TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering

Well-to-Wake Environmental Impact Assessment of Conventional and Alternative Marine Fossil Fuels for Ship's Propulsion: LNG vs MDO

Konventsionaalsete ja alternatiivsete fossiilsete laevakütuste keskkonnamõju hindamine "Well-to-Wake" meetodil: veeldatud maagaas versus kergkütteõli

MASTER THESIS

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Thesis main objectives:

1. To assess CO_2 emissions from shipping on Tallinn-Helsinki route through fuel supply chain.

2. To figure out what is the most attractive marine fuel in Baltic Region and why.

3. To provide an overview of the shipping development trends in the Baltic region

Thesis tasks and time schedule:

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PREFACE

The current thesis topic has been chosen by the author, who used to work as ship engineer on vessels with different propulsion systems and a wide range of fuels. Alternative fuels are currently of major interest to ship owners due to constantly strengthening emission requirements, especially after the new global sulphur limits of 0.5% entered into force on 1 January 2020 – so called Global Sulphur Cap 2020.

The idea of the thesis emerged while discussing the current ship design technologies and shipping trends caused by introduction of new regulations on emissions. Currently, there are two dominant opinions – a change over to alternative fuel sources or retrofitting existing vessels with exhaust gas aftertreatment systems. The third option, use of compliant fuels, doesn’t have sufficient support from shipowners due to financial reasons.

Within the present research author is trying to explain the solutions available today, their pros and cons, assess impact on Global Warming Potential when using Liquefied Natural Gas and Light Fuel Oil. Additionally, the author provides the reader with an overview on actual marine fuel supply chain and emissions from it. Relevant data on fuel consumption, ship operational data, technology used and fuel supply chain is used for the Life Cycle Assessment providing reliable results.

In the end the author provides a conclusion on the study, pointing out shipping development trends within the Baltic region. An important part of conclusion is providing the reader with potential possibility on improving GHG emissions and an overview of these solutions.

The author appreciates thesis supervisor Viktoria Voronova for her helpfulness, for attentiveness and guidance on research activity.
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Keywords: Liquefied Natural Gas, Shipping, Life Cycle Assessment, Global Sulphur Cap, master thesis

List of abbreviations and symbols

GHG – Greenhouse Gas

EU – European Union

SOx – Sulphur Oxides

NOx - Nitrogen Oxides

PM – Particulate Matter

CH_4 - methane

LPG – Liquefied Petroleum Gas

LNG – Liquefied Natural Gas

NG – Natural Gas

IMO – International Maritime Organization

MARPOL – International Convention for the Prevention of Pollution from Ships

ECA – Emission Control Area

EEDI – Energy Efficiency Design Index

SEEMP – Ship Energy Efficiency Management Plan

MDO – Marine Diesel Oil

MGO – Marine Gas Oil

HFO – Heavy Fuel Oil

LSFO – Low Sulphur Fuel Oil

LFO – Light Fuel Oil

SCR – Selective Catalytic Reduction

LCA – Life Cycle Assessment

EGCS – Exhaust Gas Cleaning System

DF – Dual-Fuel

GWP – Global Warming Potential

IGF Code – International Gas Fuel Code

CCP – Controllable Pitch Propeller

FPP – Fixed Pitch Propeller

kW – kilowatt

kWh – kilowatt-hour

GVU – Gas Valve Unit

Nm – Nautical mile

LEL – Lower Explosion Limit

UEL – Upper Explosion Limit

INTRODUCTION

Maritime shipping industry contributes to approximately 2,5% of global greenhouse gas emissions (GHG) and approximately 13% of the total transportation sector in European Union (EU). [1]

At the same time shipping industry is responsible for sulphur oxide (SO_x) and nitrogen oxide (NO_x) emissions as for decades ships have been propelled by engines using fuel oils with high sulphur content (up to 4,5% S), the so called Heavy Fuel Oils (HFO).

Use of alternative fuels, mainly liquefied natural nas (LNG), are of interest of shipowners thanks to their competitive price, no sulphur and very low CO_2 and NO_x emissions. Natural gas consists primarily of methane gas (92-98%) with some amount of heavier hydrocarbons: ethane, butane, propane.
Natural gas is liquefied by cooling down to -162 °C at atmospheric pressure. In it's liquid state gas occupies 600 less space compared its gaseous state. LNG is stored at -162 °C at nearly atmospheric pressure in special double-walled cryogenic containment systems – LNG tanks. [2]

Although burning methane is much cleaner compared to other fossil fuels it is a major cause of climate change as it is a strong greenhouse gas when released to the atmosphere. During human activity natural gas, primarily methane, is both intentionally and unintentionally released during extraction, storage, treatment, transportation and distribution.
When released to the atmosphere methane has a GWP of 25 over 100 years compared to CO_2.

Modern gas and dual-fuel engines have 25% lower CO2 emissions and 85% lower NO_x than a diesel engine. This enables compliance with the IMO Tier III levels without the need for an Selective Catalytic Reduction (SCR). Additionally, there is practically no PM emissions.
So called methane slip or any methane (CH_4) leaks during operation, bunkering or maintenance works must be avoided to keep this advantage, as methane is very strong GHG. [3] However, in practice this is not possible.

The aim of this thesis is to calculate and compare greenhouse gas emissions when using traditional fossil fuels or alternative fossil fuel, LNG. Well-to-Wake approach has been chosen for the assessment of the environmental impact throughout the complete fuel supply chain.

Calculation of the emissions is based on monitored data from approved databases and on reports by shipowners according to EU regulations on monitoring and verification of CO_2 emissions.

In sense of the research aim and objectives Tallinn – Helsinki route matches the requirements in the best way. Tallinn–Helsinki has the best suitability for the research aim and objectives. The route is located in the Emission Control Area (ECA), the distance is 44 nautical miles (nm) and two route-optimised vessels are operated on it.
Two of Tallink Group high-speed Ro-Pax ferries Star (IMO: 9364722) and Megastar (IMO: 9773064) are operated on this route. They are specially designed and optimised for Tallinn – Helsinki route providing up to 12 departures per day.
For the propulsion M/S Star (IMO: 9364722) uses Light Fuel Oil only (Reference: ISO 8217 Grades RMA trough RMD).M/S Megastar (IMO: 9773064) runs mainly on LNG with Marine Gas Oil (Reference: ISO 8217 Grades DMX trough DMB) as back-up fuel.

All these factors make M/S Star and M/S Megastar perfect choice in terms of data collection, evaluation of CO_2 emissions and environmental impact assessment as they operate on same route, within Emission Control Area, designed and optimised for the route. However, they are powered by different fuels.
Stringent environmental standards, available technologies and global economics has set new trends in development of marine powerplants as well as new environmental challenges related to their operation.
The current study will give an overview on the situation in the Baltic Region, highlight problems and advantages when using alternative fuel sources and, in conclusion, provide recommendations on limiting CO_2 emissions and reducing environmental risks. Special attention will be paid to assessment of methane slip and methane leakages during bunkering operations, frequency of bunkering operation and fuel quality.

The objective of the current thesis is to provide answers to such questions as "How much CO_2 is emitted from shipping on Tallinn-Helsinki route through fuel supply chain?", "What is the most attractive marine fuel in Baltic Region and why?", "How to reduce CO_2 emissions throughout supply chain" and "What are the shipping development trends in the Baltic region?

2. Theoretical overview

2.1 Legal background

As shipping is a global transportation business, cutting emissions also requires global solutions, approved authorities and regulatory bodies. Here International Maritime Organisation (IMO) comes into play.

IMO, as stated on their website, *is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.* [4]

IMO has set the goal towards cutting emissions and pollutants from seagoing vessels by adopting International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973.

In 1997 MARPOL Annex VI was added andentered into force on 19 May 2005. MARPOL Annex VI sets the limits mainly on sulphur and nitrogen oxides from ships flue gases, as well as defines special emission control areas with stringent standards, for example Baltic Sea, adopted in 1997.

Three IMO Tiers have been introduced (Tier I-III) to control and reduce NO_x emissions. Tier II standard can be achieved by improving engine technology, for example by reducing maximum combustion temperature .Tier III standard, in effect from 2016, is applied within ECA and requires 80% NO_x emissions reduction compared to Tier I (introduced in 2000).The only way to achieve this limit is to install selective catalytic reductors (SCR). [5] (Figure 1a,1b).

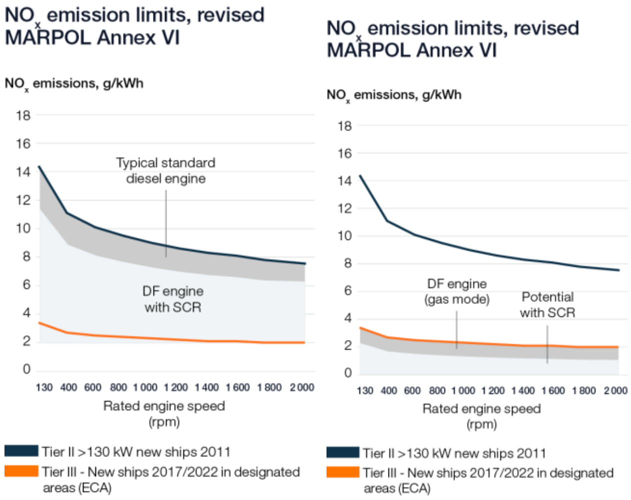


Figure 1a,1b.NOx emission limits. Source: [6]

Additionally, IMO is looking toward reduction of greenhouse gases from global shipping. Under MARPOL treaty IMO has implemented the Energy Efficiency Design Index (EEDI), which is compulsory for new ships, as well as Ship Energy Efficiency Management Plan (SEEMP).
In 2018, IMO has adopted a strategy on the reduction of GHG emissions from shipping by at least 40% by 2030, compared to 2008. [6]

In 2015 another milestone has been passed, new amendments to MARPOL Annex VI come into force as a result of adoption in 2008. As from 1 January 2015 all ships inside Emission Control Areas (ECAs) must use fuels with sulphur content less than 0.10%. Since 1 January 2020 stricter regulations have been adopted and come into force with 0.5% sulphur content globally, known as Global Sulphur Cap (Figure 2).

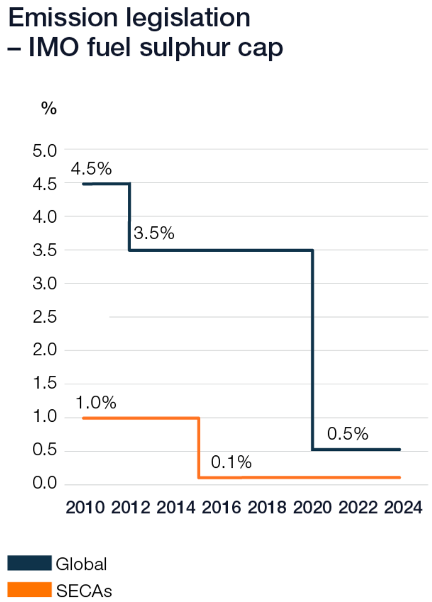


Figure 2.SOx emissioon limits.Source: [6]

To meet the new, stringent environmental requirements inside Emission Control Areas, which is Baltic Sea, shipowners are forced to look towards alternative solutions. Today there are 3 main options available to meet MARPOL requirements:

- Switching over to more expensive low Sulphur fuel oil;
- to install and use SOx scrubbers;
- using alternative fuels, such as gas fuels (LNG, LPG) is a viable alternative; Hydrogen, ammonia and methanol are also promising fuels in the long run.

Low Sulphur fuel grades, such as Marine Diesel Oil (MDO) or Marine Gas Oil (MGO), are much more expensive than heavy fuel oils. The price is estimated to grow even more with increase in demand. The HFO grade IFO380 3,5%S price on 13.02.2021 is 280EUR/mt and that of MGO 0.1%S is 390EUR/mt. [7]

Installation of exhaust gas aftertreatment systems, scrubbers for sulphur removal is a good option for existing vessels.
Tier III requires 80% reduction in NO_x emissions, which can only be achieved with use of Selective Catalytic Reduction. [8] SCR units, as well as scrubbers, require capital investments and increase operational costs. For example, scrubber pumps require additional power supply and, in case of closed loop system, the sludge needs to be discharged ashore. SCR require maintenance.

2.2 Description of technical systems and overview of alternatives

The world fleet has basically 3 options to comply with Global Sulphur Cap 2020:

1. Operate on compliant fuel, MGO/MDO/LSFO with sulphur content less then 0,5% globally and 0,1% within SECA;
2. Retrofit scrubber systems and operate on high sulphur fuel oil;
3. Retrofit the fuel system to operate on alternative fuels, LNG/methanol/ethane etc.

This applies to both existing vessels and newbuilds. [9]

Vessels unequipped with scrubbers (Exhaust Gas Cleaning System, EGCS) or alternative fuel systems can't use fuel oil exceeding 0,5% sulphur after 1 Jan 2020. [5] All remaining fuel with sulphur content exceeding 0,5% must be de-bunkered.

Changing over to low sulphur fuel oils does not require any major investments for the shipowners. Very minor modifications to fuel system are usually required, such as installation of fuel oil coolers after the main engines and cleaning of fuel tanks prior to bunkering new fuel.

Major fuel grades available on the market today are: Marine Gas Oil (MGO), Low Sulphur Fuel Oil (LSFO) and High Sulphur Fuel Oil (HSFO) for use on ships equipped with scrubber. Important to mention that different fuel blends are also available and comply with MARPOL requirements.

Tallink high-speed Ro-Pax ferry Star (IMO: 9364722) is using LFO (Grade RMB30) for propulsion. [12]

Andrus Vaher, Tallink’s Environmental & Sustainability Officer has commented on the choice of compliant fuel instead of scrubbers “Decision of using a compliant fuel instead of scrubbers has arisen from the comparison of pros and cons of both solutions. A compliant fuel (in case of Tallink is Light Fuel Oil, S<0,1%) is more expensive. However, no capital investments are needed for scrubber installation, and maintenance, and sludge discharge fees are also missing. For Tallink ships powerplants also require scrubbers with high capacity, thus installation and maintenance costs also increase significantly. Additionally operational schedule of ships is of high importance - failure of a scrubber will lead to additional delays. Tallink assumes possible further restrictions for scrubber operations, which have already been partly realized.”

Scrubbers, also known as Exhaust Gas Cleaning Systems, are the secondary treatment system of flue gases from the main engines. They are designed and accepted by authorities for reduction of sulphur oxide emissions.

There are 2 options available when retrofitting to scrubber systems: operation in open-loop only or hybrid system operating in both open and closed loop modes.
IMO has adopted criteria for discharge of washwater from the scrubber. The sludge generated by the closed-loop scrubber should be delivered ashore. It is strictly prohibited to discharge any sludge generated by scrubber to the sea or incinerate on board.

Open-loop scrubbers use sea water which turns sulphur oxides (SO_x) to sulphuric acid discharged directly overboard. [10] The washwater should meet strict criteria on pH, Polycyclic Aromatic Hydrocarbons and nitrates.

Installation of EGCS on an existing vessel is a time consuming process which requires redesign of the hull structure and existing piping systems of the ship. Additionally it requires high capital investments and dry docking process.
Scrubbers require space and additional power supply. In case of a scrubber malfunction, which is not a rare situation especially during winter season in Northern areas, the fuel system should be changed over to compliant fuel (MGO or LSFO).
When choosing an EGCS type all these factors must be considered to avoid further technical issues and malfunctions which subsequently will lead to financial losses and possible penalties from authorities for using uncompliant equipment.

Liquefied Natural Gas mainly consists of methane (up to 98%) with some amount of heavier hydrocarbons. [2]

Development of gas production processes, cryogenic equipment and liquefaction technologies have created tools needed for safe, efficient and economically profitable transportation of natural gas over long distances in its liquid state – LNG. Natural gas is liquefied by cooling down to -162 °C at atmospheric pressure. In its liquid state gas occupies 600 times less space compared to its gaseous state. LNG is stored at -162 °C at nearly atmospheric pressure in special double-walled cryogenic containment systems – LNG tanks. [2]

Additionally, to the environmental benefits of LNG, interest toward LNG is growing because of the rising costs on conventional fuel oils. Gas and DualFuel, DF engines operated on natural gas have up to 25% less CO_2 emissions, up to 85% NO_x emissions and practically no particulates. SO_x emissions are also eliminated, as sulphur is removed from natural gas stream at the early stages of production. [2]

The increasing demand for LNG as marine fuel goes hand in hand with supply chain and infrastructure development of bunkering.
LNG has been chosen as primary fuel for propulsion of Tallink Group Ro-Pax ferry Megastar (IMO: 9773064). LNG is combusted in the main generator sets and steam boilers.

2.3 Environmental drawbacks of LNG as ship's fuel

2.3.1 Overview of the gas fuel concepts and emissions

Development of technologies lead to opening of new opportunities, as well as new challenges related to safety, reliability of new equipment and environmental issues.

Methane is the main component of LNG and is a strong greenhouse gas. When released to the atmosphere methane has a GWP of 25 over 100 years compared to CO_2. Its escape during the production, supply chain and use of LNG reduces the positive impact of the fuel on GHG emissions. [10]

The greenhouse effect is the process by which radiation from the planet's atmosphere warms the planet's surface to a temperature above what it would be otherwise. Sun radiation reaches the earth's atmosphere and then some of it is reflected, but the rest is absorbed and radiated back by greenhouse. Therefore, energy absorbed by greenhouse gases warms the Earth's atmosphere and the surface. Main natural greenhouse gases are carbon dioxide, water vapour, inartificial methane, however with the development of the industry amount of carbon dioxide and artificial methane has risen significantly in past years. [14]

Combustion of gas in marine diesel engine require a high amount of oxygen and a low combustion temperature to keep the lowest possible NO_x emissions. This causes „cold areas" in the combustion chamber, where incomplete combustion takes place. [13] Additionally, the fuel gas/air ratio is not even distributed over the combustion chamber causing spots with rich mixture containing an excessive fuel proportion.
Typically such spots are formed just above the fuel injector nozzle and above the upper compression ring between the piston and cylinder liner wall causing some of the gas escape to the atmosphere through the exhaust system (Figure 3).

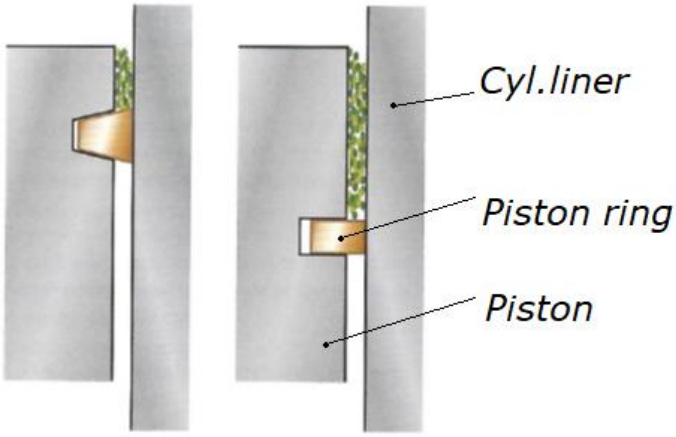


Figure 3. Captured methane between piston and cylinder liner. Source: [15]

Continuing optimization of combustion chambers is one of the major challenges for diesel engine designers on the way to increasing combustion efficiency and reducing emissions.
The ship's engine room forms enclosed space without natural ventilation, this requires special arrangements to minimize risks for the ship, crew and environment when operating with low flashpoint fuels. Requirements and standards for machinery and equipment are provided in International Code of Safety for Ship Using Gases or Other Low-Flashpoint Fuels (IGF Code). [11]

M/S Megastar is designed with „gas-safe" engine room concept, which means that a single failure of the gas equipment, such as the engine trip or pipe leak, does not release any dangerous substance into the machinery space (entire engine room). IGF Code requires double wall design for all gas fuel pipes as well as active ventilation to the atmosphere. Thereby any gas fuel leak caused by damaged piping or blown gasket is being safely vented to the atmosphere. Gas trip is an engine's protection system which cuts off the fuel gas supply to the engine, and switching engine to the back-up fuel, fuel remained in the gas fuel supply system is then isolated and released to the atmosphere. Gas trip is triggered by the engine safety system in case system detects any faults in engine's operation such as: knocking i.e uncontrolled combustion, misfiring, a pilot fuel system failure or a detected gas leak.

Another source of methane emissions to the atmosphere is the arrangement of LNG bunkering system. Due to safety reasons and the requirements of IGF Code any gas residues in the bunkering system are prohibited and should be eliminated. At the end of the bunkering operation all liquid in the bunker line is stripped to the LNG storage tank. However, very small amount of liquid and gas remains in the system since it cannot bet stripped, due to pressure in the tank being higher than that in the pipeline.

This residue of methane is then released to the atmosphere through the HV456 or HV356 (Figure 4).

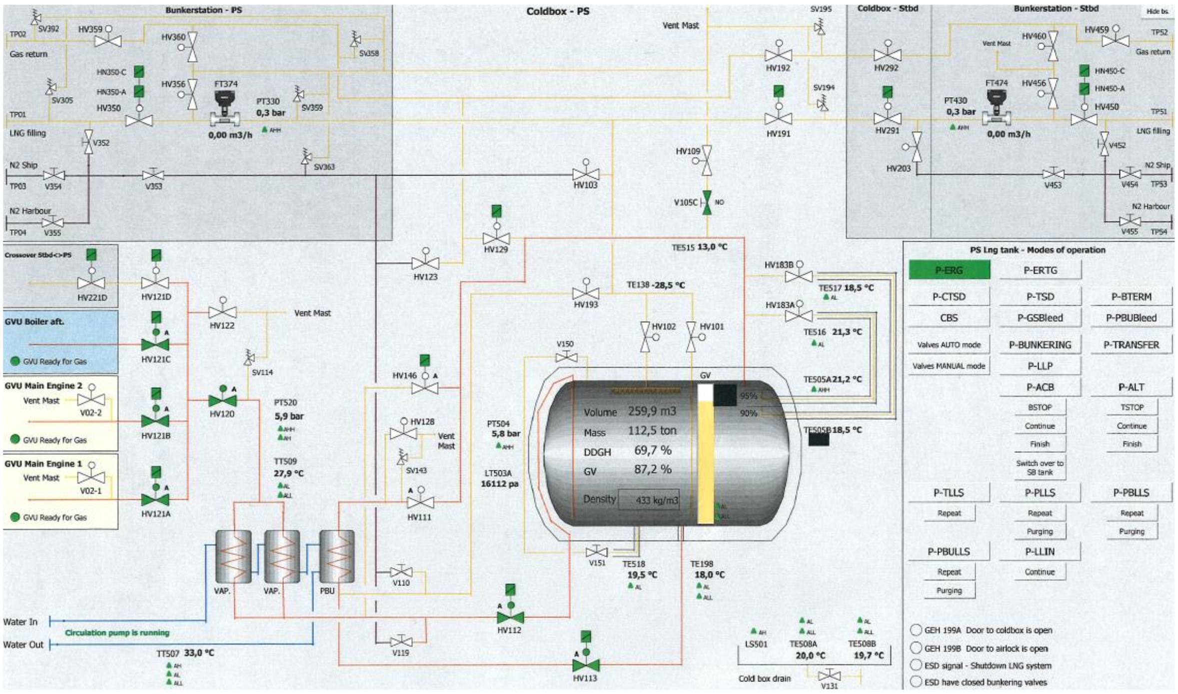


Figure 4.M/S Megastar LNG system. Source: [13]

Thus GHG emissions of a gas fuelled ship to a large extent depend on the gas quality, bunkering frequency and the working conditions of the critical equipment.

2.3.2 General overview of marine fuel supply chains

Methane slip from engines is the main cause for criticism from supporters of other alternatives. However different studies show that the main source of methane emissions are from LNG supply chain. Methane released unintentionally leaks to the atmosphere through it's life cycle. [9]

For powering M/S Megastar the value chain of LNG consists of:

1. Exploration and extraction of raw material
2. Gas production and liquefaction
3. Transportation to the ship, currently using tank trucks
4. On-board regasification and combustion

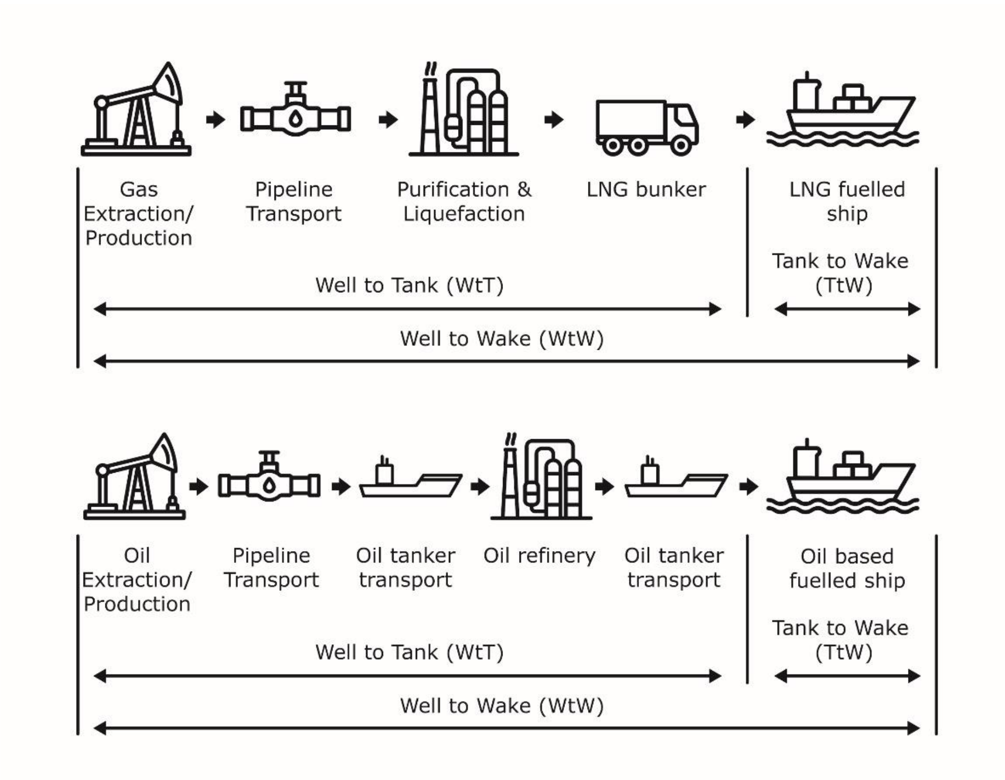


Figure 5. Ship fuel supply chain.

Fuel oil value chain is similar to the LNG value chain as often natural gas and crude oil are formed together and extracted simultaneously from wells. In this gas natural gas is called associated natural gas (Figure 5, 6).

This means that fuel oil value chain is partially responsible for methane emissions through it's life cycle.

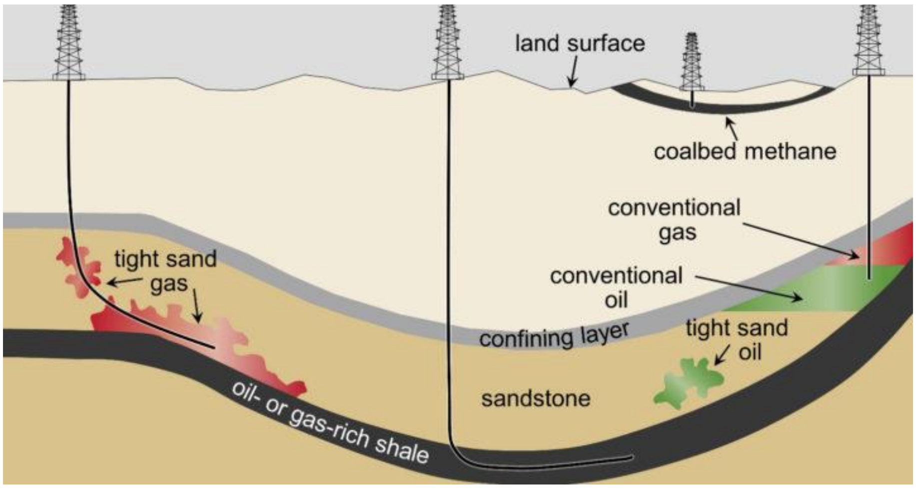


Figure 6. Schematic geology of natural gas and oil. Source: [17]

2.4 Overview of recent LCA studies

Recently published reports on GHG study on emissions from LNG engines through life cycle show no or very little advantage of LNG compared to traditional fuel oils. [9] However, these reports are based on average data available and does not take into account the route characteristics, bunkering infrastructure and particulars of the ships operated of the specific route.

In 2019 another study was published "Life Cycle Assessment of LNG Fuelled Vessel in Domestic Services".50,000 ton bulk carrier operating in South Korea had been chosen for the study. Authors of the LCA conclude, that using LNG as fuel in domestic or local service is an effective way to reduce pollution compared to conventional fuel oils. However, fuel supply chain must be well optimized from the transportation point of view. [12]

Wärtsilä, a Finnish technology company and one of the main players on a global Gas- and Dual-Fuel engines market, pointing out that report of International Cocuncil for Clean Transport does not provide latest data on the emissions from gas- and dual-fuel engines. Wärtsilä refers to the fact that only a small part of the modern fleet uses DF engines for propulsion and that the emission assessments must be based on the latest engine technologies utilised today.

Additionally, Wärtsilä refers to the fact, that study is based on the average data on methane slip from the engine – 5.5 g/kWh. However, this value is higher than that of Wärtsilä 4-stroke engine portfolio. Wärtsilä states that their moder Wärtsilä 46DF engine has the methane slip of only 2.8 g/kWh. [18]

Furthermore, as engineers are working constantly on the development of the engine technology by optimizing combustion process and reducing specific fuel oil consumption in the future methane slip can be slashed to some of 1 g/kWh.

In current thesis research only CO_2 emissions are under investigation, however there are number of studies that show significant reduction on NO_x and PM emissions, as well as SOx emissions without the need of exhaust gas aftertreatment. Additionally to the above mentioned advantages, in some cases, LNG has also financial advantage over conventional fuels – up to 31% fuel cost save per year. [19]

3. METHODOLOGY

3.1 Tallinn-Helsinki route details

Tallinn-Helsinki route is the main arteria connecting Estonia and Finland with the total of 19.9 million tonnes of cargo and 10.6 million passengers transported per annum. [10]
The route of 44 nautical miles (equals to 81.5km) is crossed by two Ro-Pax ferries Star and Megastar having 6 departures a day. The total voyage duration is approximately 2 hours.

M/S Star (IMO: 9364722) has entered service on Tallinn-Helsinki route in 2007. It was the first ferry specially designed for this route offering year-around service.
Tallink Star has a length of 186m and Gross Tonnage of 36,000 tonnes. [15] Star has conventional for RoRo vessels propulsion system consisting of four main engines connected in pairs to two gear boxes forming two independent propulsion systems on each side. Through the gearboxes torque is transferred via shaftline to the Controllable Pitch Propellers (CCP) (Figure 7).

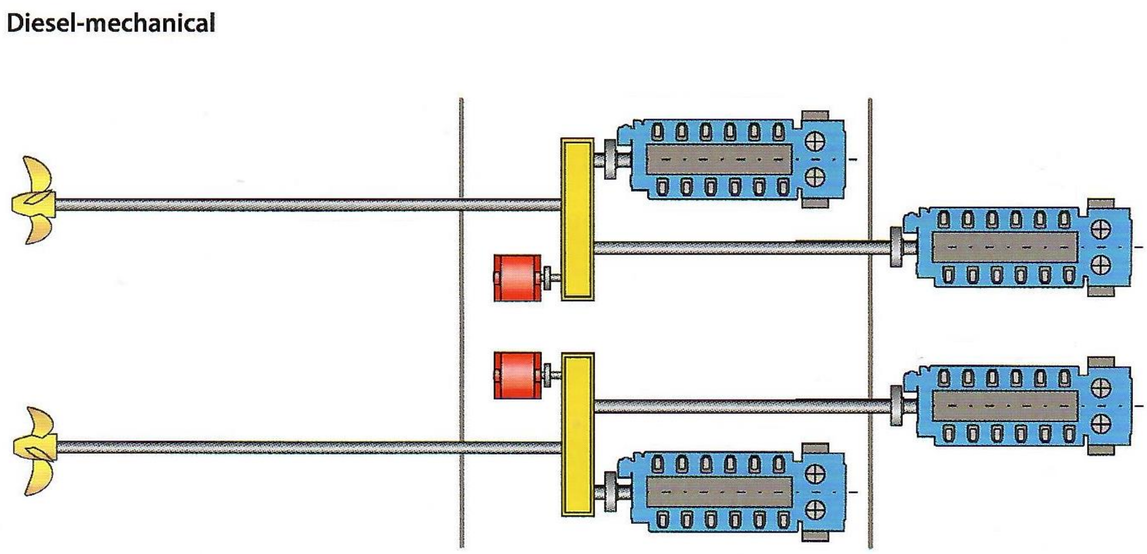


Figure 7. Conventional ship's propulsion system layout. Source: [15]

Main engines MaK 12M43C are 4-stroke medium speed turbocharged marine engines with power output of 12,000kW and 48,000kW combined. [12] This allows to operate the ship at up to 27 knots. Engines are capable to operate on most fuel oils available on the market. Due to strict environmental regulations in the Baltic Sea M/S Star is operated on LFO.

M/S Megastar (IMO: 9773064) is the newest Ro-Pax Ferry operated by Tallink Group. It began its service on Tallinn-Helsinki route in early 2017 and replaced M/S Superstar. As its predecessor, it had been designed and optimized for the Tallinn-Helsinki route. However, completely diferent propulsion system had been introduced.

Tallink Megastar has a length of 212m and Gross Tonnage of 49,000 tonnes. [15] Megastar is powered by DualFuel Diesel Electric propulsion system with LNG as a primary fuel and MDO as a pilot and back-up fuel. Diesel electric propulsion means that main engines drive generators which produce electrical power for both Propulsion Electric Motors and the vessel's own needs. The main propulsion electric motors are connected directly to the shaft line and Fixed Pitch Propellers (FPP) and are able to operate at variable speeds. Such systems are the newest development trend in marine propulsion systems, giving the powerplant flexibility and total system efficiency. Similarly to M/S Star the service speed is 27 knots. [15]
The main generating set consists of 2xWärtsilä 6L50DF and 3xWärtsilä 12V50DF DualFuel medium speed turbocharged engines, low pressure lean-burn concept. An example of dual fuel diesel electric propulsion (Figure 8).

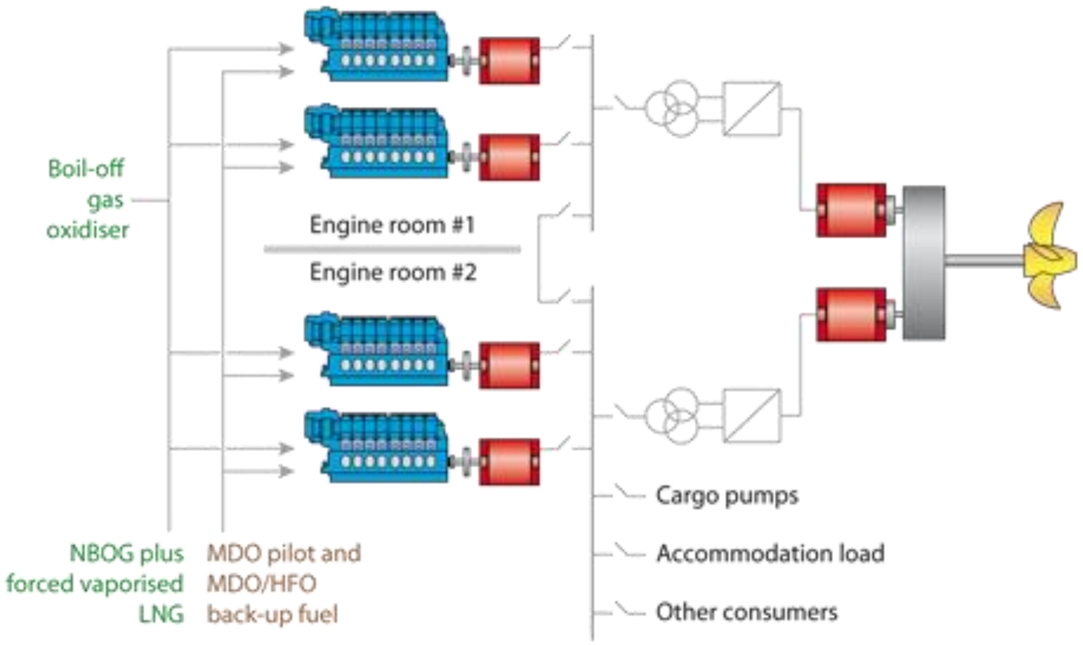


Figure 8.Dual-Fuel Diesel Electric propulsion system layout.Source: [15]

3.2 Description of ships LNG systems and sources of methane leakages

The design of LNG powered vessels corresponds to IGF Code requirements with special attention to system safety and redundancy. Ship's LNG system can be divided into two main parts:

1. LNG bunkering and storage system
2. Gas Fuel system

M/S Megastar LNG system consists of two independent bunker stations on each side, double-walled stainless steel piping with required fittings and equipment (flowmeter, safety valves, gauges etc), two vacuum insulated cryogenic storage tanks (600m3 total). [12] The so called cold-box or tank connection space with all required equipment for further regasification is connected directly to the tank and therefore forms a secondary barrier from other machinery spaces. According to the IGF Code requirements double walled pipes are constantly ventilated, keeping under pressure in the annular space. In case of a leak, due to the pressure difference, gas will be immediately ventilated to the safe area – ventilation mast.

In the current study the calculation of methane release to the atmosphere due to bunker operation is based on the size of the bunker line and end pressure in the bunker manifold (Figure 9).

Table 1. M/S Megastar LNG bunker line dimensions

Function	Pipe size	Final pressure (bar)	Length (m)
LNG bunker line	DN150	0.3	30

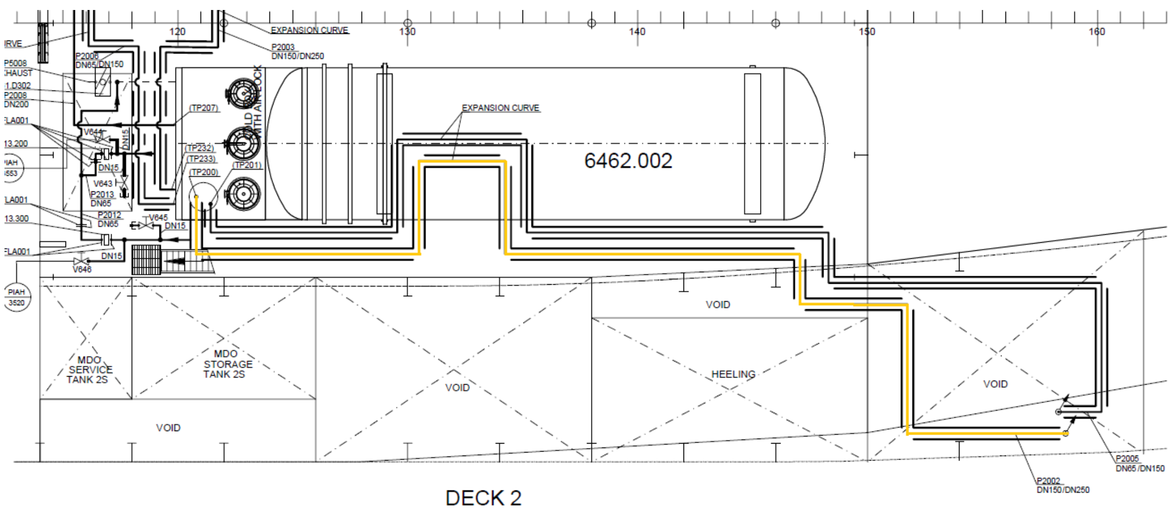
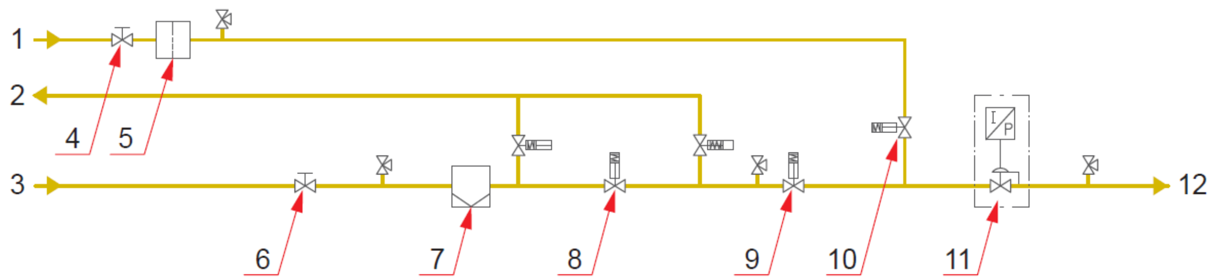


Figure 9. M/S Megastar LNG bunker line layout. Source: [13]

Gas Fuel system consists of two LNG vaporizers and one Pressure Build-up vaporizer. LNG is vaporized by the heat generated by the main engines, steam or electrical heater through the intermediate heating media – glycol. Two LNG vaporizers regasifiy LNG and send gas directly to the consumers, Pressure Build-up Vaporizer required for maintaining constant pressure in LNG tank. [12]

Regasified methane is being sent to the consumer's Gas Valve Unit (GVU) which includes a filter, a pressure regulating unit, a double block and bleed valve unit, safety valves and ventilation connections.

GVU controls and regulates fuel gas pressure. In addition, GVU is equipped with a gas leak detection system for the safe operation. In case of a leak or any emergency scenario it will cut-off gas feed, ventilate gas to the safe leak and inert the gas system with nitrogen. Each consumer has it's own independent Gas Valve Unit and automation system (Figure 10).



1 Inert gas
2 Gas venting
3 Gas inlet
4 Shut off valve
5 Filter (inert gas)
6 Manual gas inlet valve
7 Gas filter
8 Shut off valve
9 Shut off valve
10 Inerting valve
11 Gas regulating valve
12 Gas to engine

Figure 10.Gas Valve Unit P&I diagram. Source: [20]

LNG, mainly methane, is a cryogenic substance with very low flashpoint and explosion limits between 5% (LEL) and 15% (UEL) in its gas state (Figure 11). These factors require special attention, competence and procedures when performing any operation related to the LNG or Gas system. IGF Code specifies the requirements when designing bunker system of LNG vessel.

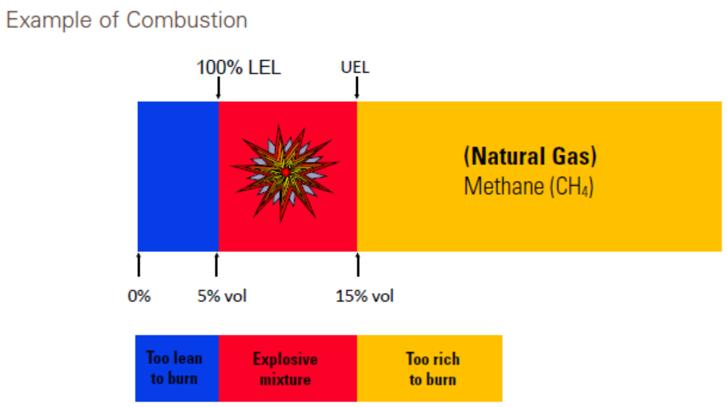


Figure 11.Natural Gas explosion limits. Source: [22]

Due to the above mentioned special properties of LNG, it can not be mixed with air, as otherwise it might form an explosible mixture. Prior to bunkering all pipelines must be stripped from air by purging them with inert gas. In case of M/S Megastar nitrogen gas is used for inerting and control of remote valves. Nitrogen is known as inert gas in a wide range of applications, it is not reactive and can be easily generated from the atmospheric air (content in air is 78%). [2]

Similarly to the air removing procedure prior bunkering, remains of methane are stripped and purged with nitrogen. Therefore, part of methane is released to the atmosphere through the ventilation mast causing methane emissions. In this paper, the amount of leaked methane will be calculated based on the piping volume, pressure, bunkering frequency and gas content.

Simplified LNG bunker procedure can be divided into the next main parts:

1. Bunker hose connection and bunker line inertization;
2. Bunker line cooling down with LNG;
3. Bunkering;
4. Line stripping from LNG residues by partial evaporation and pressure build-up;
5. Bunker line inertization and purging with nitrogen.

Design of LNG bunker system on-board LNG powered vessels does not allow to avoid methane release to the atmosphere and therefore the amount of methane emissions is strongly related to the supply chain, local infrastructure and bunker frequency. Additionally to the leaks from ship's normal operation, there might be other methane released due to the equipment malfunction or failure.

3.3.1 Overview of LNG and LSFO supply chains

Since starting its operation in January 2017 M/S Megastar has been bunkered with LNG by tank trucks. LNG is delivered from Pskov, Russia 350km away from Tallinn. A new Natural Gas Liquefaction Complex started its operation in 2016 and has been operated by Cryogas. [13]

Natural gas is supplied through Russian Unified Gas Supply System (UGSS) via pipeline to Pskov liquefaction plant. LNG plant is connected to the „Northern Lights" pipeline system. Originally the pipeline supplied natural gas from Vukhtyl gas field, but nowadays pipeline has been extended and connected to the Urengoy gas field. [14]

The total length of Norther Lights pipeline is 7,377km. However, distance from Urengoy gas field to Pskov is approximately 3800km. In Pskov natural gas is liquefied and transported to Tallinn by tank trucks. Table 1.

Potentialy, there are alternative LNG terminals available in the Nordics. Pori LNG Terminal started its operation in 2016. In 2018 another LNG terminal started its operation in Tornio. Both terminals are operated by Skangas. [16] Hamina LNG terminal is under construction and will be the third LNG terminal in Finland. The planned start of operation is 2022, LNG terminal will be operated by Haminan Energia and Alexela Varahalduse AS. [17]

Table 2. Well-to-Tank LNG supply chain

Route	**Type of transportation**	**Distance(km)**
Urengoy-Peregrebnoye-Ukhta-Gryazovets-Torzhok-Pskov	Pipeline	7,377
Pskov-Tallinn	Tank truck	350

M/S Star is bunkered with Light Fuel Oil mainly by Finnish oil refining company Neste Oyj. The fuel is delivered from Neste's refinery located in Poorvo, Finland to Helsinki by bunker barge. The distance from Porvoo, Fi to Helsinki, Fi is approximately 28 nautical miles (NM) or 52 km. [18]
The raw material is delivered to Porvoo refinery from Russia via pipeline or by crude oil tankers from any other places over the world. Modern sea transport allows to transport the raw material from any place of the world with competitive prices compared to the pipeline from Russia and therefore it's hard to predict the origin of the raw material.

In current the study it is assumed that raw material is delivered to the refinery by crude oil tanker from Ust-Luga, Russian export terminal. The distance from Ust-Luga, Russia to Porvoo, Finland is approximately 138 NM or 256 km (Figure 12). [18]

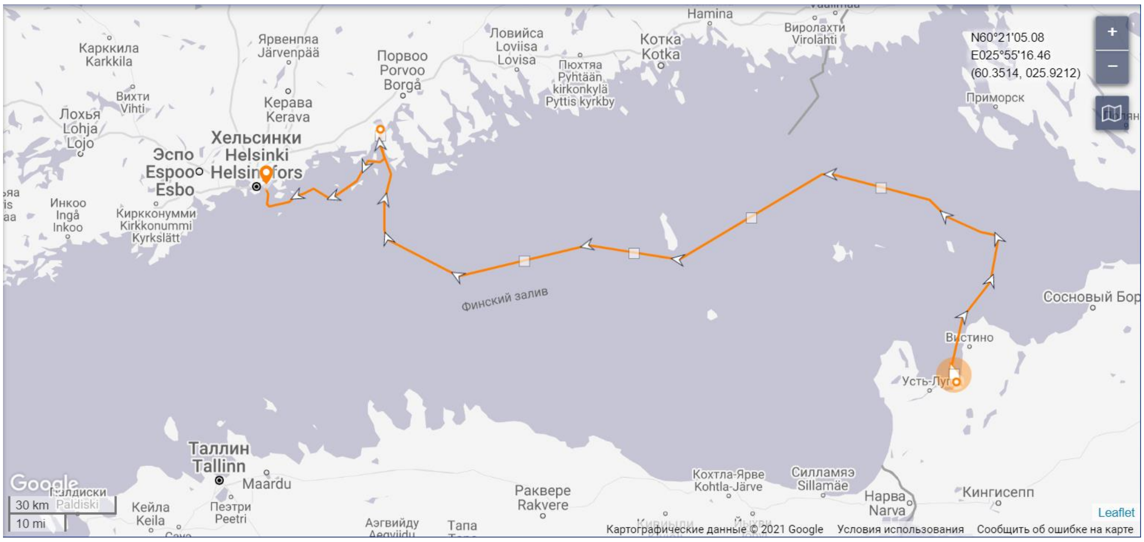


Figure 12.Crude oil tank route according to IAS data. Source: [19]

Ust-Luga together with Primorsk are the main Russian oil export terminals in the Baltics. Crude oil products have been delivered via Baltic Pipeline System 2 since 2012, operated by Russian oil pipeline company Transneft. BPS-2 has allowed to connect these ports with main crude oil export pipeline “Druzhba”. Raw material is delivered via pipeline system by a number of intermediate pump stations from Main Crude Oil Pump Station Usa, located in Usinsk, Russia. The total distance of pipeline from oil field to the export terminals is approximately 3000 km. [19]

The total distance of the fuel supply chain is 3308 km. Table 2.

Table 3. Light Fuel Oil supply chain

Route	**Type of transportation**	**Distance (km)**
Usinsk - Ukhta - Yaroslavl-Torzhok - Velikie Luki – Ust-Luga, Russia	Pipeline	3000
Ust-Luga, Russia – Porvoo, Finland	Sea transport	138NM / 256km
Porvoo – Helsinki	Seatransport	28NM / 52km

3.3.2 Life cycle assessment

For the analysis of "upstream" CO_2 emissions (i.e. Well-to-Tank) EcoInvent database is used. EcoInvent is an open source Life Cycle Assessment database which provides very detailed and high-quality data for conducting life cycle assessments. EcoInvent is used widely in industry, consultancy, research and educational purposes. [20]

LCA provides analysis of environmental impacts throughout LNG and Fuel Oil supply chain from raw material extraction, production and transportation steps. The use stage is outside of the scope of the analysis. Generally, LCA consists of "Goal and scope definitions", "Inventory analysis", "Impact assessment" and "Interpretation".

For the "downstream" (i.e. Tank-To-Wake) or "Use stage" Energy Efficiency Operational Indicator (EEOI) calculator is used. EEOI is developed by IMO Marine Environmental Protection Committee (MEPC) as a mechanism of identification of Greenhouse Gas(GHG) emissions from international shipping.

Guidelines for calculation of CO_2 emissions are provided in MEPC.1/Circ.684 „GUIDELINES FOR VOLUNTARY USE OF THE SHIP ENERGY EFFICIENCY OPERATIONAL INDICATOR (EEOI)". [21] Source of fuel consumption, distance sailed and work done data is taken from an open source EU-MRV system CO_2 emission report. [22] Guideline provides information on calculation of CO_2 emissions taking into account different fuel types, distance sailed and ship-specific tasks. The guidelines are applicable for all ships performing transport work such as different cargo ships, tankers, containerships, ro-ro/passenger ships etc and therefore the CO_2 emissions calculator is approved by authorities.

Meanwhile, EEOI calculator is considered impractical in terms of calculating emissions caused by methane leaks during operation. EEOI is only focused on calculating the emissions from complete combustion of fuel onboard. In practice, methane leaks and methane slip are undetermined and must be calculated separately using common practices in calculating the amount of methane released to the atmosphere.

For the life cycle assessment period of 30 days operation has been chosen.
During their normal operational schedule M/S Star and M/S Megastar have 6 departures per day from Tallinn and Helsinki with the average voyage duration of 2 hours and 30 minutes, and travelled distance of 44 nautical miles.

For the assessment of CO_2 emission during the operational period of the ship the Energy Efficiency Operations Indicator (EEOI) calculating method has been chosen, as it is recommended and approved by the maritime organization. It provides a transparent and recognized approach to assessment of the greenhouse gas emissions of a ship. The calculation method is based on the data on fuel consumption taken from flow meters, log-books or any other official records such as bunker delivery notes.

Complete guidelines for calculating the ship's CO_2 emissions are provided in MEPC.1/Circ.684 „GUIDELINES FOR VOLUNTARY USE OF THE SHIP ENERGY EFFICIENCY OPERATIONAL INDICATOR (EEOI)". [23]

Calculation of CO2 emissions:

The basic expression for EEOI for a voyage is defined as:

(3.1)

$$EEOI = \frac{\sum_j FC_j * CFj}{m_{cargo} * D} \quad (3.1)$$

Where the average of the indicator for a period or for a number of voyages is obtained, the Indicator is calculated as:

$$Average\ EEOI = \frac{\sum_i \sum_j (FCij * CFj)}{\sum_i (mcargo_{,i} * Di)} \quad (3.2)$$

Where the average of the indicator for a period or for a number of voyages is allocated to Gross Tonnage, the Indicator is calculated as:

$$Average_{GT}\ EEOI = \frac{\sum_i \sum_j (FCij * CFj)}{\sum_i (GT * Di)} \quad (3.3)$$

Where:

- j fuel type
- i voyage number
- FC_{ij} mass of fuel consumed j on voyage i
- CF_j fuel mass to CO2 mass conversion factor for fuel j
- m_{cargo} cargo carried (tonnes) or work done (number of TEU or passengers) or gross tones for passenger ships
- D distance in nautical miles corresponding to the cargo carried or work done
- GT Gross Tonnage

Fuel mass to CO_2 mass conversion factors CF_j is an important factor when calculating CO_2 emissions from using different fuel types. The conversion factor is provided in the guidelines and describes the relationship between fuel consumed and CO_2 emitted.

Table 4.Conversion factors.

Type of fuel	**Reference**	**Carbon Content**	**CF (t-CO2/t-Fuel)**
Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
LNG		0.75	2.750000

Table 5. 30 days period operational data

Ship name	**LNG consumed (tonnes)**	**MGO consumed (tonnes)**	**LFO consumed (tonnes)**	**GT (tonnes)**	**Distance (nautical miles)**
Megastar	1260	33,2		49134	7948
Star			1634	36249	7948

Using the above formula we can calculate the ship's efficiency in terms of CO_2 emissions:

M/S Megastar CO_2 operational emissions:

$$EEOI = \frac{(1260*2,75)+(33,2*3,206)}{49134*7948} = 9,15 * 10^{-5}\ tonnes\ CO2/(GT*Nm)\ or\ 9,15\ g\text{-}CO2/(GT*Nm) \quad (3.4)$$

Total CO_2 emissions 3571 tonnes.

M/S Star CO_2 operational emissions:

$$EEOI = \frac{(1634*3,151)}{36249*7948} = 1,18 * 10^{-4}\ tonnes\ CO2/(GT*Nm)\ or\ 17,8\ g\text{-}CO2/(GT*Nm) \quad (3.5)$$

Total CO2 emissions 5418 tonnes.

In April 2020 Wärtsilä published the study on cutting greenhouse gas emissions from LNG engines, which has been mentioned earlier also in this study.

Wärtsilä declares, that their modern marine dual-fuel engine Wärtsilä 46DF has the methane slip of only 2.8g/kWh compared to 5.5g/kWh at the competitors methane slip. [25]

Based on this information we are able to calculate the methane slip from the engines. The average power consumption per one-way trip of M/S Megastar is 19000 kWh. [12]

$$\frac{19000 * 6 * 30}{2,8} * 1000000 = 1.2\ tonnes\ CH_4$$

(3.6)

Having LNG tanks with total capacity of 252 tons , M/S Megastar consumes 1260 tons of LNG monthly at density of 420 kg/m^3. This requires more frequent refuelling with LNG during port stays. Due to insufficient infrastructural development and difficulties until now LNG is delivered by tank trucks 16 times per month on average.

As has been mentioned earlier, due to LNG bunkering system design and safety requirements after completion of bunkering operation the bunker pipeline must be drained and purged by nitrogen to avoid any combustible materials inside. Therefore, residual methane, in gaseous state, is purged and released to the atmosphere via the ventilation mast.

The bunkering pipeline has dimensions of 0.15m in diameter, 30m in length and residual pressure at the end of bunkering operation is 0.3 barg.The volume is then 0.53 m^3. Using ideal gas law formula we are able to calculate number of moles and then mass of the gas.

$$PV = nRT$$

Where: (3.7)

- P – Pressure = 0.3 barg = **30 kPa**
- V – Volume = 0.53 m^3 = **530 L**
- T – Temperature = 20 C = **293.15 K**
- n – number of moles of the substance
- R – the ideal gas constant = **8.314 J/(mol*K)**

$$n = \frac{PV}{RT} = \frac{30 * 530}{8.314 * 293.15} = 6.52\ mol$$

(3.8)

Mass can be calculating using the next equation:

$$M = molar\ mass * moles = 16.04 * 11.687 = 104.6\ g$$

(3.9)

Thus taking into account the average monthly number of bunkering operations, 1673 grams of CH_4 is released directly to the atmosphere due to the ship's routine bunker operations. The best scenario is assumed, without taking into account any emergencies or unexceptional break downs during bunker operations.

Thus, we are able to calculate the unattendedly released methane as 1.2017 tonnes per month. The amount of methane can be normalized to the CO_2 equivalent unit using midpoint approach method by multiplying it 25 times. [3] Therefore 30.04 tonnes CO_2 equivalent emission is released. For Tank-to-Wheel CO_2 emissions inventory see Table 6.

Assessment does not include any methane released due to engine shut down caused, for example, by poor gas quality or technical issues as this amount is negligible and such conditions occur at irregular frequency and therefore qualitative data can't be collected.

Table 6. Tank-to-Wheel CO_2 inventory table

Tank-to-Wheel CO2 (ton) inventory table		
	Star	**Megastar**
Operation	5418	3571
Bunkering operation		0.4175
Unburned hydrocarbons (methane slip)		1.2
Total	**5418**	**3611**

3.3.3 General overview of Well-to-Tank Supply Chain and comments

Liquefied Natural Gas (LNG): The activity starts with the drilling of the wells. The activity ends upon the delivery of LNG to the final customer – M/S Megastar. It includes all the emissions related to the well drilling, exploration, extraction and treatment of the raw gas: flaring, venting, combusting gas in gas turbines, gas transportation via long distance onshore pipeline with average compression station to the liquefaction plant.

The liquefaction activity starts with reception of pipe gas at liquefaction plant and ends with the delivery of LNG to the tank trucks. LNG is delivered to Tallinn by tank trucks, assuming no boil-off gas is released to the atmosphere and only CO_2 from the vehicle is a by-product.

Light Fuel Oil (LFO): The activity starts with the drilling of the wells.

The activity ends upon the delivery of LNG to the final customer – M/S Megastar. It includes all the emissions related to the well drilling, exploration, extraction and treatment of the raw material, transportation via long distance onshore pipeline to the sea port when it’s transferred to a tanker.

The transportation activity starts with loading oil products on a tanker, delivering to a refinery and then transferring light fuel oil to the final customer – M/S Star.
The refining activity starts with oil products entering a petroleum refinery and ends with refined products leaving the refinery.

EcoInvent database contains data on the emissions with different reference units, for example kg/kg or kg/m3. As the oil density(ρ) of the fuels varies depending on the oil origin, content and temperature it has been assumed to take density value as ρ=980 kg/m3. Therefore, we get 1634 mt or 1684 m3 of Light Fuel Oil. These values have been used as reference values for calculating emissions.

Similarly to fuel oil, gas is changes it’ state from gaseous to liquid through LNG supply chain. As has been mentioned earlier LNG occupies 600 times less volume then gas. To be able to calculate emissions from gas production it is necessary to define the extracted gas volume (m^3).M/S Megastar consumes 1260 mt of LNG, which is equal to 756 000 m3 of gas.
Results:

- **329 468 kg CO_2** is released during Light Fuel Oil supply chain
- **429 468 kg CO_2** is released during Liquefied Natural Gas supply chain

Detailed GHG emissions overview by processes is indicated in Table 7 Appendix A3.1

RESULTS

The shares of total CO_2 emissions are presented in Figure 13.

The calculation results have shown that total CO_2 emissions from both vessels during the Well-to-Wake stage are 9785 tons.

M/S Megastar is responsible for 41.3% of total CO_2 amount emitted. 4040 tons of CO_2 is released monthly through the complete supply chain and ship's operation. In particular, burning LNG for propulsion contributes to the absolute majority of CO_2 released in the supply chain – 3611 tons of CO_2 emitted allocated to the operational stage of the LNG powered vessel. It is approximately 89% of the chain emissions.

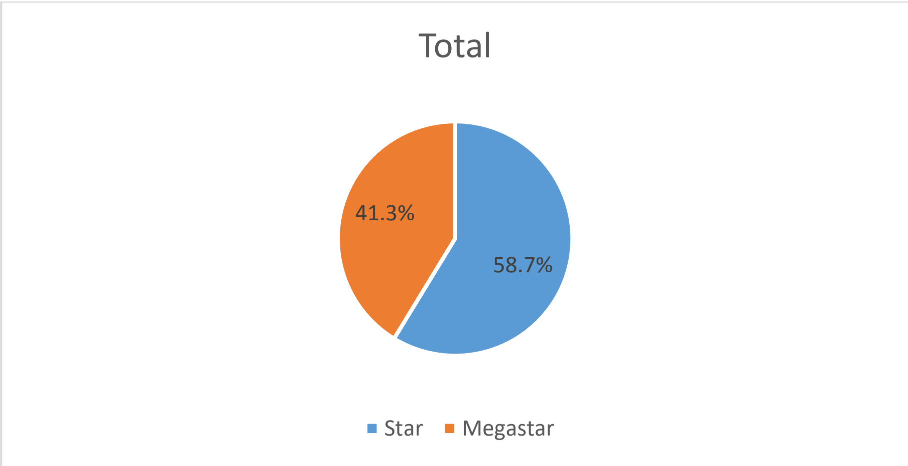


Figure 13. CO_2 emitted responsibility shares

M/S Star is therefore responsible for 58.7% of emissions with 5747 tons of CO_2 released to atmosphere monthly. Burning Light Fuel Oil for propulsion contributes to 94% of these emissions (Figure 14).

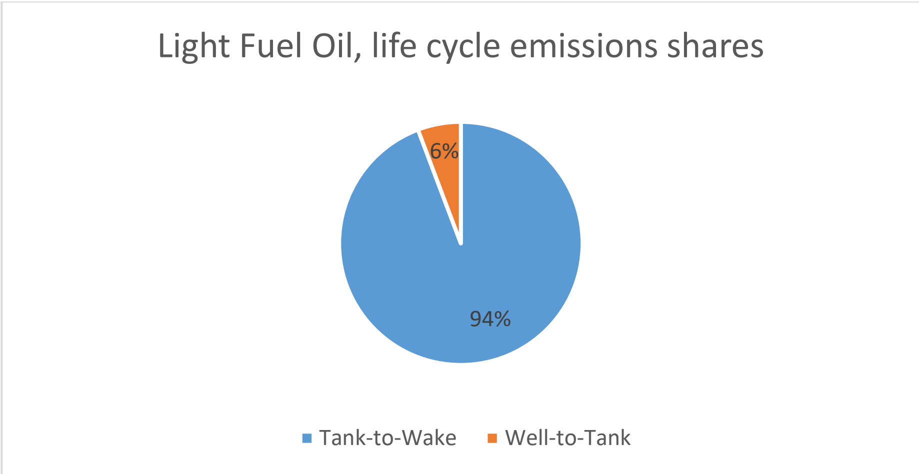


Figure 14. Light Fuel Oil life cycle emissions shares

Recent LCA studies on using LNG as marine fuel have shown, that there is very little or no advantage when using LNG as fuel. In particular, methane leakages and methane slip during Well-to-Tank stage has a significant impact on GWP, making LNG use nearly negligible from the environmental point of view. [9] [10]
However, in case of M/S Star and M/S Megastar, taking into account the real data on fuel supply chain and route specific conditions we can see an outstanding advantage of using LNG. At the operational stage M/S Megastar has 34.1% less CO_2 than M/S Star – 3571 tons against 4318 tons CO_2.

Taking into account the data from Wärtsilä Corporation on methane slip, frequency of operation and LNG system design this advantage is slightly reduced by 0.7% to 33.4% - 5418 tons and 3611 tons respectively (Figure 15).

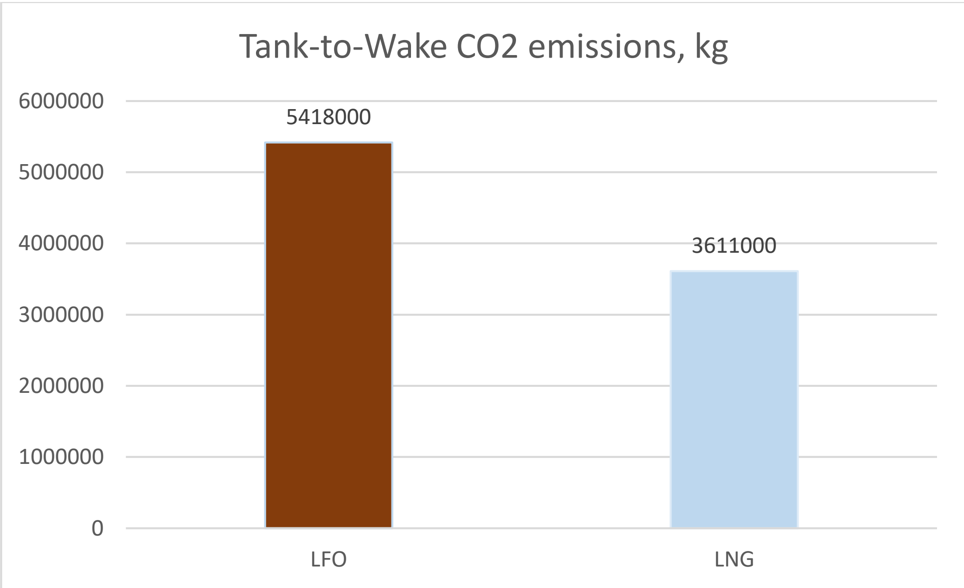


Figure 15. Tank-to-Wake emissions

Methane slip and emissions caused by leakages of methane during ship's normal operation are negligible at Tank-to-Wake stage.

However, within LNG supply chain methane leaks are a major emission part – nearly 75% of GHG emissions are caused by uncontrolled methane leaks. It is approximately 338 tons in CO_2 equivalent of total 452 tons (Figure 16).

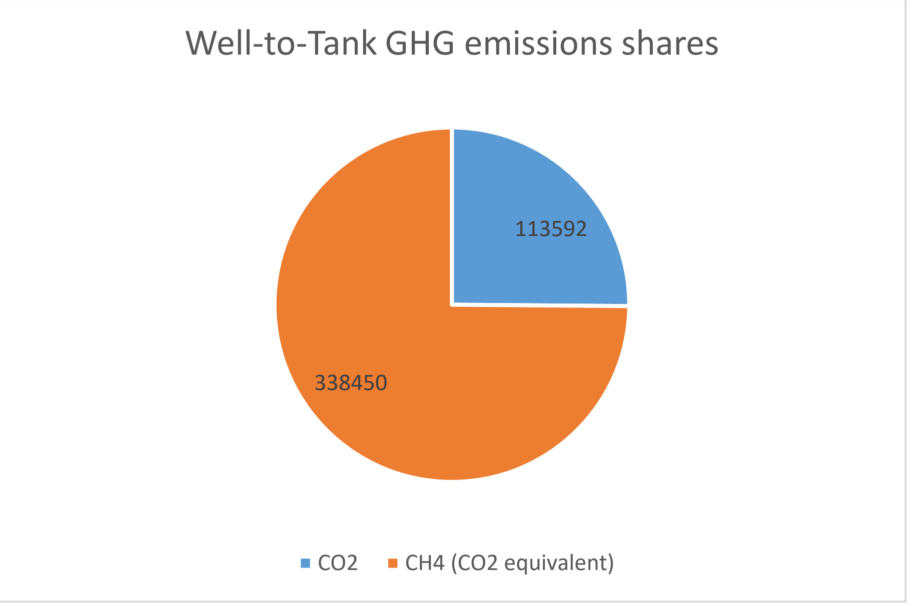


Figure 16. Well-to-Tank GHG emissions shares

General overview of GHG emissions during Well-to-Tank stage by processes is shown in Figure 17 and Figure 18.

As refining process is the most energy consuming process in the chain it is obvious that it is responsible for 96% of the CO_2 emissions within complete supply chain. Oil exctraction and transportation is responsible for another 4%.

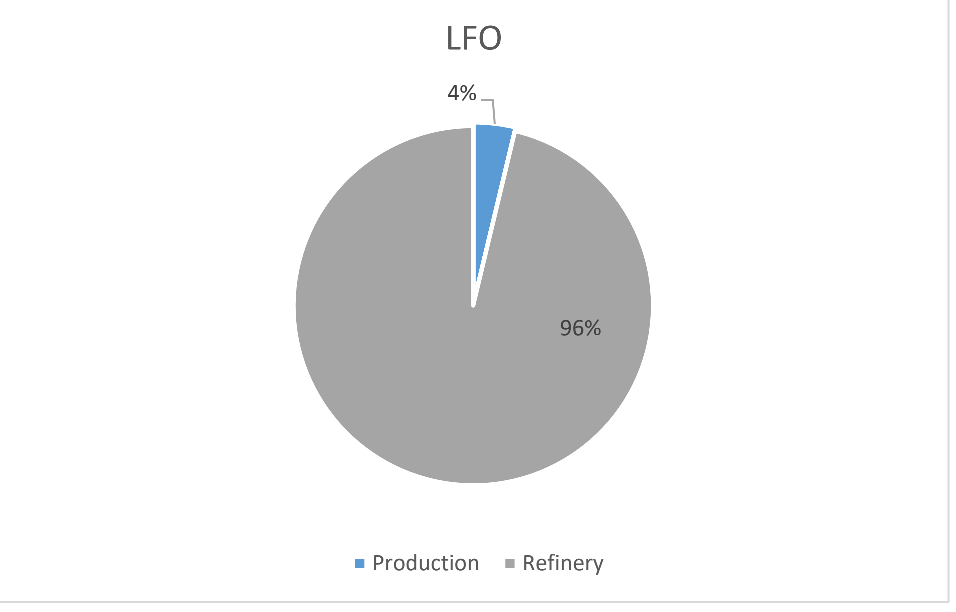


Figure 17. WtT GHG emissions shares by processes.LFO supply chain.

The calculation show that within LNG supply chain gas transportation via pipeline is responsible for the major part of CO_2 release. This can be explained with the distance of the pipeline (over 7000 km) and possible methane leaks from the pipeline and processes related to the transportation – such as methane release at the pump stations.

14% of GHG emitted is from drilling, exploration and extraction processes of the raw material – natural gas.

Residual 17% GHG emissions are caused by gas liquefaction process. Similarly to the LFO refinery process gas liquefaction is very energy consuming. Up to 10% of gas is consumed during liquefaction process by gas turbines. [2]

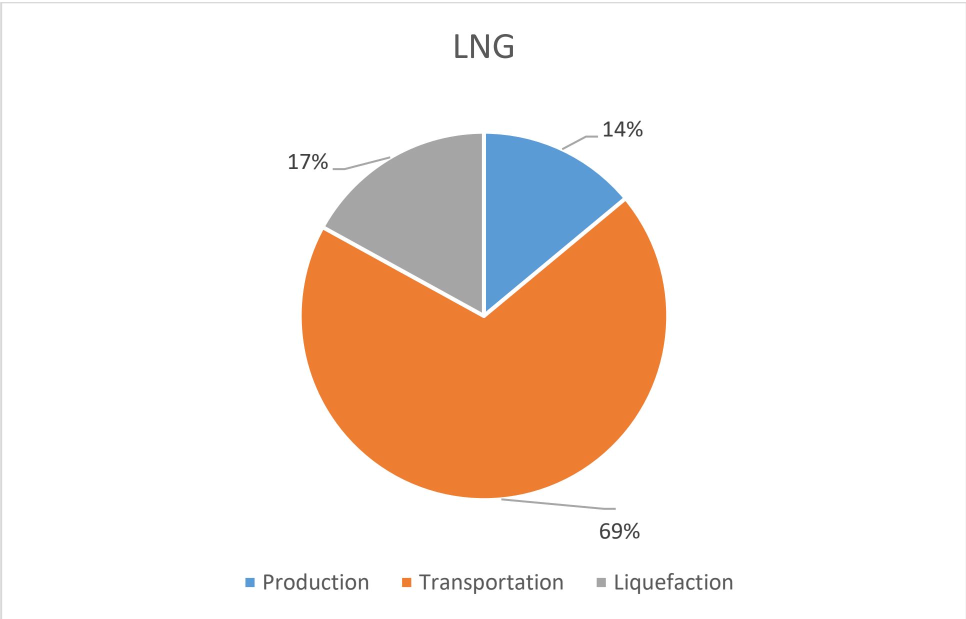


Figure 18. WtT GHG emissions shares by processes. LNG supply chain.

CONCLUSIONS

The research has revealed that despite Light Fuel Oil and Liquefied Natural Gas both meeting current environmental standards in shipping industry, the Green House Gas emissions have been found to be remarkably different. Generally, it is assumed that LNG as marine fuel contributes to 25% less CO_2 emissions compared to liquid fuels.

However, the study has shown that when specific conditions are considered, such as identical ship types compared, specific route conditions and regular fuel supply source – LNG has outstanding advantage over conventional fuels. In this research, the environmental impact of LNG has been confirmed to be significantly lower despite possible methane release during ship's routine operation – over 30% less CO_2 compared to traditional fuels.

The authors of "Life Cycle assessment of LNG Fuelled Vessel in Domestic Service" study have concluded, that despite obvious advantage when burning LNG onboard, methane slip reduces this advantage significantly. [10] Nevertheless, in current study methane release from operational stage has been calculated as well. Based on the calculations we can conclude, that methane slip from Dual-Fuel and amount of methane released due to bunker operations are extremely low – do not exceed 0,05% of total emissions at Tank-to-Wake stage.

In short, the study sustains the general opinion that LNG is a very good fuel source, having an outstanding advantage over Light Fuel Oil in the Baltic Sea Region despite relatively poor infrastructure. However, study does not allow to make any conclusion on using LNG as fuel on a global scale – separate studies must be conducted in each separate case based on actual data on technology used, route specific conditions and fuel supply chain.

SUMMARY

The research has been based on the actual data on ship's design, route conditions, technical solutions exploited, true fuel consumption and the valid fuel supply chain. Research has shown significantly better results on GHG emissions when using LNG, than it was expected.

Using LNG as a ship's fuel in the Baltic Sea Region has been proven as an excellent alternative to the Light Fuel Oil, despite possible drawbacks. Results of the environmental impact assessment have clearly indicated, that use of LNG contributes to over 40% less CO_2 emission over a complete life cycle (Well-to-Wake). Thereby, the results of the research study allow us to conclude, that LNG is highly recommended over other conventional fuel oils in the Baltic Sea region.

The main research finding can be summarized as follows:

- Using LNG as the main energy source for ship propulsion has been proven an effective way on the to reduce CO_2 emissions.
- Using LNG on Tallinn-Helsinki route has a strong impact on reducing local CO_2 emissions by 30% using Tank-to-Wake approach.
- Methane slip has been the main point of criticism of LNG. However, the research has shown, that methane slip and methane release from bunkering operation is negligibly small. In practice it does not withstand any criticism.

However, it is necessary to indicate, that there is still space to improve environmental indicators by developing engine technology, as well as reducing fuel consumption and reducing methane slip. Exhaust gas aftertreatment systems for gas engines can also be of considerable importance in reducing overall emissions.

Improving and optimizing the fuel supply chain (Well-to-Tank) will play an important role as well, as today approximately 69% of CO_2 emissions is contributed to transportation stage of gaseous fuel.

Moreover, possibility to use "green energy" within supply chain for liquefaction processes may be an option, instead of burning fossil fuels to cover energy demands. Biogas or bio-methane can also be considered as an alternative to the fossil LNG on the local scale. However, additional research is required for each case as biogas production technology is not advanced yet. Further development of biogas production technology is required to make it more efficient.

Another drawback of biogas as marine fuel is low methane content and therefore high knock probability – this requires further engine technology development.

The main conclusion drawn from the current thesis is that shipping industry in the Baltic Region is on the right way to development – using LNG as marine fuel already has a positive impact on GHG emission on the Baltic scale. The number of gas fueled vessels, as well as vessels powered by other alternative fuel sources will grow not only in the Baltic Region, but also globally as there is a global trend toward conventional fuels price increase. In addition, more stringent emissions standards are expected to be adopted by the states, making alternative fuel source more favorable than conventional fossil fuels.

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APPENDICES

Appendix 1 Table 7.Light Fuel and LNG Well-to-Tank supply chain GHG emissions inventory.

Name of process/material		LFO	LNG	Unit	TOTAL GHG EMISSIONS LFO	TOTAL GHG EMISSIONS LNG	NORMALIZED GHG EMISSIONS; LFO	NORMALIZED GHG EMISSIONS, LNG
	Resource use							
	LFO	1634		tonn				
	at 970 kg/m3 density	1684		m3				
	LNG		1260	tonn				
			756000	m3				
Emissions								
Exploration, production and processing		**LFO**	**LNG**		**kg**	**kg**	**kg, normalized**	**kg, normalized**
Emissions to air	Methane	Calculated as separate processes	0.0033413	kg/m3		2526		63150
	CO2	Calculated as separate processes	0.000004667	kg/m3		3,53		3,53
Transportation pipeline		**3000 km (Usinsk-Ust Luga)**	**7377 km(Urengoy-Pskov)**			**kg**		
Emissions to air	Methane	0	0.0019616	kg/m3*1000km		10939		273475
	CO2	2.7397E-06	2.7397E-06	kg/m3*km	13,8	15279	13,8	15279
Natural gas liquefaction								
Emissions to air	Methane	N/A	0,00005819	kg/kg		73		1825
	CO2	N/A	0.059488	kg/kg		74954		74954
LNG transportation by tank truck			**350km (Pskov-Tallinn)**					
Emissions to air	Methane	N/A	0			0		0
	CO2	N/A	0.057533	metric ton*km		1280		1280
LFO refinery process								
Emissions to air	Methane	0.0022933	N/A	kg/kg	32		800	
	CO2	0.1936	N/A	kg/kg	316353		316353	
Oil exctraction								
Emissions to air	Methane	0.0002	N/A	kg/kg	326		8150	
	CO2	0.00094	N/A	kg/kg	1535		1535	
LFO seatransport		166Nm/308km (Ust-Luga-Porvoo-Helsinki)						
Emissions to air	Methane	0	N/A					
	CO2	0.0050466	N/A	kg/metric ton*km	2617		2617	
						TOTAL CO2 kg	**329468,8**	**429966,53**