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TNO report

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Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands

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Managementuittreksel

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Summary

A study was conducted to investigate the environmental aspects, and to a lesser extent economic aspects, of using LNG (Liquefied Natural Gas) as a fuel for different types of ships. The study was supported by the Dutch Maritime Innovation Programme (MIP) and 12 industrial stakeholders.

The investigation was carried out as a case study for three different types of ships which have their base in Rotterdam, the Netherlands. The three evaluated cases are:
1) a short sea ship: an 800 TEU container feeder
2) a port ship: an 80 ton harbour tug
3) a 110 x 11.5 m inland ship

The environmental aspects include greenhouse gas (GHG) and air pollutant emissions. The GHG emission comparison included three LNG chains and three diesel fuel chains (HFO, MDO/MGO and EN590). In addition a limited economic analysis was done, comparing the potential fuel cost savings of LNG with the additional costs of LNG powered vessels. The LNG chains considered are:

- LNG from Peakshaver Rotterdam: Pipeline gas from the North Sea
- LNG supplied by LNG carrier from the Middle East (Qatar).
- LNG from Peakshaver Rotterdam: Pipeline gas from Russia (7000 km).

The last chain is not a realistic option for direct LNG supply to Rotterdam and is merely added for reference.

Greenhouse gas emissions
The greenhouse gas emissions evaluation includes CO_2, CH_4 and N_2O emissions (sum is indicated by CO_2equivalent). They are primarily dependent on the carbon content of the fuel and the efficiency of the propulsion engine. Since for the three cases the engine efficiency with LNG is only about 1% lower than for diesel, greenhouse gas emissions are simply expressed in g/MJ fuel energy. This is representative for the three cases. The results of the greenhouse gas emissions comparison of the five main fuel chains is shown in Figure 1.

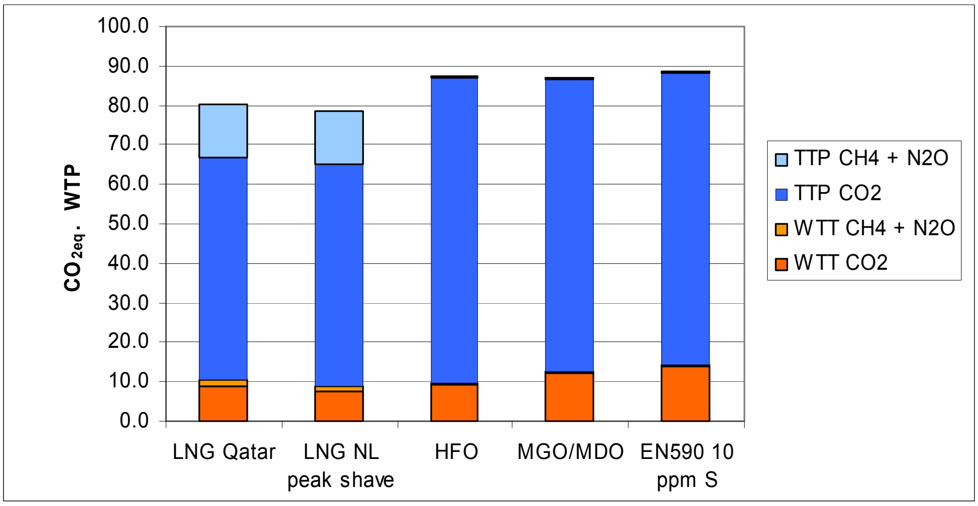
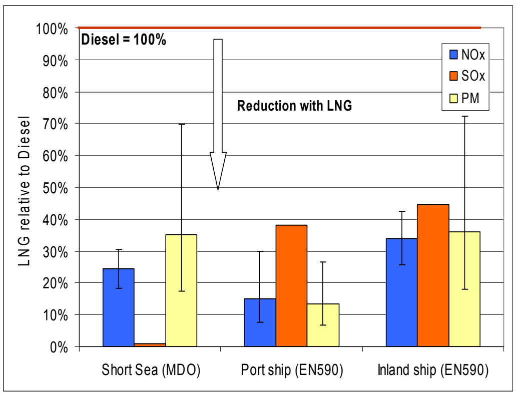
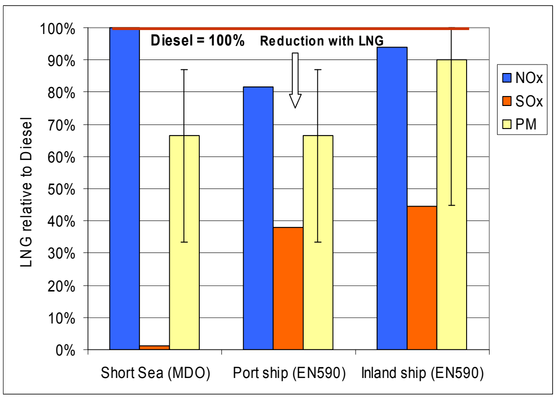


Figure 1. Overview annual Well To Propeller (WTP) GHG emissions [g CO_2eq/MJ] of the 5 most realistic LNG and diesel fuel chains, representative for the three application cases evaluated.

Air pollutant emissions
The comparison of air pollutant emissions included NOx, SOx and particulates (PM) emissions. It was done for different diesel engine types and diesel fuels reflecting the time frame 2011 to 2015 and for 2016 and later. For the latter, the diesel engines are equipped with emissions control devices in order to reduce NOx emissions by more than 75% which is necessary for Tier III (for sea ships) and the CCNR IV (for inland ships). This step also includes the use of MGO instead of MDO for sea ships, which implies that the emissions of the diesel engine (reference) are reduced. It should be noted that the use of HFO with on-board SOx abatement technologies using scrubber solutions have not been investigated as part of this study. The results are presented in Figure 2. For the 2011-2015 time frame, the reduction with LNG is about 60-85% for both NOx and PM. The SOx reduction is 99% for the short sea case. For the port and inland ships, the SOx is in absolute terms low for both LNG and diesel due to the use of low sulphur diesel fuel.



(a)



(b)

Figure 2. Comparison of annual Tank To Propeller (TTP) air pollutant emissions between diesel and LNG engines for 2011 – 2015 (a) and 2016 and later (b). The 3 selected application cases are shown. Diesel engines will be equipped with SCR deNOx catalyst for 2016 and later.

Economic aspects
The cost of an LNG engine plus LNG fuel tank system is about twice as high as a diesel engine plus fuel tank. Also the physical installation of the LNG fuel tank on board of a ship can be an issue - especially application on the tug is critical. Additional costs of SCR catalysts necessary for diesel engines in 2016 and later represent only 25% of the additional costs of the LNG fuel system plus storage. A comparison of LNG with HFO diesel plus SOx scrubber and fuel treatment was not included in this study.
The economic case for LNG comes from a lower LNG energy price compared to the price of MDO, MGO or EN590 in order to earn back the additional investment.
A detailed evaluation of future LNG fuel prices was outside of the project's scope.

Conclusions
The case study led to the following conclusions:

- Well-to-Propeller (WTP) greenhouse gas emissions with the most logical LNG chains are about 10% lower than the diesel fuel chains. Further improvement is possible by lowering the relatively high methane (CH_4) emissions of the engines (see Figure 1).

- Replacement of diesel fuel with LNG for the maritime sector offers large advantages in air pollutant emissions, and it will probably already today meet the requirements of Tier III and CCNR IV, which will enter into force in 2016. Incomplete information leads to uncertainties though (see Figure 2a).

- After 2016, when compared to Tier III /CCNR IV-compliant diesel fuelled engines, LNG will still offers benefits in the area of PM, SO_x, and CO_2 Well-to-Propeller. The benefits in NOx emissions performance will however become smaller (see Figure 2b).

- Further greenhouse gas emission reductions for both LNG and diesel are possible by using biofuels. LNG can be replaced by bio-LNG or LBG (Liquefied Bio Gas), without any impact on maintenance. Diesel can be replaced by biodiesel, HVO (Hydrotreated Vegetable Oil), PPO (Pure Plant Oil) or possibly even pyrolysis liquid, but these fuels may require engine adaptations and increase maintenance.

- Application of LNG is economically viable if the fuel price is low enough to compensate for the additional costs of the LNG fuel storage system. The cost of an LNG engine plus fuel tank is about twice as high as a diesel engine plus fuel tank. Under the assumptions made in this study, short sea (from 2016) and inland shipping (already now) seem to offer an attractive case, with realistic LNG price discounts of 2.5 EUR/MMBTU and 2.1 EUR/MMBTU below prices of diesel fuel, respectively, for payback within 10 years, and 4.4 EUR/MMBTU and 3.9 EUR/MMBTU below diesel fuel for payback within 5 years.
  With the current conventional design, the harbour vessel (tug) would require a much longer payback time or a very large LNG price discount in comparison with diesel (10.3 EUR for a payback in 10 years). However, the tug case is expected to benefit from a hybrid-electric type propulsion system.

Recommendations
Since the obtained engine emissions data did not fit well the load pattern, especially for the tug application, it is recommended to measure or obtain more detailed (real-world) emissions data. Precise NO_x and methane (CH_4) emissions data is especially necessary.

Other recommendations are:
- To investigate potential for improvement of CH_4 emissions from engines
- To study options for lower cost LNG tanks, such as with alternative insulation and/or atmospheric (rather than pressurised) configuration.
- Specifically for tugs (harbour ships), follow-up work could explore hybrid drive systems[1], which may reduce energy consumption and also reduce costs of LNG storage and engines making the LNG application more attractive.

[1] See for example [Offshore 2010] and [SMIT E3 Tug]

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1 Introduction

1.1 Background

Traditionally, natural gas has been liquefied only to transport it to the markets, where it is distributed as natural gas after regasifying. For over forty years LNG has been shipped by carriers with large cargo volumes from liquefaction plants that have been constructed in regions with large natural gas reserves and less local demand.

With its relatively high energy density, LNG is a very suitable fuel for transport over long distances. Using LNG as a clean shipping fuel fits with the aim of making ports, inland waterways and short-sea shipping as well as ferrying and fishing more sustainable. Until now, the use of LNG as a transport fuel is limited, this mainly being due to the relatively expensive infrastructure such as cryogenic tanks. Never the less several transportation companies and gas suppliers in the Netherlands are currently investing in road transportation with LNG trucks. Primary reasons for using LNG are the lower noise and pollutant emissions levels of the trucks. With respect to ships, in Norway a number of ferries, offshore supply vessels and navy vessels are equipped with LNG engines. Furthermore ship owners/operators in the Baltic Sea are evaluating use of LNG as marine fuel for different vessels. LNG tankers are then also required to ship LNG from large terminals to break bulk terminals.

Already within the EU the maximum level of sulphur in ship fuels used in ports and on inland waterways is 0.001%. In Emission Control Areas (ECAs) the maximum level of sulphur in fuel is set at 1.0%, and the requirements will be further tightened to 0.1% in 2015. It is expected that the use of LNG as an alternative to low sulphur gasoil or scrubbers will be more cost effective. Technically there are no obstacles, and while the small scale LNG supply chain is being completed it can count on various outlets such as trucks, trains and even stationary customers such as decentralised power plants.

Besides the potential of being a cleaner fuel, the global importance of LNG will grow as oil is getting scarcer and locally produced gas does not fulfil demand anymore. This is also the case for the Netherlands - after producing the Groningen gas field for almost fifty years, in Rotterdam the Gate LNG regasification terminal is being constructed in what will be the first step of entering imported LNG into the gas grid of the Netherlands.

As the traditional LNG infrastructure comes into place the possibility of connecting to a small scale supply chain to provide LNG as a fuel comes into the picture. Using the existing infrastructure from Gate or the Gasunie Peakshaver, connecting to a small scale supply chain should be less expensive, and that would make the use of LNG as a fuel for transport economically feasible.

Of course Rotterdam, being the gateway to Northwest Europe, is a perfect location for introduction of LNG as a fuel for heavy transportation. From Rotterdam goods find their way to almost 500 million Europeans by inland vessel, truck, train or coaster, with the option to use LNG as fuel. The establishment of a small scale LNG supply chain also fits into the ambition of Rotterdam as being the sustainable energy port, as well as the gas roundabout policy of the Dutch government. The transition to LNG fuel will also have an economic incentive for maritime equipment suppliers and service providers and will challenge the local technological knowledge base for new product developments.

Given this context, the claim of LNG being a cleaner fuel needs to be analysed by independently covering every step from oil and gas production, refinery or liquefaction, transport and storage to the actual combustion in a ship engine - what is known as a 'well-to-propeller' energy chain. In addition to that, this project briefly touches upon the economic effect on the shipping costs of LNG versus Diesel fuel.

This project is part of a shared vision of TNO, the Maritiem Innovatie Programma (MIP) and a large number of sector stakeholders: remove innovation barriers that are being observed by entrepreneurs which are establishing the LNG chain, such as lack of legislation, unknown permit conditions and absence of a knowledge base for safety with LNG technology.

Evaluating the *potential emission reduction of LNG as fuel for shipping is only an important first step.* While LNG is in the picture as a transport fuel for both suppliers and end users in the chain, there is yet to be a breakthrough. With the increasing possibilities to transfer LNG from traditional LNG supply routes to smaller quantities, the supply of LNG as fuel will no longer be an obstacle in the near future. However, one key obstacle to establishing an economically feasible logistical chain is the issue of who commits to the first extra measures that have to be taken. By performing this kind of projects collectively in the form of Joint Industry Projects (JIP), the required effort to take these extra measures is strongly reduced.

The results of this project can be applied for knowledge transfer and establishment of individual business cases. To have a complete picture though, a clear overview must be gained of the required links in the fuel infrastructure, such as delivery and receipt of LNG from bunker ships, land-based or on-board storage and transfer systems as well as systems for propulsion and storage on board receiving ships.

1.2 Stakeholders

A large group of stakeholders participated in the project. The group covers the whole range of stakeholders for the small scale LNG supply chain and the use of LNG as fuel for shipping. The following organizations participated in the project:

- Port of Rotterdam:
  Participating in this project fits in the port's ambition of environmental sustainability. The Port of Rotterdam plays an important role in identifying suitable locations for the small scale supply infrastructure and to ensure the safety of port operations such as LNG bunkering.

- Fuel suppliers, facilitators and energy companies (Shell, Argos, GdF-Cofeley, Gasunie, Vopak and Dong Energy) will play an important role in the establishment of the small scale LNG supply chain. These companies have to decide whether or not to invest in this new infrastructure. This will also directly influence their current business.

- Ship and engine producers:
  Marine contractors, designers and engine suppliers (Pon Power, Wärtsilä, Rolls-Royce, GE Jenbacher) are involved in the development and manufacturing of the gas-fueled propulsion systems of the ships.

- Ship operators:
  Anthony Veder is involved in relatively small scale LNG distribution in Norway, SMIT is a large, internationally operating, tug service provider.

The stakeholders provided the following type of information to the project:
- Information on standard load patterns, engine efficiencies and emissions was supplied by Damen Shipyards, SMIT, GE Jenbacher, PON, Rolls Royce and Wärtsilä. The last 4 (engine suppliers) also provided information on engine costs.
- Information on fuel costs was provided by Shell, Gasunie, Gate and VOPAK.

The precise cases and fuels to be included in the project were defined in the kick off meeting with the involvement of almost all the project participants.

1.3 Objective and activities

The objective of this project is to make an environmental and economic comparison of diesel fuel and LNG for sea ships and inland ships. The environmental comparison includes a well-to-propeller (WTP) comparison of greenhouse gas emissions (CO_2, N_2O en CH_4) and a tank-to-propeller (TTP) comparison of air quality related emissions (NOx, SOx and particulate matter).

The following activities were performed:
- Choice of applications (‘cases’) and fuel chains, including a short summary of application options in the Netherlands.
- Well-to-propeller greenhouse gas emission (CO_2, CH_4 and N_2O) with an emphasis on the performance of the various engine types in relation to the applications.
- Tank-to-propeller emissions for air quality (NOx, SOx and particulate-matter).
- Economic aspects, focused on an analysis of the consumption of LNG in relation to diesel for the various applications and, where relevant, for various engine types.

A more detailed description of the activities can be found in chapter 2. The main results are presented in chapter 3, followed by a discussion (4), conclusions (5) and recommendations (6).

2 Method

2.1 Description of selected cases

For a good understanding of the impact of LNG as fuel, a distinction is made between three different applications (cases): Short sea, Port ship, and Inland ship. The precise cases were defined in consultation with the stakeholders during the kick-off meeting. The reference diesel fuel is chosen in line with the developments in fuel specification requirements. The IMO Marpol legislation calls for max 1% sulphur in Sulphur Emission Control Areas (SECA) starting in 2010 (to be further reduces to 0.10% in 2015). For non-road engines European legislation requires max 10 ppm S starting in 2011. For inland shipping, in practice EN590 with S < 10ppm will be used, since the oil producers have this fuel available in large quantities for road transportation. This also means that the fuel can contain up to 7% biodiesel[2].

Table 1 contains an overview of the cases.

Table 1: Cases (applications) defined for LNG study

Application	Specification of ship and engine	Specification for refuelling	Diesel fuel 2011 - 2015	Diesel fuel 2015/2016 →
Short sea	Container f. 800 TEU	Several places - 15-20 day autonomy required (50% of autonomy with diesel)	MDO S < 1.00 %	MGO S < 0.10 %
	8400 kW @ 500rpm			
Port ship	tug 80 ton	Rotterdam	EN590 S < 10 ppm	EN590 S < 10 ppm
	2 x 2500 kW @ 1000rpm			
Inland ship	110 m 11,45m	Rotterdam bunkering	EN590 S < 10 ppm	EN590 S < 10 ppm
	1125 kW @ 1300rpm	Ludwigshafen return trip on 1 tank: 575km		

The following LNG chains were considered in the comparison with diesel fuels:
- LNG from Peakshaver Rotterdam: Pipeline gas from North Sea
- LNG from Peakshaver Rotterdam: Pipeline gas from Russia (7000 km)
- LNG supplied as LNG, by tanker ship from the Middle East (Qatar).

[2] It has been agreed between fuel suppliers and branch organisations (NOVE, CBRB, VIV, Scheepsbouw Nederland) to supply fuel without biodiesel for the year 2011.

2.2 Project activities

2.2.1 Greenhouse gas emission calculations

The following GHG emissions are addressed for both WTT and TTP:

- CO_2 emissions: CO_2 from a) energy usage during the production and transports of the fuel and b) the combustion of the fuel by the ship engines
- Other GHG gases composed of CH_4 (methane) and N_2O (nitrous oxide) emissions during production/transports of the fuel and during the combustion by the ship engines.

These are considered to be the three main greenhouse gas emissions. They are summed up as a total CO_2 equivalent (CO_{2eq}). CH_4 and N_2O emissions weigh much more heavily than CO_2 emission for global warming. As a result CH_4 needs to be multiplied by 25 and N_2O by a factor of 298 in order to obtain the CO_2 equivalent for global warming [source: IPCC].

The emissions from WTT (Well To Tank) and TTP (Tank To Propeller) are both expressed in gram per MJ fuel energy and are then summed up:

$$CO_{2eq}/MJ = (CO_{2eq}/MJ)_{WTT} + (CO_{2eq}/MJ)_{TTP} \quad (1)$$

If there is a significant difference in engine efficiency with different fuels, engine efficiency or the MJ of fuel energy needed for the standard load pattern should be taken into account. The LNG chain can be directly compared with the diesel chain by applying the following correction to equation (1):

$$[CO_{2eq}/MJ]_{LNG\ corrected} = \frac{[(CO_{2eq}/MJ)_{WTT} + (CO_{2eq}/MJ)_{TTP}] \times MJ_{LNG}}{MJ_{diesel}} \quad (2)$$

This should be done for each case, if there is a significant difference in engine efficiency.

2.2.1.1 TTP analysis

The CO_2 emissions are directly linked to the H-C ratio of the fuel. The more energy is derived from oxidation of H to H_2O rather than oxidation of C to CO_2, the lower the specific CO_2 emission expressed in gram per MJ fuel energy combusted (g/MJ).
In addition to this CH_4 (methane) and N_2O emissions are obtained or estimated and multiplied by their global warming factor of respectively 25 and 298.

2.2.2 Air pollutant emissions

The air pollutant emissions of the ships are addressed from a Tank To Propeller perspective. The following emissions were evaluated:

- Nitrogen oxide: NOx
- Sulphur oxide: H_2SO_x
- Particulate Matter (or Particulate Mass): PM

SOx can be split up in SO_2, which is gaseous and H_2SO_4 or sulphate which is a part of the PM. H_2SO_4 is hygroscopic. As a result of that, the PM weight then also grows because of adsorbed H_2O.

Non Methane Hydrocarbons (also referred to as Volatile Organic Components, VOC) and carbon monoxide (CO) are not addressed, because those emissions are more than an order of magnitude smaller than NOx and are considered less harmful for several reasons. Firstly the ambient concentrations of only NOx and PM are close to and sometimes surpass the European limit values. Furthermore the air pollutant external costs (estimates of negative impacts to society) of NOx, PM and SOx are much higher than for NMVOC (Non Methane VOC). Air pollutant costs include health costs, building damage, agriculture costs (crop damage) and costs for loss of biodiversity. In [Maibach 2008] the following numbers are given (reference year 2000):

- NOx: 6600 EUR/tonne
- PM: 422,500 EUR/tonne
- SOx: 13000 EUR/tonne
- NMVOC: 1900 EUR/tonne

Typical NOx (and in case of HFO also SOx) mass emissions are a factor 10-100 higher than PM and NMVOC emissions. This makes NOx as costly as PM in practise and NMVOC relatively less important.

The following method was primarily used to evaluate the air pollutant emissions:

- The ship operators were asked to provide the usage pattern of the ship including 4 to 5 characteristic engine operating points. Other load points or transient operating conditions are not expected to play a significant role in the emissions evaluation.
- The engine manufacturers were asked to provide the emissions data (primarily NOx and PM) for these characteristic load points.
- SOx emissions were calculated from the fuel sulphur content.

2.2.3 *Economic comparison of LNG vs Diesel, based on fuel and on-board equipment costs*

Simple calculations were carried out based on figures provided by project participants and, where needed, expert opinion and brief market consultations. The comparison focused on the fuel costs and on board equipment costs (mainly engine, aftertreatment and fuel storage system). For the diesel engines for the year 2016 and later, the estimated costs of an SCR aftertreatment system were included.

Although an evaluation of future LNG fuel prices was outside of the project's scope, it is not expected that long term LNG prices will increase at a higher rate than crude/oil prices.

Operational costs (maintenance, repair) were judged to be equivalent for both fuels based on feedback of the engine manufacturers and hence not included. After a brief consultation, it was also decided not to include potential reductions in fees and incentives offered by the Port of Rotterdam/inland shipping authorities for LNG (e.g. ESI, Green award) – while these can amount to 5-10% in some cases, their timing and application is complex. Other costs which lie outside the scope of this project were not considered, such as Safety, Education, PR. Since they are relevant for widespread use of LNG in shipping, it is recommended that they are looked at in follow-up projects.

3 Results

This chapter describes the 6 selected fuel production pathways and their Well To Tank (WTT), Tank To Propeller (TTP) and Well To Propeller (WTP) emissions. All pathways are chosen for the Dutch situation, *i.e.* all fuels are delivered and used in The Netherlands.

For LNG, the following Well to Tank pathways were defined:

- LNG 1 transition path:
  For this LNG pathway LNG from Qatar is transported over 10000 km by vessel to Rotterdam, Gate terminal. From there it is transported as a liquid to a breaker bulk terminal which can either be near the Gate terminal or this can be combined with the peakshaver.
- LNG 2 transition path:
  For this LNG pathway Dutch natural gas from the North Sea or Slochteren is transported to and liquefied in Rotterdam at the peakshaver. At the same location a breaker bulk terminal to load ships is realised.
- LNG 3 transition path:
  For this LNG pathway Russian natural gas from Siberia is transported over 7000 km by pipeline to Rotterdam and liquefied in the peakshaver. At the same location a breaker bulk terminal to load ships is realised.

The LNG pathways are compared to three liquid fuel pathways, namely: HFO, MDO/MGO and EN590 low sulphur diesel.

3.1 Well To Tank energy analysis

The determination of the required energy for production of a fuel is a very complex task because fuel sources and refineries are very different and the allocation of certain energy quantities to products is based on several assumptions. In this study for LNG three very different but realistic pathways are chosen. The diesel, MDO/MGO and HFO pathways are related because they are products of one refinery which is a state of the art production plant in The Netherlands.

3.1.1 Introduction LNG

Natural gas as recovered from the underground contains mainly methane (CH_4), but it also contains heavier gaseous hydrocarbons such as ethane (C_2H_6), propane (C_3H_8), butane ($C4H_{10}$) and sometimes pentane (C_5H_{12}). Some other heavier hydrocarbons are removed prior to liquefaction. Other gases such as carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S) and water are also often present. At the liquefaction process all CO_2, H_2S, water and heavier hydrocarbons (C_{5+}) are removed. Natural gas contains small amounts of helium too, and is the main source of helium production. Small amounts of mercury may also be present. The exact composition varies from one field to another.
The methane content of LNG is typically 70-90 %, ethane 5-15 %, propane and butane up to 5%. Water, CO_2, sulphur compounds, heavy HCs and mercury (if present) must be removed before liquefaction.
So the treatment before liquefaction of the LNG depends on the composition of the natural gas as well as presence of LPG extraction facilities and for each type of natural gas the treatment can differ.

In Appendix A, a list of typical LNG compositions is reported [GIIGNL 2009].

3.1.2 Production and delivery of LNG

The principal steps and transitions from well to tank for LNG are:

1. Production of the natural gas
2. Treatment [Groen 2010], [Kohl 1997], [Butts 1995], [Howard 1998]
   - Condensate removal
   - CO_2 removal
   - Dehydration
   - Mercury removal
   - Potentially LPG extraction
   - H_2S removal
3. Transportation
4. Refrigeration and liquefaction
   -During liquefaction a lot of the components (*i.e.* O_2 and N_2) with a lower liquefaction temperature than methane will be removed.
5. Storage and loading
   -When boiling of LNG occurs during storage the extracted vapour is mainly gaseous methane and nitrogen.
6. Bulk Transportation in large LNG carriers
7. Storage in regas terminal
7. Secondary LNG distribution
8. Tank filling

3.1.3 Energy content of LNG

The caloric value of LNG depends on the type of mixture and the method of production which is considered. When a well to tank analysis is performed the amount of energy which is used to produce the "tank product" has to be taken into account.

To make it more complicated for a calculation: sometimes in the modern processes the heavier hydrocarbons will be (partly) removed from the natural gas (*e.g.* for LPG production) whereby the energy content per kg of the LNG decreases, the energy for production increases and an additional energy line exists.

Examples/facts Higher Calorific Value [GIIGNL 2009]:

LNG Algeria	54,1 MJ/kg
LNG Indonesia	54,5 MJ/kg
LNG Egypt	55,2 MJ/kg
Yemen	50,1 MJ/kg

An overview of LNG specification from sources around the world is presented in Appendix A.

3.1.4 Situation for LNG usage in The Netherlands

LNG can currently be bought in Norway, Spain, Belgium, France, Italy and the UK (depending on whether it will be re-exported by truck or small LNG carrier) but for the scope of this project the best assumption is probably to focus on the type of LNG which could be delivered at the Gate terminal because this will soon be the most obvious landing spot for LNG for use in the Netherlands.

Basically for Gate-LNG the basic NG composition at the well is unknown and its composition after cleaning too. Subsequently, the origin of the LNG delivered to the Gate terminal is unknown and therefore so is the transport distance.

3.1.5 Assumptions for the energy footprint of LNG

In the production and delivery of LNG three main issues determine the energy footprint:
1. Composition of the natural gas at the well.
2. Applied liquefaction process.
3. Distance of transportation.

Although the origin of the gas is unknown, in energy sense a best, mean or poor situation can be defined for any of these 3 issues. This basically leads to a 3 dimensional matrix of combinations, where each element must be filled with the required amount of energy.

Liquefaction is the process which costs the most energy. There are many different processes and there is significant research on that item at the moment. Still most liquefaction plants are of the pre-cooled mixed refrigerant type (C3 precooled MR) [Barclay 2005].

For the Qatar case, LNG production in Qatar and transport to Gate Rotterdam, the following steps are evaluated:

1. Production
Circumstances in the Middle East are quite favourable. Installations are land based and the composition of the gas from the well is quite good with limited amount of CO_2 and N_2. Consequently 1.2% energy consumption is estimated for the production process.

2. Purification
The following gas composition was taken for purification: 5-15% CO_2 + N_2, 1-3% H_2S and 1-3% water. Applying a conservative calculation, it was calculated that about 640 kJ is needed per kg of gas.

3 Liquefaction
In Qatar, the pre-cooled mixed refrigerant type (C3 precooled MR) is used. This is relatively well described [Barclay 2005]. The energy consumption is about 3700 kJ/kg.

4. Transportation
The energy consumption due to heat input from the ambient during transportation is much larger than energy needed to move the ship. To maintain cryogenic temperatures some LNG is continuously vaporised. A part of it can be used by the engines. With the newest ships, the vaporised LNG is however re-liquefied and added to the stored LNG again. For this case (transport from Qatar to Rotterdam), a relatively new ship is chosen with a ratio between energy needed for cooling and for the engines of a factor of seven. In combination with the transportation distance via the Suez Canal of about 10,000 km, this resulted in an energy consumption of 2140 kJ/kg LNG.

5. Terminal
The energy footprint here consists of the energy needed for off-loading from the ship and the heat input during storage at the Gate terminal. Gate is a terminal with high throughput since the majority of the gas is vaporised and added to the pipeline

infrastructure. So energy consumption for heat input during storage is small. Consequently for this case, a relative low value within the range specified by Shell was chosen.

6. Distribution
For the distribution from the Gate terminal to the ships, there are several options. The first option is a pipeline of 3 km from the gate terminal to the peakshaver LNG storage facility with a ship bunkering facility at the peakshaver. The second option is a breaking terminal at Gate to lead bunker ships. The energy consumption and CO_2 emission is not analysed in detail. Instead 50% is used of the estimation form ECN/JRC for distribution for road transportation. Bunkering of ships should be more efficient due to the much larger quantities.

An overview of the Well to Tank (WTT) energy consumption is presented in Table 2. The values are given in kJ/kg and in kJ/MJ. For the latter the energy content of LNG of 49 MJ per kg is used.
In Table 3, the results are compared to typical ranges used by the LNG industry depending on the natural gas source, the process equipment used and the transportation distances. It can be seen that the calculated values of this study are within this range.

Table 2: WTT energy consumption for different LNG pathways, mass based and energy based

	Qatar, Qatar to Rotterdam	
	[kJ/kg]	[kJ/MJ]
Production	600	12.2
Purification	640	13.1
Liquefaction	3700	75.5
Transport	2142	43.7
Terminal	270	5.5
Distribution	525	11

Table 3: WTT energy consumption for different LNG pathways, energy based

	Qatar	typical - range
	[kJ/MJ]	[kJ/MJ]
Production	12.2	10-40
Purification	13.1	70 - 110
Liquefaction	75.5	
Transport	43.7	5 - 60
Terminal	5.5	5 - 15
Distribution	11	

3.2 Well To Tank emissions analysis

3.2.1 CO_2 emissions

LNG Qatar – Rotterdam
In Table 4, an overview of the CO_2 emissions is given for the WTT part. The CO_2 emission in g/MJ is calculated using a specific CO_2 emission of 56 g/MJ. This is

assuming that all energy needed is coming from natural gas with high methane content. Possible direct CO_2 emission from the purification is not taken into account. This is not necessary when the associated CO_2 is re-injected in the field or used for another purpose.
The calculated results are compared with those of the ECN and JRC studies [Kroon 2008] and [JRC 2007]. It can be seen that the values compare reasonably well, except for the CO_2 value for transportation and distribution where ECN and JRC indicate a factor of two higher. For distribution this was an assumption of this study since the relative energy needed for bunkering ships is lower that for supplying LNG to trucks.

Table 4: WTT CO_2 emission: LNG supply to ships, comparison with ECN/JRC

	Qatar	**ECN / JRC**
	[g/MJ]	**[g/MJ]**
Production	0.7	1.2
Purification	0.7	4.7
Liquefaction	4.2	
Transport	2.5	5.5
Terminal	0.3	0.7
Distribution	0.6	1.2*
Total	**9.0**	**13.3***

* CO_2 emission of LNG supply for road transportation

LNG peakshaver: NG from North Sea or Russia via pipeline
Energy consumption and CO_2 emission of the pipeline transport of about 7000 km from Russia vary strongly depending on the reference: [Kroon 2008] gives for the transport a range from 6% to about 20% for the energy consumption. Corresponding CO_2 emission would range from 3.4 to 10.2 g/MJ. The latter value was chosen, and also used here.
For the liquefaction of the peakshaver a 20% higher energy consumption and CO_2 emission is used, because of the small scale installation compared to a typical large scale installation such as in Qatar. The values are given in Table 5 below.

Table 5: WTT CO_2 (only) emission for different LNG pathways for ships

	LNG Qatar	**LNG NL peakshaver**	**LNG NL peakshaver gas pipeline 7000 km**
Production	0.7	0.7	0.7
Transport gas	-	0.5	10.2
Purification	0.7	0.7	0.7
Liquefaction	4.2	5.0	5.0
Transport LNG	2.5	-	-
Terminal	0.3	-	-
Distribution	0.6	0.6	0.6
Total	**9.0**	**7.5**	**17.2**

3.2.2 Methane emissions

Methane (CH_4) emissions can often be avoided by good design of the systems used. For example at the production well, some unusable methane or leaked methane can always be flared and does not need to escape as methane. Of course when flared it still contributes to greenhouse gas emission, but it is not multiplied by the factor of 25 for methane emission. The LNG engines used for transportation probably do emit some 2 to 3% of the fuel used as methane. This is primarily caused by the lean burn operating principal of the engines and is hard to avoid. At the distribution part of the chain some methane emission is possible during the filling of tanks. Careful design with very small dead volumes of filling nozzles and such could avoid this to a large extent, but this is not always the case.

LNG Qatar – Rotterdam
The following methane emissions are used:

Production:
Different sources give a large range. According to the national emission registration is it 0.007 g/MJ, while JRC gives a value of 0.09 g/MJ. Experts find the high values unrealistic, so the 0.007 g/MJ is used here.

Purification / liquefaction:
The value provided by the JRC study of 0.04 g/MJ is used here.

Transport / shipping:
Based on the energy consumption of the ships of 44 kJ per MJ of LNG and a specific methane emission of the engines from 2-3% the methane emission is about 0.02 g per MJ of LNG transported. This value is used.

Terminal:
Due to large quantities which are pumped, no significant methane emission will occur: 0 g/MJ is used.

Distribution:
A leakage of 0.5 kg methane per 100 m^3 LNG bunkered is equivalent to 0.0002 g methane per MJ. So even a 10x larger leakage (for example when disconnecting the filling nozzle) would be negligible. Consequently 0 g/MJ is used.

The methane emissions are summarized in the table below.

Table 6: WTT methane emission from LNG supply from Qatar to Rotterdam for ships

	Methane [g/MJ]	Remark / Source
Production	0.007	from national emission registration
Purification	0.04	JRC 2007
Liquefaction		
Transport	0.02	calculated
Terminal	0	leakage negligible
Distribution	0	leakage negligible

LNG peakshaver: NG from North sea or Russia via pipeline
For most steps within the chain, the same values for methane emissions are used as for LNG from Qatar. For the pipeline transport from Russia, the value from [Kroon 2008] is used: 0.19 g/MJ of CH_4. This corresponds to a gas leakage of about 1%.

Table 7: WTT methane emission for different LNG pathways for ships

Methane	LNG Qatar	NL Peakshaver	NL Peakshaver pipeline 7000 km
	[g/MJ]	[g/MJ]	[g/MJ]
Production	0.007	0.007	0.007
Transport gas	-	0.01	0.19
Purification Liquefaction	0.04	0.04	0.04
Transport LNG	0.02	-	-
Terminal	0.00	-	-
Distribution	0.00	0.00	0.00

3.2.3 N_2O emissions

[ECN 2008] uses the value zero for N_2O for the well to tank emissions. This is also used for this study. In another study a value of around 10^{-5} g/MJ is used for both the production as well as the transportation of the LNG. This would be equivalent to about 1% of the WTT GHG emission.

3.2.4 Well To Tank emissions 6 pathways

In Table 8 the WTT-emissions of 6 fuel pathways are summarised. The detailed emissions are reported in Appendix B.

Table 8: WTT emissions 6 fuel pathways in g CO_2eq/MJ

	LNG Qatar	LNG NL peak shave	LNG NL pipeline 7000 km	**HFO**	**MGO / MDO**	**EN590 10 ppm S**
WTT summary						
CO_2	9.0	7.5	17.2	9.1	12.0	13.8
CO_2 equivalent of CH_4	1.7	1.4	5.9	0.7	0.7	0.7
CO_2 equivalent of N_2O	0.0	0.0	0.0	0.0	0.0	0.0
Total WTT	**10.7**	**8.9**	**23.1**	**9.8**	**12.7**	**14.4**

For refinery products such as HFO, MDO/MGO and EN590 diesel fuel it is hard to determine the allocation of energy/emissions into products because refinery energy structures are very complex and diverse. In this study the following assumptions have been made:

- Energy consumption and emissions of the most complex product (EN590 diesel fuel) with the highest numbers have been marked as the reference.
- The WTT-emissions of the products with lower quality can be derived from the reference because production processes are similar but less complex.

The diesel transition path is very well studied by different parties. It consists of the following steps:

- Exploration
- Crude oil transport
- Refining
- Distribution

HFO transition path:
Heavy fuel oil is mainly produced in the first distillation step, *i.e.* this product requires a relatively low amount of energy because no further energy consuming processes are needed. The amount of energy for distillation is 60% of the required energy of an EN590 diesel fuel [Bredeson2009] and the WTT emission is 9.8 g CO_{2eq}/MJ.

MGO/MDO transition path:
These two diesel fuels require less energy for production than EN590 diesel fuel because their sulphur content is higher (less desulphurization) and the density specifications are broader.
In literature no data were found about the MGO/MDO production. The estimated amount of energy for distillation is 90% of the required energy of an EN590 diesel fuel and the WTT emission is 12.7 g CO_{2eq} /MJ.

EN590 diesel transition path:
Sulphur free EN590 diesel fuel is the most extensively processed diesel fuel and consequently its WTT emission is relatively high. The value 14.4 g CO_{2eq}/MJ corresponds to [JRC 2007]. For MDO/MGO and HFO less treatments of the fuel are needed and consequently their WTT-emissions are lower.

In The Netherlands crude oil from many sources has been refined to products and exported. For this study an average crude oil transport distance of 8000 km and an average Dutch refinery have been chosen.

3.3 Well to Propeller greenhouse gas emissions

The Well To Propeller (WTP) greenhouse gas emissions are calculated by adding up the Well To Tank (WTT) and the Tank To Propeller (TTP) emissions.
The WTT values were determined in section 3.2.

3.3.1 Tank to propeller emissions

The TTP part consists of the following:
- The direct CO_2 emissions of the combustion of the fuel
- The indirect CO_2 emissions composed of CH_4 (methane) and N_2O emissions of the engines.

The direct CO_2 emissions are directly linked to the H-C ratio of the fuel (in case of biofuel also to possible CO branches with single or double bonds). The more energy is derived from oxidation of H to H_2O rather than oxidation of C to CO_2, the lower the specific CO_2 emission expressed in gram per MJ fuel energy combusted (g/MJ). The specific CO_2 emissions can for example be found in [Vreuls 2009]. The values for combustion are as follows:
- Gasoil / diesel oil (EN590, MDO, MGO): 74.0 g/MJ
- Heavy Fuel Oil (HFO): 77.3 g/MJ
- Natural gas: 56.1 g/MJ

These values correspond to the IPCC good practice guidance for national greenhouse gas inventories workbook, section 1.6.

Apart from the fuel composition the CO_2 emission is dependent on the engine efficiency. The lower the engine efficiency, the more MJ fuel needs to be combusted in order to have a certain mechanical work output.

The engine efficiency is analysed in section 3.4.3. It is estimated that the efficiency of the gas engines for the 3 cases is only 0-2% lower than that of the diesel engines. This means that the WTP analyses can be done on a gram per MJ fuel energy basis, without special correction for engine efficiency.

Methane (CH_4) and N_2O emissions weigh much more heavily than CO_2 emissions for global warming. As a result CH_4 needs to be multiplied by 25 and N_2O by a factor of 298 in order to obtain the CO_2 equivalent for global warming.

The methane emissions of the applicable lean-burn spark ignition and (also lean-burn) compression ignition engines are rather high.
According to [Engelen 2009] the average methane emission of stationary lean-burn gas engines is 1200 mg C per Nm3 (normal-m^3) at 3% O_2. Also refer to [Olthuis 2007].

The gram per MJ CH_4 emission can be calculated as follows:
- at 3% O2 the exhaust flow is 16.36 m3/kg fuel or 61 g fuel / Nm3
- 1200 mg C = 1.2 g C = 1.6 g CH_4 (per Nm3)
- Slip percentage: 1.6/61 = 2.6% or 26 g/kg
- Lower combustion value of LNG is: Ho= 49 MJ/kg
- Methane emission is 26/49 = 0.53 g/MJ

In combination with the multiplying factor of 25 for CH_4, the CO_2 equivalent will be: 25 x 0.53 = 13 g/MJ fuel energy.

From one gas engine supplier detailed CH_4 data was submitted. This indicated a relatively constant slip percentage of around 20 g/kg at high loads to a rather variable slip percentage between 25 and 85 g/kg at very low power points. This means that there is a risk of higher specific CH_4 emission for applications such as the tug with a low power load pattern.

N_2O emissions are generally very small for both diesel and gas engines. If significant N_2O emissions were measured, it was related to a poorly functioning catalyst (oxidation catalyst or 3-way catalyst). Refer to [Havenith 1995]. In a TNO study of four fuels for passenger cars, the global warming potential of N_2O was always below about 1.2% of the global warming potential of the CO_2 emissions [Hendriksen 2003]. The four fuels were petrol, diesel, CNG and LPG. For this study a CO_2 equivalent value for N_2O of 0.4 g/MJ is used for all engines. This corresponds to about 0.6% of the CO_2 emission itself.

3.3.2 Well To Propeller emissions

In this section the results of the Well To Tank analysis (section 3.2) and the Tank To Propeller analysis (section 3.3.1) are combined. The overview is presented below.

Table 9: Overview Well To Propeller (WTP) GHG emissions of 6 fuel pathways. Split in Well To Tank (WTT) and Tank To Propeller (TTP) emissions in g CO_2eq/MJ.

		LNG Qatar	LNG NL peak shave	LNG NL pipeline 7000 km	HFO	MGO / MDO	EN590 10 ppm S
WTT summary							
CO_2	[g/MJ]	9.0	7.5	17.2	9.1	12.0	13.8
CO_2 equivalent of CH_4	[g/MJ]	1.7	1.4	5.9	0.7	0.7	0.7
CO_2 equivalent of N_2O	[g/MJ]	0.0	0.0	0.0	0.0	0.0	0.0
Total WTT	[g/MJ]	**10.7**	**8.9**	**23.1**	**9.8**	**12.7**	**14.4**
Tank To Propeller (TTP)							
CO_2	[g/MJ]	56.1	56.1	56.1	77.3	74.0	74.0
CO_2 equivalent from CH_4	[g/MJ]	13.0	13.0	13.0	0	0	0
CO_2 equivalent from N_2O	[g/MJ]	0.4	0.4	0.4	0.4	0.4	0.4
Total TTP	[g/MJ]	**69.5**	**69.5**	**69.5**	**77.7**	**74.4**	**74.4**
Total WTP	[g/MJ]	**80.2**	**78.4**	**92.6**	**87.5**	**87.1**	**88.8**
Application / case		Sea ships, port ships and inland ships			Sea ships		port ships inland ships

Note: because of rounding, the partial and global sums may not add up exactly with the individual components.

The table clearly shows that path 3, LNG produced in the Netherlands from pipeline gas from Russia, has a relatively poor performance compared to the other two LNG pathways. The cause of the poor performance is the high methane emission during production and transport. If gas needs to come from far away, production of LNG and shipment as LNG (path 1) is the more environmentally friendly option. It can also be seen that the global warming potential of the methane emissions of the LNG engines (13 g/MJ CO_{2eq}.) is very high. Although this justifies specific attention to this point in the future, it can still be concluded that the two most logical LNG chains - LNG from NL peakshaver and LNG from Qatar - have a 10% lower GHG emission than the three diesel fuel chains.

The five most realistic fuel pathways are presented in Figure 3. LNG NL from pipeline 7000 km is omitted because of its poor performance compared to LNG Qatar and because LNG is already supplied to Rotterdam.

Table 9 and Figure 4 can directly be applied to the three cases because in section 3.4.4 it is concluded that the differences in engine efficiency are very small (<2%). The following diesel fuels are applicable to the application cases:

- Short sea: SECA: MDO (2010 – 2015), MGO (2016 ->). Non SECA: HFO
- Port ship: EN590 (2011 ->)
- Inland ship : EN590 (2011 ->)

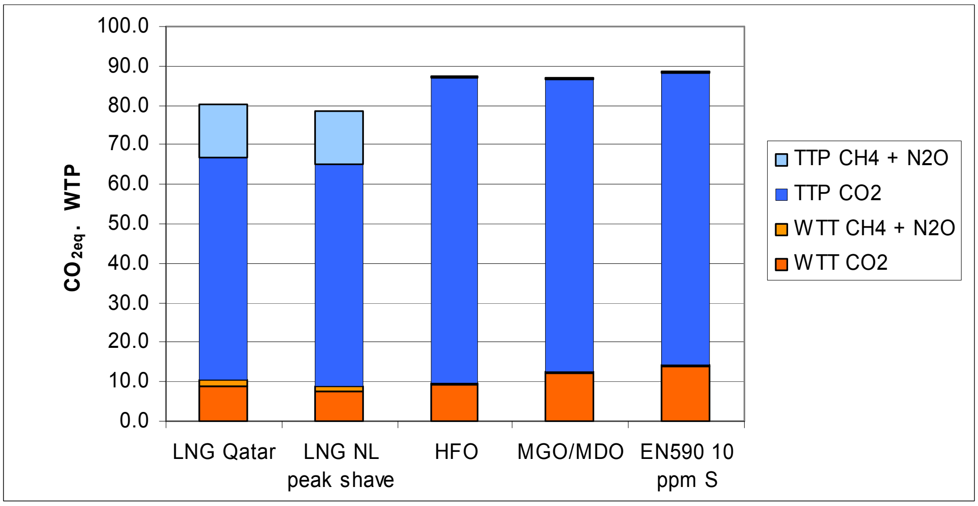

Figure 3. Overview annual Well To Propeller (WTP) GHG emissions [g CO_2eq/MJ] of the 5 most realistic LNG and diesel fuel chains, representative for the three application cases evaluated.

3.3.3 Biofuels

For both the LNG engines and diesel engines the WTP greenhouse gas emission can be strongly reduced by replacing the fossil fuels by biofuels. LNG can be replaced by bio-LNG, also called LBG (Liquid Bio Gas). Diesel can be replaced by several types of biofuel of which the suitability will depend on the application. In [van der Steeg 2009] a number of biofuel options are analysed regarding their suitability for application in different ship types.

- Pure Plant Oil (PPO) and pyrolyse liquid can be considered for sea ships
- Biodiesel and BTL or HVO (Hydrotreated Vegetable Oil) are good candidates for inland ships and port ships.

PPO and biodiesel may require engine adaptation and additional maintenance. This is certainly the case for pyrolyse liquid which required a special corrosion resistant fuel injection system. It is desirable that the specific engine is delivered by the manufacturer for the specific fuel or blend. Effects on emissions and maintenance of the regular biofuels are for example described in [TNO/CE 2009].

Typical values for the reduction in GHG emissions with the use of biofuels can be found in the Renewable Energy Directive [EC 2009]:

- Biodiesel: 19 – 83% GHG reduction
- Biogas from pure manure: 81 – 82% GHG reduction
  When biogas is made via co-fermentation of manure plus corn, the GHG reduction potential is smaller [Bleuanus 2010].

3.4 Tank To Propeller air pollutant emissions analysis

3.4.1 Fuel consumption and air pollutant emissions

This chapter contains the fuel consumption and air pollutant emissions calculations. This is done for the three cases for both the reference with diesel engines and the LNG engines.

Information on standard load patterns, engine efficiencies and emissions was supplied by Damen Shipyards, SMIT, Jenbacher, PON, Rolls Royce and Wärtsilä.

The calculations were made in the following order:
-Step 1: Obtained data was converted to a uniform format;
-Step 2: Calculate the Total (engine) Work [kWh/y] for each case;
-Step 3: Establish a most common load profile for each case;
-Step 4: Calculate BSFC [g/kWh] at the most common load profile for each engine;
-Step 5: Calculate the total fuel consumption [MJ/y] for each engine;
-Step 6: Calculate the specific NO_x, SO_x and PM emissions for each engine, at the most common load profile;
-Step 7: Calculate the total NO_x, SO_x and PM emissions [kg/y].

A schematic of the overall calculation procedure is presented in Figure 4.

3.4.2 Standard load patterns

For confidentiality reasons, the standard load patterns for the three cases cannot be shown in this report. Still, the main characteristics such as max power and speed, average power and speed and propulsion type are presented in Table 10. The average numbers are weighted averages, which means taking into account the number of hours per year of each load point. This is calculated by multiplying the parameter per mode point with the number of hours of that mode point, then adding up al mode points and dividing this by the total number of hours.

Table 10 shows that the average power can be much lower than the maximum power. This is especially the case for the tug ship with an average power of only 15% of maximum power. The container feeder (Short Sea) has a constant speed propulsion system while the other two ship types have a variable speed propulsion system.

Table 10: Specifications of standard load pattern for the three cases

Case	P_max [kW]	Max speed	P_avg [%/P_max]	Speed [rpm]	Propulsion	Emission test Cycle
Short Sea	8,400	500	45%	500	Constant speed	E2
Port ship	2x 2,500	1000	15%	668	Variable speed	E3*
Inland ship	1,250	1500	73%	1,171	Variable speed	E3

* not representative for tug application

3.4.3 Engine data

For each case, engine data was provided of one (reference) diesel engine and two or three LNG engines. In Table 11 an overview is given of the specific engine types for which energy consumption and emissions data was made available. The table also shows the engine technology (lean-burn/spark ignition or dual fuel) and the maximum power output. In some cases, the maximum power of the gas engine is lower than for the reference diesel engine. This is especially the case with the short sea application where the power for one LNG engine is almost 17% lower. The reference diesel engine for the tug (port ship) is normally a Caterpillar engine, but no data for this engine was available. The Jenbacher engine is a stationary engine, normally applied for total energy.

Table 11: Engine data

Case	Fuel	Brand	Type	Injection	Pmax [kW]
Short sea	Diesel	Wärtsilä	8L46 (DE)	Conventional	8,400
	LNG	Rolls Royce	B35:40V16AG	Lean burn	7,000
		Wärtsilä	Wärtsilä 8L50 DF (DE)	Micropilot/dual fuel	7,600
		Wärtsilä	Wärtsilä 9L50 DF (DE)	Micropilot/dual fuel	8,550
Port ship	Diesel	Wärtsilä	8LW26 (AE/DE)	Conventional	2,600
	LNG	Rolls Royce	C26:33L9AG	Lean burn	2,430
		Jenbacher	J616 GS	Lean burn	2,745
Inland ship	Diesel	Caterpillar	DM8467	Conventional	1,118
	LNG	Jenbacher	J416 GS	Lean burn	1,161
		Caterpillar	3512 dual fuel	Dual Fuel	1,118

The completeness of the data varied from reasonably complete to very incomplete. This was different for the several required parameters:
- Fuel or energy consumption (and thus CO_2): reasonably complete for most engines
- NO_x: As a function of load or power for several engines, only average numbers or targets for other engines.
- PM: hardly available except for average reduction percentage (target).
- CO and NMHC: available for some engines as a function of load or power
- Methane (CH_4): available for only a few engines

Even if the data was specified as a function of load or power, it generally did not fit exactly to the load points of the standard load patterns. Also, the Port ships and Inland ships have variable speed load patterns, but in several cases only constant speed data was available.

Taking into account the limited level of completeness of the data, the data was processed as follows (also refer to the flow chart in Figure 4 below):
- The fuel or energy consumption at the key points was calculated using linear curve fits in which energy consumption (in MJ/h) is presented as a function of engine power and engine load. The latter are called Willans Lines. This fit is generally quite linear, even at very low load or power. The energy consumption at zero torque represents the friction torque of the engine. In one case with insufficient points at low load the friction torque is manually set to 7.5% of the max torque. The constant speed data is converted to variable speed values. For example the torque as a function of fuel per revolution is kept constant across a certain part of the speed range.
- Specific emissions were used as specified for the standard test cycle (usually E2 or E3). Only for the port ship (the tug) a correction was done for the low average power of 15% of Pmax. The correction was based on the specific energy input or BSFC. This lead to a correction (increase) of about 20% for the specific emissions NOx and PM.
- SOx emissions are calculated from the (actual) fuel consumption.

It should be noted that for conventional engines the NOx and (a somewhat lesser extend) PM emissions behave quite linearly with energy consumption and engine torque. For that reason these emissions can be corrected based on the actual or real-world fuel energy input (or based on the ratio of real-world and nominal specific fuel consumption). The same principles are applied by [Hollander 2007].

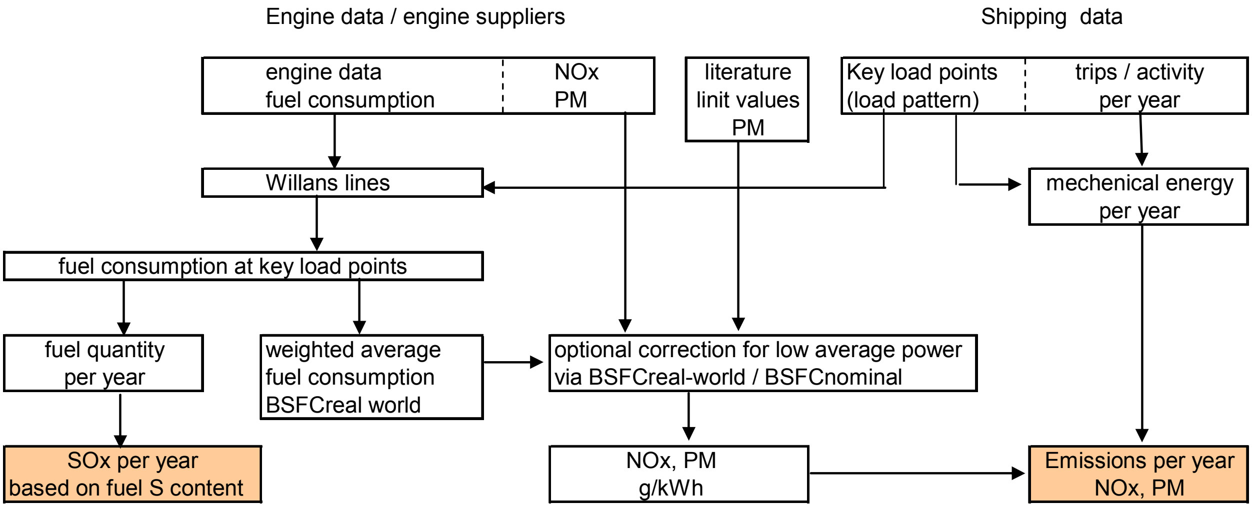

Figure 4. Flow chart of data processing

3.4.4 *Energy consumption*

The Total work (output) and Total fuel (input) provide the basis for each total emission calculation. Table 12 compares the diesel engine with all LNG engines (average values are shown).

The mechanical energy (per year) delivered to the output shaft of the engine is only dependent on the standard load pattern. This is the same for each engine within one case (application). The energy input (per year) is determined for each engine, diesel as well as LNG. The energy input is calculated by using the linear functions of energy input as a function of power output and then using the standard load points and the time per year for each point.

The results are presented below. The results for LNG are the average results of two or three engine depending on the case. Consequently the average engine efficiency is calculated by dividing the energy output by the energy input (using MJ for both).
The results show that for two cases there is a small decrease in efficiency of 1% or 2% when replacing diesel by LNG. On the average the decrease is 1% absolute, which is about 2% relative reduction.

Table 12: Energy consumption

Case	Fuel type	Mechanical energy (work)	Energy input (fuel)	Average Efficiency
		[kWh/y]	[MJ/y]	[%]
Short sea	Diesel	23,905,000	187,794,700	46%
	LNG	23,905,000	197,534,983	44%
Port ship	Diesel	1,459,600	14,708,526	36%

	LNG	1,459,600	14,697,724	36%
Inland ship	Diesel	5,437,500	45,507,525	43%
	LNG	5,437,500	46,172,531	42%

3.4.5 Pollutant emissions
Reasonably complete information was available for NO_x. Other components such as particulate mass (PM) and methane (CH_4) were primarily based on literature and expert views. Sulphur dioxide emissions (SOx) are based on fuel sulphur contents.

3.4.5.1 NOx emissions

2011 – 2015
The NOx data was made available in different formats. For most engines it was provided as a function of load or power or a value was given applicable to a certain power range. In several cases the data was only given at constant speed while variable speed data was needed (port ship and inland ship). For some engines the NOx emission was only available as one average number. The method that is applied to calculate the NOx during the actual load profiles is the one of 'constant NOx to CO_2 ratio'. This is equivalent to 'constant NOx to fuel consumption ratio'. This is for example an accepted and used method for on-road heavy-duty engines [Verbeek 2008]. The way in which it is applied is the following: Fuel consumption is calculated at the nominal engine power for which the NOx is specified. Consequently the NOx/CO_2 ratio is established. The specific fuel consumption is calculated for the actual load profile. Then the nominal NOx is multiplied with the ratio of actual and nominal specific fuel consumption: the higher the specific fuel consumption (g/kWh), the higher the NOx. The precise data and calculations are not included in this report because of confidentiality reasons.

For conventional diesel engines, such as applied in ships (*i.e.* without special NOx control devices), the constant NOx to CO_2 ratio is reliable and often published. For lean-burn spark or compression ignition LNG engines, there is not very much data available to confirm this so there is more uncertainty. For example the air/fuel ratio has an impact on NOx for these engines and it is not known how well this is controlled at low torque and power. The limited torque dependent data that was made available was in line with these estimates. For the short sea and inland ship cases the uncertainty of the NOx/CO_2 ratio does not pose a problem because the average power is high enough (respectively 45% and 72%). There is however more uncertainty for the tug ship because the average power is only 15% of maximum power.

The overall results for the specific NOx emissions are presented in Table 13. The LNG results are averaged over the two or three engines for which information was available. The engines which were used are specified in Table 11.

2016 and later
In 2016 more stringent emission limits are expected. In that year Tier III for sea going vessels as well as CCNR IV will enter into force. The NOx limits are up to 75% lower. For this study, it has been assumed that SCR deNOx with urea injection will be applied to achieve the required reduction for the diesel engines. Also for some of the LNG engines some additional NOx reduction may be necessary. With CCNR IV, the PM limit for inland ships is some 90% lower. It is assumed that this can be achieved by engine optimisation without aftertreatment (in combination with low sulphur fuel). This

is very similar to the strategy used for most Euro V truck engines (SCR, but no DPF). The PM emissions for sea ships will especially benefit from the required fuel sulphur content reduction. An overview of the emission limits is included in Table 15 and Table 16.

The estimated NOx emissions for 2016 and later are presented below. It should be noted that the gas engines do not have a formal Tier III and CCNR IV certificate, even though their emissions are below the limit values.

Table 13 Overview specific NOx emissions for engines running on diesel fuel and LNG

Case	2011 - 2015		2016 →	
	Fuel	NOx g/kWh	Fuel	NOx g/kWh
Short sea Container feeder 800 TUE	MDO	10	MGO	2
	LNG	1.3 - 3	LNG	1.3 – 2.3
Port ship: 80 ton TUG	EN590	12	EN590	2.2
	LNG	1.7 – 1.85	LNG	1.7 – 1.85
Inland ship 110 m 11,45m	EN590	8.8	EN590	1.8
	LNG	1.6 – 4.4	LNG	1.6 – 1.8

Note: NOx emissions for the port ship on EN590 are based on average engine power being 15% of max power. The 2016 onwards scenario includes SCR deNOx for diesel engines.

3.4.5.2 SO_2 emissions

Table 14 lists the maximum sulphur levels within the fuels and the values used for the emissions calculations. HFO is added for comparison only, because it is not the reference fuel within any case. 2.7% (27000 ppm) is considered to be the world-wide average. For the other diesel fuels a sulphur content of the fuel for the emissions calculation is used of 20% below the limit value, because in practice the actual emission levels are below the limit values. No compensation is applied for the sulphur ending up as sulphate in the PM emission (5-10% of the S) [Duyzer 2007].
For the sulphur content of LNG, information was made available from Shell. The average S content of a set of shipments was 2.8 mg/Nm3. This corresponds to 3.5 ppm by mass. It is not expected that sulphur levels in LNG will cause an issue regarding SOx emissions, but they should be monitored and measured regularly as the sulphur grid specs are typically a bit higher (Netherlands GTS spec for total sulphur is 30 mg/Nm3).

The specific SO_2 emission is calculated with the following lower heating values:
-MDO & EN590 : 42.7 [MJ/kg]
-LNG : 49 [MJ/kg]

For LNG refer to Appendix A.

Table 14: Fuel sulphur (S) content and values used for the emissions calculations

Fuel	S content [m/m]				SO_2 emission	
	max		used			
	%	ppm	ppm	g/kg	g/kg	g/MJ
HFO	4.5*	45000	27000	27	54	1.265
MDO	1.00	10000	8000	8	16	0.375
MGO	0.10	1000	800	0.8	1.6	0.0375
EN 590	0.001	10	8	0.008	0.016	0.000375
LNG	0.0037	37	3.5	0.0035	0.007	0.000143

* 2012: 3.5%

PM emissions

Very little PM emissions data were made available by the manufacturers. Consequently the PM emissions are primarily based on literature and expert view. For the diesel fuels with substantial sulphur a correction is made based on the S contents of the fuel. This is done for MDO, MGO and HFO. The correction is 0.138 g PM per g sulphur (from the fuel) based on a formula used by TNO for heavy-duty engines. Other sources gave even somewhat higher numbers such as 0.157 g/g from EPA and 0.184 g/g from CONCAWE. The latter was however meant for very low fuel sulphur contents, so not applicable for the high sulphur contents of MGO, MDO and HFO. The TNO equation for example leads for an MDO fuel with 0.8% S content to a correction of 0.22 g/kWh. A nominal diesel fuel consumption of 200 g/kWh is used for this calculation. Together with a base PM emission of 0.2 g/kWh, the overall PM number (for short sea) becomes 0.42 g/kWh.

For the dual fuel engines, reduction percentages compared to the diesel values were given. For the spark ignition engines, the PM emissions are derived from heavy-duty bus engines. PM emissions of these engines range from 0.003 to 0.02 g/kWh [Verbeek 2010b]. The 0.02 g/kWh is used for the spark ignition ship engines due to the absence of more accurate data.

Table 15 and Table 16 give an overview of the PM limit values as well as the estimates or submitted PM emissions for the diesel and gas engines. A range is specified when there are more engine options with a difference in PM emissions.

Table 15: NO_x and PM limits and estimated PM levels for short sea and port ships with diesel and LNG engines.

Short Sea and **Port ship**	Unit	**Tier II** (2011)	**Tier III** (2016)	**optional**
NO_x limit	g/kWh	7.7 - 14.4	2 - 3.4	
PM limit	g/kWh	none	none	
Fuel		MDO	MGO	HFO
PM estim. short sea				
- diesel engine	g/kWh	0.42	0.22	0.95
- LNG engine	g/kWh	0.02 - 0.21	0.02 - 0.21	
PM estim. Port ship				
- diesel engine	g/kWh	0.15	0.03	
- LNG engine	g/kWh	0.02	0.02	

Table 16: NO_x and PM limits and estimated PM levels for the inland ship with diesel / LNG engines.

Inland ship	Unit	**CCNR II** (2007)	**CCNR IV** (2016)	**optional**
NO_x limit	g/kWh	6.0 – 11.0	1.8 - 2.0	
PM limit	g/kWh	0.2 - 0.8	0.025	
Fuel		EN590	EN590	MGO
PM estimation				
- diesel engine	g/kWh	0.09	0.025	0.17
- LNG engine	g/kWh	0.02 - 0.045	0.02 – 0.025	

3.4.6 Emissions per year

The pollutant emissions in this report include NO_x, SO_x and PM. The emissions for each engine are calculated at the reference load profile. The mass per year (kg/y) calculations are done as follows:

- NOx and PM: Specific emissions per kWh mechanical work x total work per year ([g/kWh] x [kWh/y])
- SOx: Specific emissions per MJ fuel energy x fuel energy per year ([g/MJ] x [MJ/y])

In Table 17 and Table 18 the results are presented for the period 2011 – 2015 and for 2016 and later, respectively. The latter is based on the assumption that the diesel engines will comply with the Tier III legislation (sea ships) and the CCNR IV legislation (inland ships and port ships). The diesel engines will then have NOx emission control devices, most probably being the SCR catalyst with urea injection.

Table 17: Annual pollutant emissions for ships with diesel and LNG engines for 2011 - 2015

Case	Fuel type	NO_x [kg/y]	SO_x [kg/y]	PM [kg/y]
Short sea	Diesel	239,050	70,368	10,040
	LNG	58,169	596	3,506
Port ship	Diesel	17,515	6	219
	LNG	2,620	2	29
Inland ship	Diesel	47,865	17	489
	LNG	16,262	8	177

Table 18: Annual pollutant emissions for ships with diesel and LNG engines for 2016 and later (diesel engines equipped with deNOx SCR catalyst).

Case	Fuel type	NOx [kg/y]	SOx [kg/y]	PM [kg/y]
Short sea	Diesel	47.810	7.037	5.259
	LNG	47.810	85	3.506
Port ship	Diesel	3.211	6	44
	LNG	2.620	2	29
Inland ship	Diesel	9.788	17	136
	LNG	9.189	8	122

Figure 5 and Figure 6 graphically present the comparison between diesel and LNG engines for respectively the period 2011 to 2015 and 2016 and later. The error bars in the figures are added based on expert view. For NOx the possible error is related to the different load points needed and for which data was provided. For PM it is primarily related to the estimation of the PM value itself since very little data was provided. No error bars are given for SOx, since SOx is only dependent on fuel S content. For short sea, the difference is very large with an insignificant error. For the port and inland ships the sulphur level is extremely low for both the LNG and the EN590 10 ppm S, so differences are also insignificant. For NOx for 2016 also no error bars are added, since the NOx values are primarily based on emission limits. In [Verbeek 2010] it was shown though, that there can be large differences between real world NOx emission and emission limits for trucks equipped with SCR deNOx systems.

From Table 17 and Figure 5, it can be concluded that NOx is three to eight times lower for the LNG engines compared to the diesel engines. For SOx the improvement ranges from a factor of two for the inland ship to a factor of more than 100 for the short sea applications. The very large reduction for the latter is due to the high sulphur content of MDO. Finally, the improvement of PM with LNG ranges from a factor of two to a factor of ten.

For 2016 and later, the differences in emissions will become much smaller (refer to Table 18 and Figure 6). Especially the differences in NOx will likely be small. For short sea shipping in particular, a substantial reduction in SOx and PM level will remain, since the sulphur level within diesel fuel for sea ships is still high compared to the sulphur content in LNG.

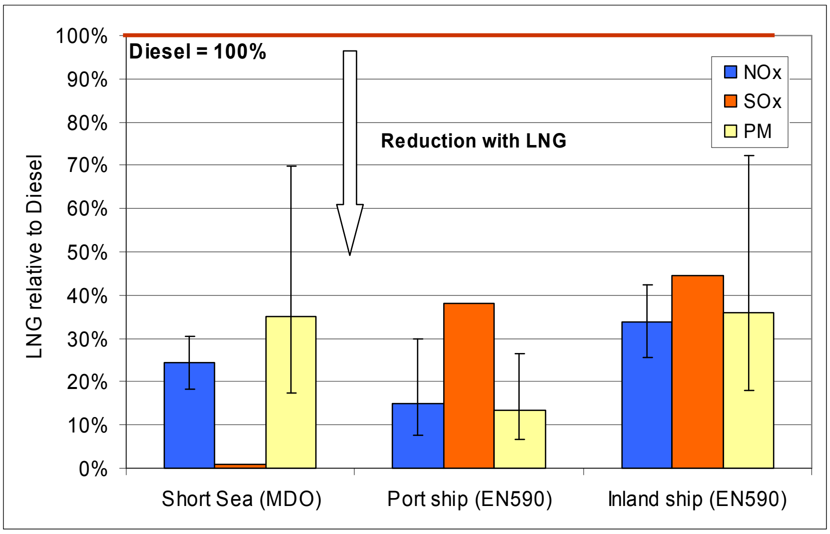

Figure 5. Comparison annual air pollutant emissions between diesel and LNG engines for 2011 – 2015.

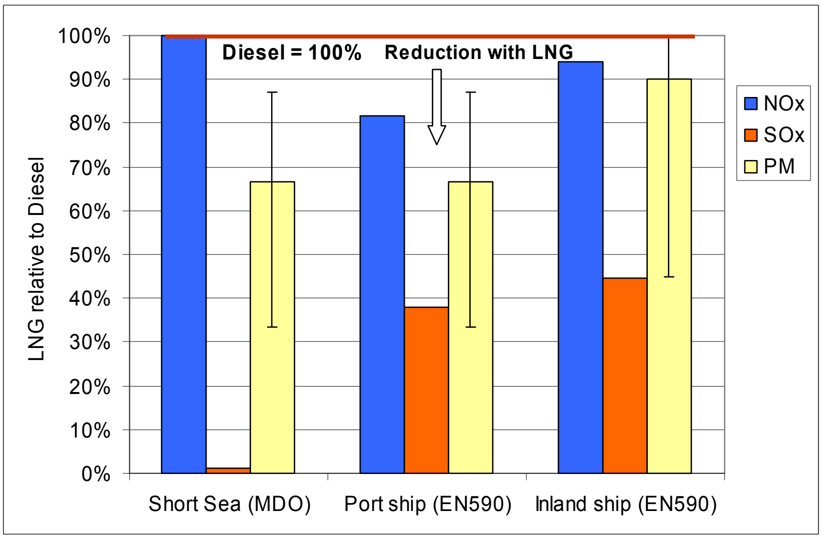

Figure 6. Comparison annual air pollutant emissions between diesel and LNG engines for 2016 and later (diesel engines are assumed to be equipped with deNOx SCR catalyst).

3.5 Economic comparison

This section presents the results of the simple economic comparison between LNG and Diesel fuels from the perspective of "usage costs", focused on an analysis of the fuel consumption. That is in turn based on the earlier estimates of yearly energy expenditure.

Some of the costs considered in the calculation are confidential (e.g. the engine prices), and hence not all results can be shown.

A number of general notes are worth mentioning:

- Based on input from stakeholders, it is assumed that maintenance costs are comparable for LNG and the distilled diesels and were hence not included
- HFO is not considered among the fuels for the economic comparison
- Consumption of Adblue for SCR $deNO_x$ systems is not taken into account. This could add about 3-6% on top of the fuel costs of the diesel cases
- Differences in engine efficiency are not taken into account. Energy consumption for the LNG engines can be around 2% higher
- Additional shipping costs as a consequence of reductions in usable cargo capacity (because of large LNG tanks) are not taken into account

The IMO legislation mentioned earlier implies that from 2016 onwards the requirements for the diesel fuel will be more stringent (which impacts which fuel is appropriate for the comparison) as well as introducing the need for after treatment (SCR $deNO_x$ system) and hence also the considered costs. Since not all cases have a positive marginal comparison towards LNG in both time periods, this issue opens the section.

It should be noted that, although that is outside the scope of the present study, the general environmental advantage of LNG (both in terms of air quality-related pollution and GHG emissions) could also be monetized and considered in the economic estimates. Further, some other financial and non-financial impacts (e.g. port fee reductions of up to 5-10% in some cases, green awards, reputation) could not be included but may contribute to the overall case for deciding towards LNG vs Diesel.

These benefits might make LNG more attractive already now for all cases.

3.5.1 *2011-2015 vs 2015/2016-onwards*

The current fuel for Short Sea shipping is MDO, which is cheaper per MJ than expected prices for LNG, thus making the LNG case less attractive for the time being. From 2015 onwards Short Sea shipping will be required to use MGO as fuel or to use MDO/HFO in combination with an SOx scrubber. From 2016 onwards SCR afterteatment is also necessary, to comply with the NECA (NOx Emission Control Areas). For this evaluation only MGO is considered and the cost of the aftertreatment system is included. So strictly speaking this economic evaluation is valid for 2016 onwards, but the most relevant change for Short Sea (fuel change) takes place already from 2015 onwards. MGO is (depending on the selected chain) generally more expensive than LNG per MJ. Because of the very high fuel consumption in MJ per year (due to high total work per year), as well as the fact that diesel engines will face more costs because of the required aftertreatment, LNG will probably be attractive from 2015/2016 onwards. That is investigated in the following sub-sections.

The fuel used for Inland vessels is EN590 (currently as well as from 2015/2016). EN590 is more expensive per MJ than expected prices for LNG, and also the fuel consumption in MJ per year (due to high total work) is relatively high, which implies Inland ships may be expected to be attractive in the current period as well as from 2016. However, the 2016 scenario is more interesting because of the additional after treatment costs which will only need to be applied to Diesel engines. Once again, this is investigated below.

Based on this simple economic comparison, it seems that for the tug (harbour vessel) to be attractive (in either the current period or from 2016), very low LNG prices would be required. This is a result of relatively low fuel consumption, due to low total work per year.

The following sub-sections explore each of the considered cost components assuming the 2016-onwards situation (because the cost of SCR aftertreatment is included for the diesel ships). Given that the exercise is a first-order comparison, **the differences to the current situation are not significant except for short sea shipping which does not seem attractive now but will probably become attractive by 2015.**

3.5.2 *Fuel costs*

LNG supply costs depend on the distribution chain considered, and hence the estimate for fuel prices was different for 2 possible chains:

- Chain 1: Gate (peakshaver) – uses Gate terminal in combination with buffering facilities of the peakshaver. This would require a pipeline between Gate and Peakshaver, but has the lowest investment costs overall.
- Chain 2: Gate terminal – in combination with a new breaking bulk terminal. This can be of high or low volume resulting in lower or higher LNG costs.

An overview of the diesel and LNG fuel costs (expressed in US Dollars/MMBTU) based on input from the stakeholders is presented in Table 19. Although the calculations are always based on energy units (MMBTU), the USD cost per ton of LNG can be obtained by multiplying the values on the right side of the table by 46.5 MMBTU/ton.

Table 19: Estimated fuel costs at a crude price of 75 $/bbl. 1 MMBTU is 1055 MJ.

	Fuel costs USD/MMBTU					
	Diesel			LNG		
	MDO	EN590	MGO	Gate (peakshaver)	Gate high/low volume	
Short sea	$10.4		$16.2	$12.5	$13.5	$15.5
TUG		$16.5		$12.5	$13.5	$15.5
Inland ship		$16.5		$12.5	$13.5	$15.5

Since the ensuing calculations were performed in Euro, the first step was converting the currencies at an exchange rate of 0.80 Euro to the Dollar:

Table 20: Estimated fuel costs at a crude price of 75 $/bbl and EURO/$ rate of 1.25. 1 MMBTU is 1055 MJ.

	Fuel costs EURO/MMBTU					
	Diesel			LNG		
	MDO	EN590	MGO	Gate (peakshaver)	Gate high/low volume	
Short sea	8.3		13.0	10.0	10.8	12.4
TUG		13.2		10.0	10.8	12.4
Inland ship		13.2		10.0	10.8	12.4

As noted before, MDO is expected to stay less expensive per MJ than LNG. Where LNG does have the lowest cost per MJ, the economic benefit depends on enough fuel/energy consumption (MJ) a year to offset the higher installation costs of LNG.

Based on the estimated fuel costs provided by stakeholders and the yearly energy consumption of the 3 cases, the following overview was made to express the benefit of fuel costs (LNG vs the appropriate diesel) on a yearly basis.

Table 21: Benefit of fuel costs (LNG vs the appropriate diesel) on a yearly basis for the 3 cases (short sea from 2015 onwards, tug and inland ship from 2016 onwards)

Case	Benefits of fuel costs (Thousand Euro / Year)		
	LNG compared to MGO & EN590		
	Gate (peakshaver)	Gate (high/low volume)	
Short sea (MGO)	435	285	-15
Tug (EN590)	45	34	11
Inland ship (EN590)	132	97	27

It should be noted that, even for the same supply chain, the fuel costs depend on the oil price (calculations are based on current oil prices and an exchange rate of 1EUR to 1.25USD), as well as demand and supply. None of these effects was considered here.

3.5.3 *Fuel storage system costs*

LNG tank costs are considerably higher than for diesel because of the inherently more complex design (maintaining a relatively high pressure and ensuring safety at all times). For a tank of higher volume, the cost per cubic meter is lower because of scaling benefits, but nevertheless, the higher the volume, the higher the total tank costs.
The usable volume of the LNG tanks was assumed to be 90%.

Table 22: Volumes and estimated costs of "total gas train including LNG tank" for the 3 cases. Note that these estimates include gas regulation, vaporizer, gas detection etc.

Case	LNG storage capacity required (m3)	LNG tank capacity required (m3)	Cost of LNG tanks (Thousand Euro)
Short sea	550	610	3080
TUG	40	45	570
Inland ship	40	45	570

These estimates for LNG tank systems – "LNG tank including total gas train", thus including gas regulation, vaporizer, gas detection etc – cover the best quality tanks, with high insulation standards and stringent class approval. Less expensive systems are available (in some cases up to 50% cheaper on the tank itself), but these do not meet the quality standards desired in the industry.
Tank costs for diesel were simply assumed to be 10% of the LNG case.

3.5.4 *Engine and aftertreatment costs*

LNG and Diesel engine costs were received from stakeholders and compared. It was found that the LNG packages (including control equipment) are estimated to cost approximately 40 to 45% more than Diesel, depending on the amount of engine power (the higher the power, the lower the cost per unit of power). For the inland ship no engine cost figures were provided, and thus the estimate was expert-opinion-based.

Expert-opinion-based estimates for the cost of aftertreatment systems for the diesel cases were also included. In fact, unlike diesel engines, LNG engines will in most cases not require aftertreatment. Diesel engines are expected to fulfil the emission limits from

2016 with SCR deNOx aftertreatment systems. The costs of aftertreatment systems become higher for higher engine power. A need for diesel particulate filters is not expected. The following additional costs for the SCR aftertreatment systems were used:

- Inland ships: EUR 90,000
- Tug ship: EUR 200,000 (for two engines)
- Short sea ship: EUR 300,000

In some cases these costs are lower than what is currently quoted for individual ships. In fact, based on experience with SCR systems for trucks, it is expected that prices will go down substantially when series application picks up under pressure of the legislation. It can be observed that the diesel aftertreatment system costs are low compared to the additional costs of an LNG installation (engine + fuel storage).

3.5.5 On-board operational costs

In discussion with the relevant stakeholders (engine suppliers and ship builders), the team found the consensus that on-board operational costs (*e.g.* maintenance, repair) could be considered to be equivalent for LNG and (non-HFO) diesel. They were thus not included.

3.5.6 Not considered costs

A number of relevant non-operational – *e.g.* safety measures, education, PR – costs lie outside the scope of this project and were therefore not considered. However, given their importance and probable distinction between the 2 fuels, the team recommends that these are included in follow-up studies.

3.5.7 Conclusions

Based on the numbers provided by stakeholders, as a first order approach the overall engine + aftertreatment + tank costs of LNG seem to be a factor of ~1.5 to ~2.0 higher.

Taking the above and the fuel costs into account, a cost comparison was made between LNG and diesel for the 3 cases on a yearly basis in the 2015/2016 onwards situation. The differences to the current situation are not significant except for short sea shipping which does not seem attractive now (because it is still allowed to use MDO which is cheaper than LNG) but will probably become attractive by 2015 (when using MGO).

To that end, a breakeven LNG price was calculated as a discount in relation to the relevant liquid fuel (MGO or EN590) in order to cover the additional investment costs plus cost of capital at a rate of 5%. This exercise was performed for a payback of 5 and 10 years and the required price difference (in Euro/MMBTU) is shown below.

Table 23: Break-even price of LNG vs diesel fuels (in Euro/MMBTU) for the 3 cases in the 2016 onwards situation (for short sea from 2015 onwards)

Case (liquid fuel)	Needed LNG discount to break even [EUR] (in relation to relevant diesel)	
	… in 5 years	… in 10 years
Short sea (MGO)	4.4	2.5
Tug (EN590)	20.6	10.3
Inland ship (EN590)	3.9	2.1

(Note: the engine cost for the inland ship was estimated through expert opinion, and non-operational costs are not considered. All financial figures assumed constant)

When comparing Table 23 with Table 20, it can be concluded that for the short sea and the inland ship application, the required discount on the LNG price vs diesel in order to break even in 5 to 10 years could be realistic. For the tug case to be attractive other benefits (*e.g.* environmental) should be valued. In any case, investments in LNG systems (including engine) can possibly be reduced by applying a hybrid powertrain, since the LNG tank size and possibly also engine size can then be reduced. Pollutant emission levels for both the LNG as well as the diesel engines are also expected to benefit from a hybrid powertrain since long periods of low power can be avoided.

4 Discussion

The results of this study show that, with the application of LNG, reductions can be achieved for both greenhouse gas (GHG) as well as air pollutant emissions. This was concluded for all three studied cases: a short sea ship, a port ship (harbour tug) and an inland ship. Compared to other studies the results are more favourable for both the GHG emissions as well as the air pollutant emissions.

Greenhouse gas emissions
The advantage in GHG emissions with LNG can be attributed to the following reasons:
- the carbon content of the fuel (or the lower C-H ratio, *i.e.* a relatively large part of combustion energy is from oxidation of H to H_2O rather than C to CO_2)
- the engine efficiency of ship engines running on LNG is only marginally lower than the efficiency of diesel engines. This in contrary to other applications such as passenger cars and trucks where efficiencies with natural gas are generally 20-30% lower.

The high engine efficiency is probably related to the advanced stage of development of the gas engines for ships (and stationary engines) in combination with the combustion principles chosen. The combination of lean burn combustion with a relatively high specific power output can lead to high engine efficiency. That is basically the case for all LNG engines evaluated in this study.
Naturally, GHG emissions can be further reduced with the application of biofuels.

Air pollutant emissions
Given its intrinsically global and complex environment, the shipping sector **currently** has relatively less stringent emissions legislation in comparison with other sectors (*e.g.* road transport). That is part of the reason for the large advantages in air pollutant emissions obtained with gas engines, since the liquid fuel engines they would replace basically do not have any special NOx control device such as an SCR catalyst or EGR (Exhaust Gas Recirculation). In 2016 however, NOx and PM limits (for inland ships) need to be reduced by 75% or more. Most LNG engines evaluated can already achieve these limits now. This means of course an enormous improvement in air pollutant emissions if LNG is used in the coming five years. For sea ships there is also an enormous improvement in SOx and PM emissions due to the high sulphur content of the current fuels: HFO and MDO. The sulphur content is about 1% - 2.7%. This is to a large extent responsible for the PM emissions. It should be noted that the LNG engines do not have a formal Tier III and CCNR IV certificate, even though their emissions are below the limit values. This would be desirable in order to demonstrate their good performance with low emissions.

For the harbour tug, there is more uncertainty about the air pollutant emissions levels (especially NO_x) due to the load pattern which implies long periods at low power output. Diesel aftertreatment systems necessary for 2016 and later are not expected to work properly but also for LNG the emissions may be compromised. Apart from potential savings in energy consumption, the air pollutant emissions are a reason to strongly consider a hybrid driveline for tugs to avoid the long low-power periods.

Accuracy of the data

The supplied engine data was not very complete. Therefore for all engines, projections needed to be made to calculate the emissions and energy consumption for the medium and lower power engine points. This leads to uncertainties. It is therefore recommended to obtain data for the precise engine load pattern when an engine is selected, if needed by performing independent testing. Also performance during engine transients could be important.

Especially for the tug application, with its average power of only 15% of Pmax, there is a risk that the projected data differs from the real world situation. The energy consumption and emissions at the very low load point may not be very reliable. The LNG engine may be more sensitive to engine efficiency due to the necessary throttling.

Dual fuel engines may stop using LNG at very low load. On the other hand (NOx) emission control devices of future diesel engines may not work very well at the low power points. In a recent study on Euro V trucks it was concluded that NOx emissions under urban driving conditions were up to 3 times higher than what would be expected based on the emissions limits [Verbeek 2010]. Based on the differences in calculated engine efficiency, it can be concluded that for the tug there is a potential of some 10% to 20% reduction in energy consumption if the low engine power modes can be avoided by for example a hybrid drive line. The advantages in pollutant emissions would be even much larger. So developing environmentally friendly tugs is not only about fuels and/or exhaust aftertreatment, but also about hybridisation of the drive train. During recent years, several studies about tugs with hybrid drivelines have been done. Refer to E3 tug [Botke 2009], [SMIT E3 Tug] and Greentug [Offshore 2010].

Ship design and operational aspects

The energy content per litre LNG is only 45% of that of diesel fuel. In combination with the less efficient packaging of the cylindrical tank(s) and the insulation of the cryogenic tanks, the space required for fuel storage is about a factor of three larger with LNG. Especially for the tug it appeared difficult to find space for a reasonable amount of LNG storage and even then the autonomy would be reduced from several months to several weeks. A further design study might clarify and potentially improve this situation.
Also for ships with diesel engines more space will be required in the future. To meet the Tier III limits for sea ships or the CCNR IV limits for inland ships, the manufacturers will most likely choose SCR deNOx catalysts to meet the NOx limit levels.

Costs

A ship with an LNG engine is considerably more expensive than a diesel ship. This is mostly due to the high costs of the vacuum insulated, cylindrical LNG tanks and associated gas fuel system. Also the LNG engine itself is often more expensive than the diesel engine. Roughly speaking, the price of the engine plus fuel storage is twice as high as with a diesel powertrain. After 2016 the difference will be smaller because the diesel engines will need an SCR catalyst. The price of the SCR catalyst however is expected to add only about 10% to the engine costs, which is low compared to the costs of the LNG storage system. There may be scope for LNG storage at lower cost, for example by using lower quality insulation and/or by using atmospheric tanks instead of pressurised tanks. This has however an influence on the fuel system design and would need to be investigated. It should still be mentioned that for a dual-fuel engine where the gas is mixed with the inlet air (20% diesel, 80% gas), atmospheric pressure is fine and consequently the application of atmospheric tanks is more feasible.

Concretely, this study allows for the following observations:

- Short sea shipping on LNG (alternative fuel: MGO) would have high initial costs because of the large tank (610m^3), but still be viable for 2016 and later with an LNG price discount of 4.4 EUR/MMBTU below the diesel price for a payback of 5 years and 2.5 EUR/MMBTU for a payback of 10 years. The main driver is the high yearly energy consumption. Once again, it should be noted that before 2016 short sea shipping can use low cost MDO and avoid aftertreatment (SCR deNO$_x$), which does not seem to present an attractive economic case for LNG.

- Harbour vessels (tugs) on LNG, assuming the current conventional design, do not seem to present a reasonable breakeven time – for a payback within 10 years, an LNG price discount of 10.3 EUR/MMBTU below the diesel price would be needed, which is not realistic. This is mostly due to the relatively low yearly fuel consumption and high costs for LNG engines and LNG tanks. Because of their usage profile, tugs would be ideally suited to explore hybrid electric drive systems. This would probably reduce energy consumption by 10% to 20%. It would also reduce LNG systems (tank + engine) costs depending on the hybrid configuration. Both reductions would likely make application of LNG more attractive and reduce the breakeven time. This topic could be covered in depth as a part of a follow-up study[3].

- Inland shipping on LNG (current fuel: EN590) implies a relatively high yearly fuel consumption and requires a relatively small tank (45m^3) at a contained cost. The inland ship thus seems to offer an attractive case: for a payback in 5 years the LNG price discount would be 3.9 EUR/MMBTU below diesel price, while for 10 years that discount would stand at 2.1 EUR/MMBTU. Note: engine costs for the inland ship were expert-opinion-based.

For the near future, a relatively high LNG price is more likely due to the low overall LNG volumes. In that case, primarily environmental reasons will stimulate the use of LNG. Also, LNG long term fuel prices were not estimated, but they are not expected by stakeholders in the fuel sector to increase at a higher rate than long term crude/oil prices.

[3] See for example [Offshore 2010] and [SMIT E3 Tug]

5 Conclusions

A case study has been done in which air pollutant and greenhouse gas emissions of LNG and diesel fuel for marine applications were compared. Three cases were evaluated:
1) a short sea ship: 800 TUE container feeder
2) a port ship: 80 ton harbor tug
3) an inland ship: 110 x 11.5 m

The main conclusions are:

- Well-to-Propeller (WTP) greenhouse gas emissions with the most logical LNG chains are about 10% lower than the diesel fuel chains. Further improvement is possible by lowering the relatively high methane (CH_4) emissions of the engines (see Figure 1).

- Replacement of diesel fuel with LNG for the maritime sector offers large advantages in air pollutant emissions, and it will probably already today meet the requirements of Tier III and CCNR IV, which will enter into force in 2016. Incomplete information leads to uncertainties though (see Figure 2a).

- After 2016, when compared to Tier III /CCNR IV-compliant diesel fuelled engines, LNG will still offers benefits in the area of PM, SO_x, and CO_2 Well-to-Propeller. The benefits in NOx emissions performance will however become smaller (see Figure 2b).

- Further greenhouse gas emission reductions for both LNG and diesel are possible by using biofuels. LNG can be replaced by bio-LNG or LBG (Liquefied Bio Gas), diesel can be replaced by biodiesel, HVO (Hydrotreated Vegetable Oil), PPO (Pure Plant Oil) or possibly even pyrolysis liquid, but these fuel may require engine adaptations and increase maintenance.

- Application of LNG is only economically viable if the fuel price is low enough to compensate for the additional costs of the LNG fuel storage system. The cost of an LNG engine plus fuel tank system is about twice as high as a diesel engine plus fuel tank. Also the packaging of the LNG fuel tank on board of a ship can be an issue - especially application on the tug is critical. Under the assumptions made in this study, short sea (from 2016) and inland shipping (already now) seem to offer an attractive case, with realistic LNG price discounts of 2.5 EUR/MMBTU and 2.1 EUR/MMBTU below prices of diesel fuel, respectively, for payback within 10 years, and 4.4 EUR and 3.9 EUR below diesel fuel for payback within 5 years. The harbour vessel (tug) would require an LNG price discount of 10.3 EUR below the diesel fuel for a payback in 10 years, which does not seem to be realistic.
  LNG long term fuel prices were not estimated, but they are not expected by stakeholders in the fuel sector to increase at a higher rate than long term crude/oil prices.

6 Recommendations

The following recommendations are made:

- Measure or obtain more detailed (real-world) air pollutant and greenhouse gas emissions data for future applications. Precise NO_x and methane (CH_4) emissions data is especially necessary.

- Investigate potential for improvement of:
  - CH_4 emissions from engines
  - CH_4 emissions during production and transport of LNG

- Study options for LNG tanks of lower cost, such as with alternative insulation and/or atmospheric (rather than pressurised) configuration.

- Specifically for tugs (harbour ships), follow-up work could explore hybrid electric drive systems in depth[4], which may reduce energy consumption by more than 10% and make application of LNG more attractive.

[4] See for example [Offshore 2010] and [SMIT E3 Tug]

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8 Signatures

Delft, March 1st, 2011

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A Appendix A: LNG Compositions

Source: http://www.giignl.org/fr/home-page/lng-industry/ [GIIGNL 2009]

		Nitrogen	Methane	Ethane	Propane		LNG	Gas	HCV	HCV
		N2	C1	C2	C3	C4+	density	density	gas	gas
		%	%	%	%	%	kg/m3	kg/nm3	MJ/nm	MJ/kg
1	Algeria -Arzew	0,6	87,6	9,4	2	0,5	462	0,809	44,1	54,5
2	Algeria -Betioua 1	1,0	87,8	8,4	2,1	0,7	466	0,814	44	54,1
3	Algeria -Betioua 2	0,8	90,7	7,7	0,7	0	450	0,779	42,4	54,4
4	Algeria-Skikda	0,7	91,7	6,9	0,6	0,1	448	0,777	42,2	54,3
5	Egypt-Damietta	0,1	97,7	1,8	0,2	0,2	427	0,73	40,8	55,9
6	Egypt-Idku	0,0	95,8	3,1	0,8	0,4	436	0,753	41,5	55,1
7	Equatorial Guinea	0,0	93,4	6,5	0	0	439	0,755	42	55,6
8	Lybia	0,7	81,6	13,4	3,7	0,7	485	0,867	46,6	53,7
9	Nigeria	0,1	91,3	4,6	2,6	1,4	458	0,809	44,2	54,6
10	Norway	0,7	92,2	5,3	1,2	0,4	449	0,782	40,1	51,3
11	Trinidad	0,0	96,8	2,7	0,3	0,1	432	0,741	41	55,3
12	Abu Dhabi	0,3	84,8	13,2	1,6	0,1	467	0,826	44,9	54,4
13	Oman	0,4	87,9	7,3	2,9	1,6	470	0,834	45,3	54,3
14	Qatar-Qatargas 1	0,4	90,1	6,2	2,3	1	460	0,808	44	54,5
15	Yemen	0,0	93,3	5,7	0,9	0,1	434	0,765	38,5	50,3
16	USA-Alaska	0,2	99,7	0,1	0	0	423	0,719	39,9	55,5
17	Australia-NWS	0,1	87,4	8,3	3,4	0,8	467	0,831	45,3	54,5
18	Brunei	0,1	90,6	5	2,9	1,5	461	0,816	44,6	54,7
19	Indonesia-Arum	0,2	90,7	6,2	2	1	457	0,803	43,9	54,7
20	Indonesia-Badak	0,0	91,2	5,5	2,4	0,9	456	0,801	43,9	54,8
21	Malysia	0,3	90,3	5,3	3,1	1,1	461	0,813	44,3	54,5
22	Russia-Sakhalin	0,1	92,6	4,5	1,9	0,2	449			
									average	54,33

B Appendix B: WTP emissions

Well To Tank details

Well To Tank (WTT)		LNG Qatar	LNG NL peak shave	LNG NL pipeline 7000 km		HFO	MGO/MDO	EN590 10 ppm S
CO_2								
Production	[g/MJ]	0.70	0.70	0.70	Production	1.35	1.35	1.35
Transport gas	[g/MJ]	-	0.50	10.20	Transport oil	1.53	1.53	1.53
Purification	[g/MJ]	0.70	0.70	0.70	Refinery	5.79	8.69	9.65
Liquifaction	[g/MJ]	4.20	5.00	5.00	Desulphurization	0.00	0.00	0.75
Transport LNG	[g/MJ]	2.50	-	-	Distribution	0.17	0.17	0.17
Terminal	[g/MJ]	0.30	-	-	Misc and fill. tank	0.30	0.30	0.30
Distribution	[g/MJ]	0.60	0.60	0.60				
Subtotal	**[g/MJ]**	**9.00**	**7.50**	**17.20**		**9.14**	**12.04**	**13.75**
CH_4								
Production	[g/MJ]	0.007	0.007	0.007	Production	0.02	0.02	0.02
Transport gas	[g/MJ]	-	0.01	0.19	Transport oil	0.00	0.00	0.00
Purification / liquefaction	[g/MJ]	0.04	0.04	0.04	Refinery	0.00	0.00	0.00
Transport LNG	[g/MJ]	0.02	-	-	Desulphurization	0.00	0.00	0.00
Terminal	[g/MJ]	0.00	-	-	Distribution	0.00	0.00	0.00
Distribution	[g/MJ]	0.00	0.00	0.00	Misc and fill. tank	0.00	0.00	0.00
Subtotal	**[g/MJ]**	**0.07**	**0.06**	**0.24**		**0.03**	**0.03**	**0.03**
N_2O								
Production	[g/MJ]	0.00	0.00	0.00	Production	0.00	0.00	0.00
Transport gas	[g/MJ]	0.00	0.00	0.00	Transport oil	0.00	0.00	0.00
Purification / liquefaction	[g/MJ]	0.00	0.00	0.00	Refinery	0.00	2.00E-05	2.00E-05
Transport LNG	[g/MJ]	0.00	-	-	Desulphurization	0.00	0.00	0.00
Terminal		0.00	0.00	0.00	Distribution	0.00	0.00	0.00
Distribution		0.00	0.00	0.00	Misc and fill. tank	0.00	0.00	0.00
Subtotal	**[g/MJ]**	**0.00**	**0.00**	**0.00**		**0.00E+00**	**2.00E-05**	**2.00E-05**

Well To Tank and Tank To Propeller summary

		LNG Qatar	LNG NL peak shave	LNG NL pipeline 7000 km	**HFO**	**MGO / MDO**	**EN590 10 ppm S**
WTT summary							
CO_2	[g/MJ]	9.0	7.5	17.2	9.1	12.0	13.8
CO_2 equivalent of CH_4	[g/MJ]	1.7	1.4	5.9	0.7	0.7	0.7
CO_2 equivalent of N_2O	[g/MJ]	0.0	0.0	0.0	0.0	0.0	0.0
Total WTT	[g/MJ]	**10.7**	**8.9**	**23.1**	**9.8**	**12.7**	**14.4**
Tank To Propeller (TTP)							
CO_2	[g/MJ]	56.1	56.1	56.1	77.3	74.0	74.0
CO_2 equivalent from CH_4	[g/MJ]	13.0	13.0	13.0	0	0	0
CO_2 equivalent from N_2O	[g/MJ]	0.4	0.4	0.4	0.4	0.4	0.4
Total TTP	[g/MJ]	**69.5**	**69.5**	**69.5**	**77.7**	**74.4**	**74.4**
Total WTP	[g/MJ]	**80.2**	**78.4**	**92.6**	**87.5**	**87.1**	**88.8**
Application / case		Sea ships, port ships and inland ships			Sea ships		port ships inland ships

Well To Propeller: split between direct and indirect

Well To Propeller (WTP)		LNG Qatar	LNG NL peak shave	LNG NL pipeline 7000 km	HFO	MGO/MDO	EN590 10 ppm S
CO_2	[g/MJ]	65.1	63.6	73.3	86.4	86.0	87.8
CO_2 equiv. of $CH_4 + N_2O$	[g/MJ]	15.1	14.8	19.3	1.1	1.1	1.1
CO_2eq.	[g/MJ]	**80.2**	**78.4**	**92.6**	**87.5**	**87.1**	**88.8**