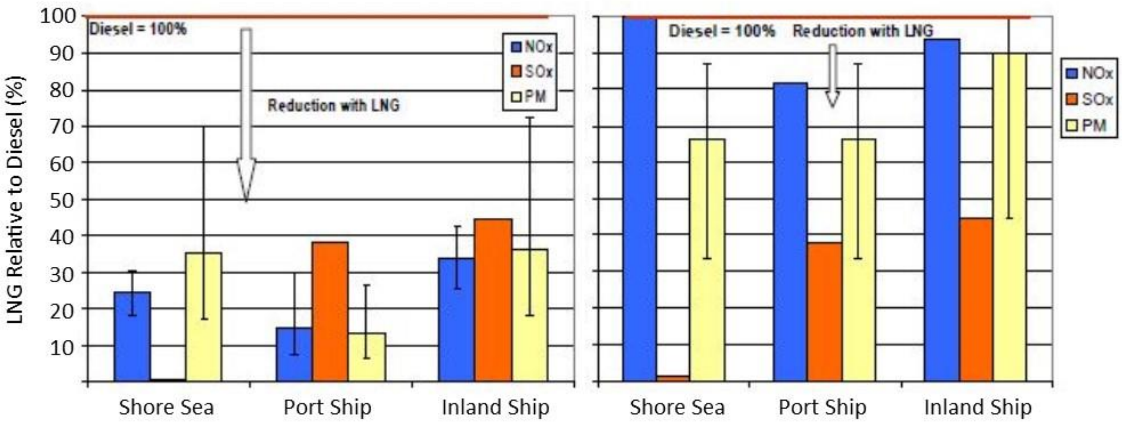

Figure 5: Comparison of annual Tank to Propeller (TTP) air pollutant emissions between LNG and diesel for 2011-2015 (left) and 2016 and later (right). Modified after Verbeek et al., 2011.

Brynolf et al. (2014b) compared the life cycle environmental performance of different marine fuels; LNG, liquefied biogas (LBG), methanol and bio-methanol. Regarding environmental impact, they concluded that health impact, as well as the potential impact on acidification and eutrophication, are lower for LNG than for the other maritime fuels. The NO_x emission factors used for this evaluation are those reported by Nielsen and Stenersen (2010), which are already below the Tier III level established in MARPOL Annex VI (IMO, 2013), and therefore explaining such as low environmental impact associated with NO_x emissions.

5 Recommendations

Shipping emissions depend on the operational mode of the vessels, consequently emissions will be different when cruising, slow cruising, manoeuvring and when the vessels are at berth. European Commission and Entec UK Limited (Entec UK, 2002) published emission factors for different types of vessels and operational modes. These emission factors are commonly accepted and used in emission inventories and environmental impact assessments. However, the study only takes into account emissions from marine diesel/gas fuels, and no information on LNG is available.

There are very few studies that establish air pollution emission factors for LNG-fuelled vessels, and none of them establishes emission factors per operational mode. Therefore, the available information is limited and the existing emission factors are rather generic, without discriminating between operational modes, or types of vessels. This generic aspect involves uncertainties.

Nielsen and Stenersen (2010) published emission factors based on measurements carried out in Norwegian vessels running on LNG as fuel (Table 2). These emission factors are the most commonly used in environmental impact assessment studies (e.g. Brynolf et al. 2014b). Emissions factors established by Nielsen and Stenersen (2010) were obtained from passenger ferries, offshore supply vessels and guard vessels, which could be classified as harbour vessels. However, the vessels reported as typical in Estonian waters are mainly oceangoing vessels (e.g. passenger ships, tankers, carriers and container vessels). Therefore, and for the purpose of our study, the use of emissions factors determined from harbour vessels may involve high uncertainties.

Based on the information available in the literature and expert view, we recommend the **NO_x emission factors** shown in Table 3 for the different vessels operating in Estonian waters. Emission factors established by Nielsen and Sternersen (2010) are recommended for the passenger ships, whereas for tankers, carriers and container vessels, emission factors determined by Verbeek et al., (2011) for container vessels with engines produced between 2011 and 2015 are selected.

Table 3: NO_x emission factors for vessels operating in Estonian waters.
[a] Passenger ships with gross tonnage (GT) between 5 000 – 5 999.
[b] Passenger ships with gross tonnage (GT) between 30 000 – 39 999.
Number in [] is the average.

Type of Vessels	NO_x emission factors (g/kWh)	Source
Passenger Ship[a]	1.1	Nielsen & Stenersen 2010
Passenger Ship[b]	1.1	Nielsen & Stenersen 2010
Tankers	1.3 – 3 [2.15]	Verbeek et al., 2011
Dry Bulk Carrier	1.3 – 3 [2.15]	Verbeek et al., 2011
Container Ship	1.3 – 3 [2.15]	Verbeek et al., 2011

The **emission factors for SO_2** depend on the sulphur content in the LNG, therefore the same emission factor is recommended for the different vessels operating in Estonian waters. Evaluating the information provided by Verbeek et al., (2011), we recommend a SO_2 emission factor of about $0.51 * 10^{-3}$.

Regarding emissions of PM, very little information is available therefore existing data is still very uncertain. The **PM emissions factors** established by Verbeek et al., (2011) for container vessels are based on the percentage reduction regarding emission from diesel which is also determined based on the sulphur content in the fuel. The PM emission factor recommended for the vessels operating in Estonian waters is of about 0.02 to 0.21 g/kWh.

Emission factors for CH_4 or CO_2, values established by Nielsen and Stenersen (2010) and CNSS (2013), respectively (Table 2), can be used.

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ABSTRACT
This report is part of the project "Developing the programme of measures for the Estonian marine area in compliance with the requirements of the EU Marine Strategy Framework Directive, including feasibility study on using LNG as an alternative ship fuel to reduce pollution". This report presents and assesses the available information regarding pollutant emission factors (NOx, particulate matter, organic compounds) for ships using Liquid Natural Gas (LNG) as fuel. This evaluation, based on a literature review, will support the selection of scenarios for using LNG along with the information from the feasibility study performed within the project.

NORWEGIAN TITLE
Utslipp fra LNG skip – vurdering og anbefaling

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ABSTRACT (in Norwegian)
Denne rapporten er en del av prosjektet "Developing the programme of measures for the Estonian marine area in compliance with the requirements of the EU Marine Strategy Framework Directive, including feasibility study on using LNG as an alternative ship fuel to reduce pollution". Rapporten presenterer og vurderer tilgjengelig informasjon vedrørende utslippsfaktorer for relevante forurensningskomponenter (NOx, partikler, organiske forbindelser) for skip som bruker flytende naturgass som drivstoff. Evalueringen er basert på en litteraturgjennomgang og vil støtte valg av scenarioer for bruk av LNG sammen med informasjonen fra mulighetsstudien utført innenfor prosjektet

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