Sustainability in Inland Shipping

The use of LNG as Marine Fuel

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Preface

In September 2010 we, six students Marine Engineering at the TU Delft in the Netherlands, started our Minor project called "Verduurzaming van de Binnenvaart" (translated: Sustainability in Inland Shipping). In this project we were faced with some challenges provided to us by MARIN, the Port of Rotterdam, Interstream Barging and our teachers at the TU Delft concerning inland shipping and making it more sustainable and environmental friendly. One of these tasks concerned some research for the Port of Rotterdam Authority concerning three different subjects, the Container Transferium at Alblasserdam, the use of LNG as fuel for inland barges and the emissions of inland barges. In this report use of LNG as fuel for inland barges will be discussed, evaluated and reviewed by two to the six students of the group.

This report can be useful for anyone interested in the matter. First of all the chemical composition and the properties of LNG are discussed. Then, three different kinds of engines that run on LNG are described and an analysis of the necessary adjustments to the ship is made. The necessary bunkering facilities are examined as well. The use of LNG as marine fuel for inland shipping has an economical impact; this is discussed in one of the chapters. At last, some measures to assure the success of LNG operation are described.

The entire group of six would like to thank its teachers Ir. R.G. Hekkenberg, Ir. J.H. Welink and Ir. P. de Vos for their advice and assistance in the completion of these reports. We would also want to mention the Port of Rotterdam Authority for their critical and supportive advice and suggestions and Interstream Barging, more specifically Ton Mol and Rene Overveld, for their field experience and the necessary data. Also TNO, Rijkswaterstaat, EICB and the crew of the MS Aventura and the Da Vinci deserve credit for giving us a view on the world of inland shipping and help broaden our horizon. Last but not least we would want to thank TopTrack, the excellence program of the 3mE faculty of the TU Delft, for enabling us to do this project.

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Summary

To reduce the emissions of inland shipping, several methods have been introduced. One of these methods is the use of LNG as marine fuel. To evaluate this subject, research is needed. In this report some of the most important issues are discussed.

LNG Is a mixture of hydrocarbons, primarily of methane (more than 90 %). It has a high energy density, but compared to diesel the same amount of volume had only 60% of the energy. In other words: a bigger amount of LNG is needed to produce the same amount of energy.
Compared to diesel, the emission of CO_2 is lowered with 20 to 25%. The NO_x emission is reduced between 85 and 90 % and the SO_x production is virtually zero. The amount of particulate matter is close to zero as well.

Three types of engines can be used to run on LNG: lean burn gas engines, dual fuel engines and bi fuel engines. Lean burn gas engines operate on exclusively LNG. Dual fuel engines can run on a mixture of diesel and LNG (the amount of LNG can be up to 90%). Bi fuel engines can run on either diesel of LNG, not on a mixture of both.
It is hard to say how the maintenance costs of thse engines are compared to the maintenance costs of regular diesel engines. This is because of the lack of experience with these engines.

To operate on LNG not only a suitable engine needs to be installed. An LNG storage system and pipes are required as well. So far, pressurized cylindrical tanks have been used to store LNG on board of ships. Double walled pipes can be used to cancel the need for an explosion chamber. These and many more safety precautions must be taken to operate on LNG. Several authorities can have regulations concerning the use of LNG as marine fuel for inland shipping. The IMO, CCR, Port Authorities and National authorities have rules, procedures and guidelines for this.

Bunkering can be done in two different ways, the normal way, which is bunkering the LNG from shore or a ship to the barge, or via a container that is loaded on board. At the normal bunker points special LNG storage and bunker station need to be constructed. The costs for these stations can't be determined in detail, because new technology makes it possible to create less expensive stations.

The costs of building an LNG fueled ship are 30 % higher than the building costs of a diesel fueled ship. The costs of the LNG systems are more expensive and the engineering work is costly. The difference will change since the larger scale of production for the LNG systems will lead to cheaper equipment. The engineering work will cost less since the engineers will become more experienced. Once clear regulations for the construction of LNG fueled ships are made, the engineering costs will drop considerably.

In order to recuperate the higher initial cost, the cost of LNG must be lower than that of an equivalent amount of energy of diesel. An analysis model is made to estimate the pay back time of

the higher initial investment. The distance a ship covers and the price difference between diesel and LNG are two very important factors.

LNG can be a cheaper alternative for diesel, but only when a certain amount is used for marine fuel. Only then the costs for infrastructure will be overcome by the lower price for LNG. This means that approximately at least 120 inland barges of the 110 meter length class need to be powered by LNG to make LNG a cheaper alternative. Or other types of vessels need to be powered by LNG.

Several measures can be taken to ensure the success of the use of LNG for inland shipping. Since the building costs of LNG ships are considerably higher, some kind of stimulation will be needed to convince ship owners to choose for LNG. Subsidies, tax reductions and other financial benefits could be offered. To ensure bunkering facilities will be made, the cost of these facilities can be stimulated as well. Anyway, clear regulations concerning the construction of LNG fueled ships must be made. This will lower the high building costs on a natural way and will make subsidies unnecessary.

It is concluded that LNG can be a working alternative for diesel, but only if the regulation is distinct and the infrastructure is well produced and supported. Another demand is that the government should support LNG as fuel. These demands are essential to bridge initial higher costs and make LNG a cheaper alternative for diesel.

1 Introduction

An overall growing conscience of climate change is having its effects on governments and regulations. Harmful emissions are being set to maximum boundaries that are lowered step by step. This is also the case in the sector of inland shipping. The sector is therefore looking for different ways to accomplish a reduction of emissions. Different types of fuel and propulsion systems are being investigated and the use of LNG as marine fuel seems to be one of the most promising developments. In this report some of the most important issues are investigated. This research is needed in order to evaluate this subject.

In the first chapter the properties of LNG will be briefly discussed. In the second chapter the emissions of LNG are discussed. The technologic aspects of LNG driven prime movers will be examined in the third chapter. In chapter four the infrastructure needed to assure LNG storage and bunkering will be investigated. Chapter five gives insight in the costs concerning the use of LNG as marine fuel for inland shipping. The sixth chapter then examines weather operating on LNG would be a success, and if not: which measures would be necessary to make it a success. The conclusions of this entire research can be found in the last chapter.

2 What is LNG?

LNG Is the abbreviation for 'liquefied natural gas'. As the name suggests it is the liquid state of natural gas, which is a very common fossil fuel.
Natural gas is made liquid for the ease of transporting and storage. To get LNG at its liquid state, it's dried, cooled and dry-cleaned until it is at a temperature of -162°C at atmospheric pressure. When liquefied, the volume of natural gas decreases about 600 times. (1) In other words: the same amount of LNG and natural gas, has a volume difference of about 600 times.
At this moment, LNG is mostly used for domestic heating or as fuel for producing electricity. (2)

2.1. Chemical composition of LNG

LNG is a mixture of hydrocarbons, primarily of methane. Table 1 gives an overview of the composition of LNG from various origins.

Table 1: Composition of LNG in mole percentage (3)

Hydrocarbon	Methane	Ethane	Propane	Butane	Nitrogen
Alaska	99.72	0.06	0.005	0.005	0.20
Algeria	86.98	9.35	2.33	0.63	0.71
Baltimore Gas & electric	93.32	4.65	0.84	0.18	1.01
NY City	98.00	1.40	0.40	0.10	0.10
San Diego Gas & Electric	92.00	6.00	1.00	-	1.00

The high concentration of methane gives LNG a very high energy density. Methane is the simplest of hydrocarbons. Each carbon atom has four hydrogen atoms attached to it; this makes methane the hydrocarbon with the highest percentage of hydrogen atoms per carbon atom attached. This gives methane the best ratio of heat per mass unit of hydrocarbons, which makes methane a very suitable and efficient hydrocarbon for the use of energy generation. Figure 1 shows the structural formula of methane.

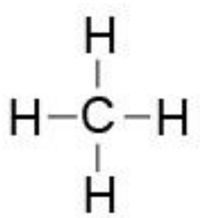

Figure 1: Methane

The lower heating value of diesel fuel is about 42.7 MJ/kg, the lower heating value (LHV) of LNG is about 49.46 MJ/kg. The density of LNG is lower than that of diesel fuel, so the LHV's become 35014 MJ/m^3 for diesel and 22460 MJ/m^3 for LNG. (4)
A quick calculation shows that the energy density in volume of LNG is about 60% of that of diesel fuel. (4)

2.2. *Emissions*

Since the maximum emissions of inland shipping are being lowered, the sector is looking for ways to reduce the formation of CO_2, SO_x, NO_x and PM. One of the ways to reduce the emissions is to switch from diesel fuel to LNG as marine fuel.

Figure 2: Exhaust of a cruise ship (5)

2.2.1 CO_2

Since LNG is primarily made of methane, we will compare the combustion process of methane with the combustion process of diesel fuel. The combustion process of methane is shown in comparison 1.

$$CH_4 + 2 \cdot O_2 \longrightarrow CO_2 + 2H_2O \qquad [1]$$

For combustion engines running on diesel fuel, the amount of CO_2 created is shown in comparison 2.

$$n_c^f \cdot C + n_c^f \cdot O_2 \longrightarrow n_c^f \cdot CO_2 \qquad [2]$$

It shows that the amount of CO_2 created is dependant of the structural composition of the hydrocarbons in the fuel. That is why it is less efficient to combust advanced hydrocarbons with long carbon chains instead of burning simple hydrocarbons like methane. More mass of diesel fuel than methane is needed to achieve the same amount of energy.

A calculation can be made to compare the CO_2 emission of different fuels. The carbon content of the fuel (the percentage of carbon in the fuel) and the lower heating value must be known. The calculation method is described below.

First of all, the carbon content of the fuels must be known. To estimate what the carbon content of LNG and diesel is, a simple calculation is made. The chemical composition of diesel is assumed to be $C_{12}H_{26}$ and that of LNG is CH_4.
The carbon content is then calculated by dividing the weight of carbon in the fuel by the total weight of the fuel.
For diesel the calculation becomes 12*12/(12*12+26*1) and for LNG it equals 1*12/(12*1+4*1). The results are a carbon content of about 85% for diesel and for LNG about 75%.

The amount of fuel needed to get a certain amount of energy can then be calculated with the LHV of the fuel. As stated above in chapter 2.1, this is about 42.7 MJ/kg for diesel and 49.46 MJ/kg for LNG. In other words:

1kg diesel equals 42.7 MJ
1 kg LNG equals 49.46 MJ
1.16 kg diesel equals 49.46 MJ

At last, the CO2 emission for this amount of energy can be calculated and compared. The following formula is used:
CO_2 emission for 1 MJ = mass of fuel needed for 1 MJ * carbon content of fuel * 44/12
For diesel this calculation is 1.16*0.85*44/12 and for LNG this is 1*0.75*44/12. The results are 3.62 and 2.75 kg CO_2. This is a reduction of CO_2 emission of about 25%. The real emission reduction will probably not be this high due to impurities in the fuel. A reduction of 20 to 25 % is therefore realistic.

2.2.2 NO_X

NO_x Is made of nitrogen and oxygen particles. At ambient temperatures the reaction to form NO_x does not take place since it is a heat-absorbing reaction. That is why at high temperatures, for example in an combustion engine, the formation of NO_x is possible. (6)

LNG Driven engines have lower NO_x emissions than diesel fuel driven engines. The lower emission of NO_x can be explained by the lower combustion temperatures. These are accomplished by the large

amount of air that is admitted. Up to 75% more air than needed for complete combustion is admitted into the combustion chamber, causing lower combustion temperatures.
Also, NO_x has less time to form in an LNG engine than in a diesel engine. LNG is premixed with air so when it ignites, it burns faster. The combination of the lower maximum temperature and the shorter period of that temperature, would lead to lower NO_x emissions. (7)

The amount of NO_x reduction is not easy to estimate. According to Det Norske Veritas the NO_x reduction is between 85 and 90 %. (8)

2.2.3 SO_X

The amount of SO_X formed is completely dependent of the amount of sulfur in the fuel. Since the amount of sulfur in LNG is virtually zero, almost no SO_X is formed. (1)
Compared with diesel fuels, where the amount of sulfur is significant, the switch to LNG as marine fuel would mean a total drop of SO_X emissions.

2.2.4 Particles / soot

Particles are the result of incomplete combustion. The fuel composition determines the sooting tendency during combustion. The amount of naphthalene's, benzenes and aliphatics (alkanes, alkenes and alkynes) are measures for the sooting tendency. Since none of these can be found in LNG in considerable amounts, the emission of Particulate matter is close to zero. (4)

3 Technical issues of using LNG driven prime movers

If LNG is to be used as marine fuel, the possible power generation systems need to be examined. Subsequently the requirements of storage and transportation of LNG on board of the ship will need to be investigated. The auxiliary systems that are needed to operate on LNG will be discussed in this chapter as well. This chapter ends with an overview of regulations concerning the use of LNG as marine fuel.

3.1. Technical analysis of LNG engines

Tree types of gas engines can be used to operate on LNG; lean burn gas engines, dual fuel engines and bi-fuel engines. The basic difference between the systems is that lean burn engines operate on gas only. Dual fuel engines run on a mixture of LNG and diesel fuel. Bi-fuel engines can run on either diesel or gas, but not on a mixture of both.

For all these engines it is still very hard to say how the maintenance cost is compared to regular diesel engines. This is because of the relatively young age of these engines. They have not been in production/ use for a long time and that is why not much is known about this issue.

3.1.1 Lean burn gas engines

Lean burn gas engines work on a similar way to regular diesel engines. These engines have lower CO_2, NO_x and particles emissions than diesel engines.
Lean burn gas engines are therefore attractive to use as main engine. The same amount of power can be produced whilst lowering the emissions.

Figure 3: Lean burn gas engine, manufactured by Rolls Royce

3.1.2 Dual fuel engines

Dual fuel engines can run on a mixture of diesel fuel and LNG. The mixture consists of up to 90% gas. The engines can also operate on diesel fuel alone. This gives the advantage that when bunkering of LNG is impossible, the engine can keep running. Another advantage is that many existing diesel engines can be retro fitted to be a dual fuel engine. This makes it very attractive for many ship owners who wish to accomplish a reduction of emissions without buying an entirely new engine.

3.1.3 Bi-fuel engines

Bi-fuel engines can operate on diesel fuel or on LNG. When no LNG is available, the engine can still keep running on diesel fuel. When operation on LNG is possible, the engine has considerably less emissions.

3.1.4 Maintenance of LNG engines

It is hard to give judgement about the maintenance of these LNG engines for inland shipping. Not many of these engines have been manufactured and none of them have been working as long as diesel engines.

One could try to compare the marine engines with the performance of LNG engines that operate at sea. These engines have been used for quite some time now and they have not yet shown big issues concerning maintenance; this can be assumed because of the lack of alarming information about this theme. This could be seen as an assurance that no major problems will occur.
It must be said that this comparison is not conclusive. The engines that operate at sea are larger and produce considerably more power than the engines that would be used for inland shipping. This scale difference can lead to different problems.

Comparing to trucks and other transportation methods that run on LNG will also lead to inconclusive results. The same conclusion can be made for comparison with land based LNG engines.

3.2. LNG Reservoir and pipe requirements

To operate on LNG, not only a suitable engine needs to be installed. The system that leads the LNG to the engine is one of the necessary installations. Of course a storage system for the LNG is required as well.

So far pressurised cylindrical isolated stainless steel tanks have been used to store LNG on board of a ship. The use of pressurised tanks makes the transportation of LNG to the engine easy. Since there are no moving parts in this transportation system, it is a simple way to carry the LNG to the engine. A pressure smaller than 5 bar is common for these reservoirs.
The biggest issue of this kind of LNG storage is the size of the installation. The space needed to place the tank is considerably larger than the space needed to store an equivalent amount of MDO (Marine Diesel Oil). It can take up 2 or 3 times the space of the equivalent MDO storage.
Another point of attention is the weight of the installation. Even though an equivalent (energy-) amount of LNG is less heavy than MDO, the entire storage installation (fuel included) of LNG is about 1.5 times as heavy as that for storage of MDO. (9)

3.3. Auxiliary requirements for operation on LNG

In the storage tank there will always be a small amount of LNG that becomes gaseous. A system that extrudes this gas from the tank is needed to ensure a constant pressure inside the tank. When the pressure is kept constant, no energy is needed to maintain the low temperature.
This can be explained by the ideal gas law that states “pV=mRT”. In words this is “pressure*volume = mass*universal gas constant*temperature”. Since the mass, volume and universal gas constant do not change, the temperature will stay constant if the pressure is kept constant.

LNG is not explosive, corrosive or toxic. When it leaks, it will become gaseous since the ambient temperatures are higher than LNG’s boiling temperature. Natural gas is flammable. It has an ignition temperature of about 600 ^{o}C, but can only combust when the concentration of air is between 5 and 15 %. (4) Thus, when the correct safety precautions are taken, LNG is as safe as other fuels.

Some possibilities to reduce hazardous situations will now be discussed.
In case of a leak or spillage, safety may not be endangered. Normal steel is not up to the cold temperatures of LNG, which means that suitable materials must be used in the areas that can be soiled with LNG.
LNG Supply to the engine must be stopped when a leak occurs. When LNG leakage is not stopped by turning of the supply, the room in which the LNG is stored can be closed down.

When the room is closed down, systems that prevent fire and an explosion can be set to use. The room can be designed as an explosion chamber in case of an explosion, so no further harm can be done to the ship.
Double walled pipes can decrease the necessity of these safety measurements like the explosion chamber. The working principle of these double walled pipes is as stated next. The inner pipe lets the LNG be transported. When a leak occurs in this pipe, it is caught in the outer pipe. The leaked LNG turns into natural gas in this second pipe and can then be extracted from it.
Double walled LNG tanks can also be used to decrease the risk of an explosion. The working principle is the same as that of double walled pipes. (9)

These systems are very expensive. More about the cost of operating on LNG is found in Chapter 5.

Several organisations can have regulations concerning LNG systems and safety precautions. A list of these instances is given below in table 3.

Table 2: Regulations concerning LNG operation

authority	**Edition**	**Subject**
IMO	Marpol Annex VI	Emissions
IMO	Interim guidelines for gas fuelled ships	Design and operation rules for gas fuelled ships
IMO	'formal safety assesment'	Procedure for ships that aren't built 'by the book'
CCR	ADNR	Procedures, guidelines and safety precautions
International Authorities (e.g. European Union)	Several editions (e.g. Inland waterway transport legislation)	Procedures, guidelines and safety precautions
National Authorities (e.g. Ministerie van V&W)	Several editions (e.g. Binnenvaartwet 2007)	Procedures, guidelines and safety precautions
Port Authorities (e.g. Port of Rotterdam)	Several editions (e.g. Havenbeheerdverordening 2010)	Procedures, guidelines and safety precautions

The biggest issue of these regulations is that they have been made without consideration of LNG fuelled ships. According to The MAGALOG regulations need to be further developed and specified for this cause. (4)

4 Necessary infrastructure for bunkering of LNG

There are two ways of bunkering LNG, the first one is with the use of pumps and the second way is by loading a container with an LNG tank aboard. For the bunkering of inland barges new bunker stations will be needed.

4.1 Bunkering LNG and the ordinary way of bunkering

The Norwegian ferry Fjord1 is LNG powered and has two bunkers of 125m^3 each. Every three nights the Fjord1 is bunkered. In a total of two hours the bunkers of Fjord1 are filled up. The bunker station has two tanks of 500 m^3 with pumps that can bunker the Fjord1 in only two hours. This means that the pumps have a capacity of *at least* 62,5m^3/h each. (10)

LNG is used in a variation of other industries, like the household energy supply market or the transportation of LNG in large LNG tankers. Way larger pumps are used in these kinds of industries. It can be concluded that pumps made especially for the transportation of LNG are developed well enough to be used at bunker stations.

For comparison barges that are powered by diesel with LNG powered barges, an inland barge is chosen with a length of 110 meter. These inland barges have three bunkers. Two bunkers aft with capacities of approximately 20 to 25 m^3 and one fore with a capacity of about 10 to 15 m^3. It's normal for these barges to bunker 20 to 30 m^3 about two times a month (11). If these tanks were replaced by tanks capable of holding the same energy-wise amount of LNG, the tanks would be needed to be 1.56 times larger, as shown in paragraph 1.1. Having larger tanks is not desired, since there is little room to fit these cylindrical tanks and strong regulation about the location of the tanks.

The assumption is made that the inland barge has the same bunker capacity of LNG as diesel fuel. The energy density, with respect to capacity, of diesel fuel is 1.56 times larger than the density of LNG, as stated above. Assuming the tanks remain the same size, the inland barge will have to bunker three times a month instead of two times.

Bunkering of diesel oil usually happens in three different ways: at a bunker station (or bunker barge), during sailing and during (un)loading. Due to current regulation it is impossible to bunker LNG during sailing or during (un)loading (12). This is a big disadvantage of powering a ship by LNG, because the barge-owners cannot be as flexible with the LNG powered barges as with an ordinary diesel powered barge. Plus the fact that the LNG powered barges have to bunker at least one time more per month makes it harder to handle the barges in a flexible way.

When research has been done about the effects of bunkering LNG during sailing and (un)loading regulation can be made. Safe ways of bunkering LNG need to be developed so LNG powered barges can be as flexible as diesel powered barges.

Because of the fact that the barges need to bunker LNG more often than diesel, it is very important that there is sufficient capacity at the bunker stations. The port of Rotterdam for example will soon have an LNG terminal (13), where it would be the cheapest and easiest to create a bunker station. The advantages are that there already is a flow of LNG towards the terminals and the terminals only have to grow, very little scale-wise, instead of invest in a lot of different new equipment.

However, the flow of LNG for bunkering is insignificantly small in comparison with the flow of LNG to energy suppliers, one could question if the investments for installations, permissions and safety procedures are not too large for the bunker station to be profitable.

There is no need to add more bunker locations if the current locations are expended so they can serve more barges at once. It is recommended that the bunker locations are placed at the big ports and important transitions. The inland barges will always at a certain time be near a bunker location three times per month when the locations are placed in larger ports. To make LNG an attractive alternative, the bunker locations should be very accessible and there should be as little waiting time as possible.

The bunker stations, the ones that are not next to an LNG terminal, will receive relatively more LNG than diesel because of the fact that the barges powered by LNG will have to bunker more often. The transport of the LNG to the bunker locations can be fulfilled by few inland LNG carriers and the smaller stations can be supplied by tank trucks. The costs of the transportation of LNG to the bunker station will probably be relatively more expensive than the current diesel flow.

It is impossible to have economically viable LNG terminals with less than 10.000 m^3 capacity. The investment costs of a terminal of this size are in order of tens of millions Euros. LNG tank stations for road traffic already exist, for example the tank station in Oss of Vos Logistics. If these tank stations would be combined with bunker stations for marine traffic, costs could be pressed. (14)

4.2 Bunkering by container

Another way of bunkering is by the use of an LNG container. This container can hold up to 31.5 m^3, at the size of a 40 foot container (15). If the tank is empty, it can be replaced in very little time. This system is a lot more flexible than the one described above.

However, it can be very unpractical to have a container on deck. Inland barges have to take account of height restriction, because of bridges. So it is not desired to have additional height on deck. Another issue is that there is not always enough room on deck to fit a 40 foot container. There also still are safety regulations that need to be worked out on this topic.

4.3 Onshore storage of LNG

There already are regulation (16) and ISO norms (nen-en 13645:2002) about storing LNG onshore. However, there is none yet about bunkering LNG to ships. This makes it difficult for parties to invest in bunker stations. It is considered important that clear regulation and norms exist about LNG bunker stations to make it possible and easier to find investors and to increase the rate that bunker points will be placed.

Relative small LNG terminals have investment costs of tens of millions Euros. It is unsure what the exact numbers are, because new technologies have been developed which can lower the costs (14).

5 Impact on costs

The initial cost of building an LNG fueled ship is higher than the cost of building a diesel fueled ship. The costs are up to 30% higher. (17) This cost is higher because of the (additional) LNG installations that are discussed in Chapter 3.3. Most of all the higher costs ate because of the engineering work that is needed.
Engineers are faced with new systems they have to incorporate into a ship. Since it's all pretty new it costs more time and energy to get it right. This higher cost due to engineering work will become lower over time. Once clear regulations are made that can be followed by engineers, this cost will probably drop considerably.

The cost of LNG is lower than that of an equivalent amount of diesel. The figure below shows the price evolution of both fuels. Notice that the price of crude oil is given and not that of diesel, just as the price of natural gas is given instead of the price of LNG. The cost of diesel is higher than that of crude oil, this also accounts for LNG and natural gas. Calculations are based on these prices since better information is hard to find and hard to compare. Taxes, location and many other circumstances have a large effect on these prices and it can make a good comparison very difficult to make.
On the graph below the scales are different to show the correlation of the evolution. To compare equivalent amounts of energy one must know that 1 barrel of crude oil equals 5,6 MMBtu. (18)

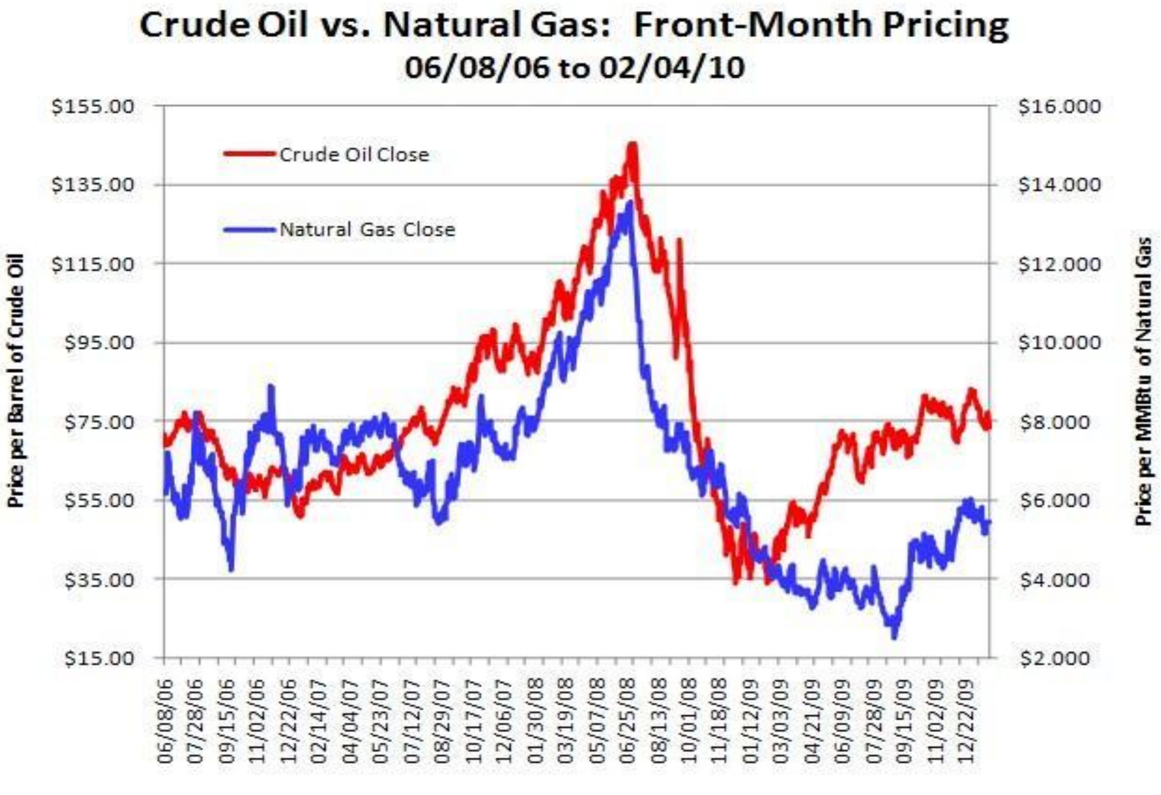

Figure 4: price evolution of LNG and crude oil (19)

When comparing the last data of about 75 dollars per barrel of crude oil and 5.5 dollars for one MMBtu of natural gas, one can see that the same amount of energy has an 'energy price difference factor' of about 2.4. This is calculated by multiplying 5.5 by 5.6 to achieve the price of an equivalent amount of energy. This equals about 31 dollars; this is 41% of the 75 dollars. This means that for the same amount of energy the price of crude oil is 2.4 times higher than that of natural gas, 2.4 is calculated by dividing 100 by 41. The energy price difference factor is 2.4.

The price difference factor used in chapter 5.1 is not this 'energy price difference factor' described here above. The energy price difference is for an equivalent amount of energy. The 'volume price difference factor' is for an equivalent amount of cubic meters of the fuel. This is used in Chapter 5.1. Calculating the volume price difference factor when the energy price difference factor is known can be done like this:

Crude oil: 1 amount of energy equals	1 m^3 equals	100% of the price
LNG: 1 amount of energy equals	1.66 m^3 equals	41% of the price
LNG: 0.6 amounts of energy equals	1m3 equal	25% of the price

The volume price difference factor is calculated by dividing 100 by 15. The price difference factor is just about 4.
Don't forget that this is the volume price difference factor with crude oil and natural gas and not with diesel and LNG.

When the price of LNG stays lower than that of diesel, the extra cost of building an LNG powered barge will be payed back by the lower energy costs. When the cost of LNG and diesel are the same for an equivalent amount of energy (the volume price difference factor in that case is 1,666) the investment will not be regained.

5.1 Analysis model

To compare LNG and diesel driven ships an analysis model has been made in Excel. It compares four kinds of ships with different kinds of prime movers. A diesel engine, a lean burn gas engine, a dual fuel engine and a bi fuel engine are chosen for this analysis.

The input parameters for the model are:

- The purchase price of a diesel powered ship
- The distance the ship covers in one year
- The average fuel consumption over 1 km
- The fuel price of diesel (and LNG)
- The volume price difference factor of LNG and diesel
- The average percentage of LNG in a dual fuel engine
- The percentage that a bi fuel engine runs on LNG

The assumptions made in the model are:

- The purchase price of a ship with a lean burn gas engine is 30% higher
- The purchase price of a ship with a dual fuel engine is 10 % higher
- The purchase price of a ship with a bi fuel engine is 30 % higher
- The yearly maintenance cost of a diesel fueled ship is 10 % of the purchase price of the ship
- The maintenance costs of ships with a lean burn gas engine are 10 % lower
- The maintenance costs of ships with a dual fuel engine are 10 % higher
- The maintenance costs of ships with a bi fuel engine are 10 % higher

These assumptions are made because of a lack of information. It is still very hard to find concrete values about this because LNG as marine fuel for inland shipping is a new development. The lack of experience in this matter causes difficulties when trying to make calculations.

The calculations made in the model are:

- The yearly total operation price equals the fuel and maintenance costs
- The yearly saving of operation price is the difference of the operation price compared to the operation price of a diesel fueled ship
- The pay back time is calculated by dividing the purchase price difference through the yearly saving of operation price
- The price of one m^3 LNG is calculated by dividing the fuel price for one m^3 diesel through the volume price difference factor

The results of the model are:

- The pay back time of the three LNG powered ships
- The reduction of emissions (expressed in percentage)

The model does not take into account:

- Possible loss of time (and money) because of change in yearly bunkering time and frequency
- Financial effects caused by interest, taxes and reduction of emissions

A visual representation of the results is given in the next figure. It shows the pay back time for the three different kinds of LNG engines for a range of total yearly distance.
The volume price difference factor is 4 for these graphs.

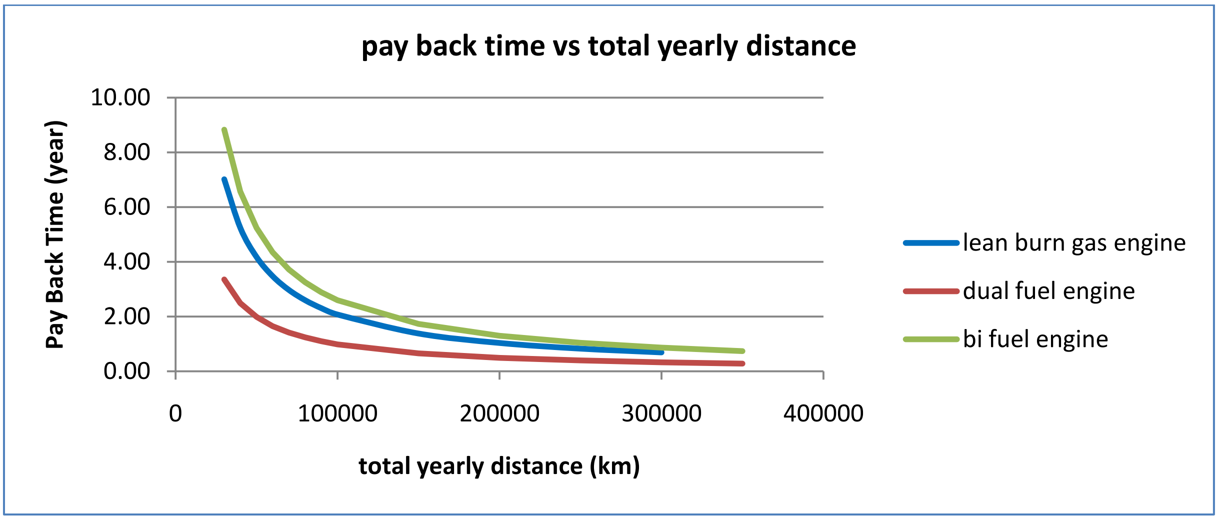

Figure 5: pay back time different LNG engines, variation on total yearly distance

Another figure that can provide a good insight in the matter is about the price difference factor. The graph shows the lower limit at a price difference factor of about 1.66. This affirms what is said in the last sentences before this chapter; that the use of LNG will only be payed back when the volume price difference is higher than 1.66.
The total yearly distance is 80000 km for these graphs.

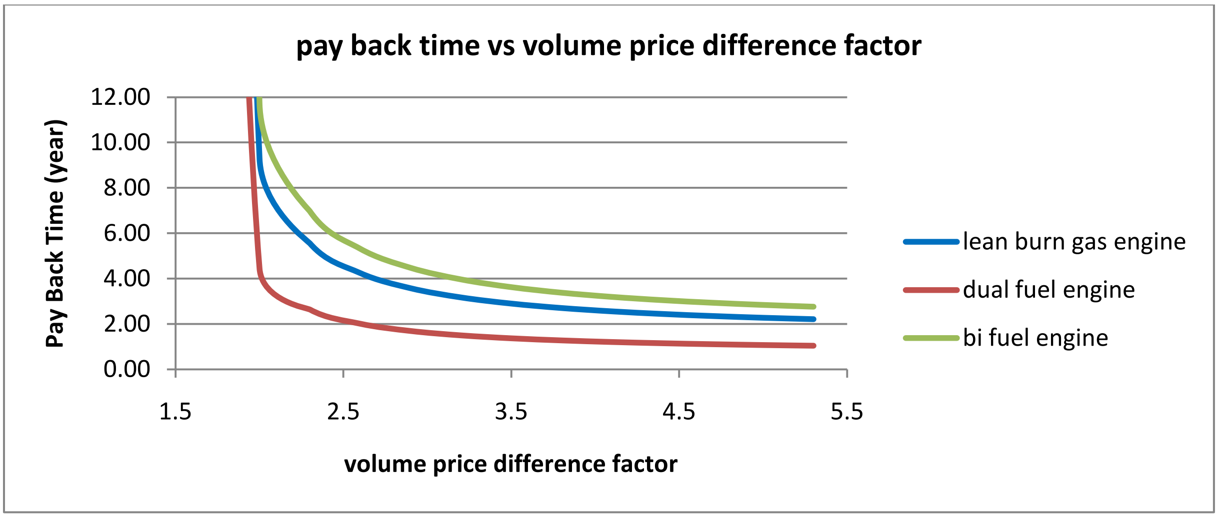

Figure 6: pay back time different engines , variation on price difference factor

5.2 LNG price

In figure 7 the price of LNG is compared to the price of oil at different crude oil prices according to a research performed by MARINTEK. In the figure it can be seen that the LNG price is dependent of the crude oil price. The figure also shows that LNG will be a lot more attractive if used on larger scales. As described in paragraph 6.2, a partner is needed to overcome the first investment costs that will be higher than diesel prices. When there are sufficient customers for LNG there is no need any more for the support of a third a party.

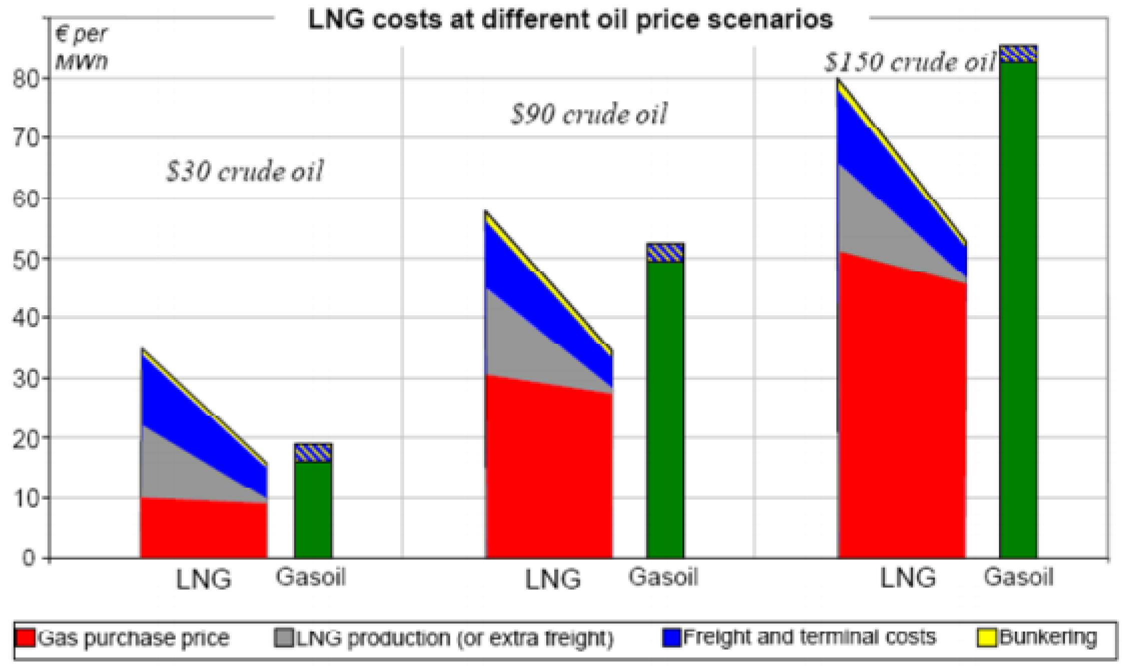

Figure 7: LNG costs at different oil price scenarios (20)

Figure 8 shows the transport en storage costs of LNG. These costs are based on the application of LNG powered barges in Norway. The LNG price therefore is related to the European gas price.

Transport and storage costs exist of:

- Small scale LNG production
- Freight to a bunkering port
- Terminal at bunkering port
- Bunkering operation for a terminal at bunkering port

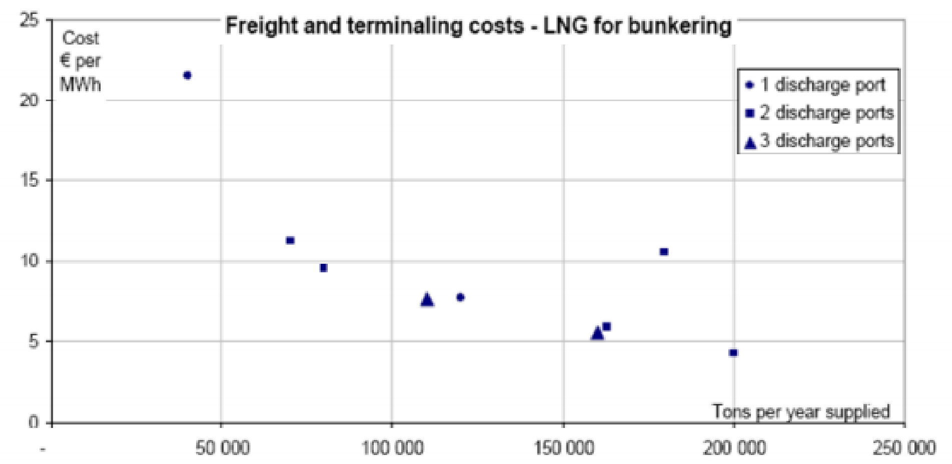

Figure 34: Shipping and terminaling costs at different discharge port combinations and different annual quantities. Costs in € per MWh of energy in LNG. Based on calculations by MARINTEK.

Figure 8: Freight and terminaling costs (20)

At the current crude oil price, 83 dollar per barrel at 26-11-2010 (21), the $90 crude oil scenario can be adopted, with a small correction. At a production of 50.000 ton per year or more, LNG will currently be a cheaper alternative. With an important note that one time investments needed for infrastructure, storage and bunker stations are not taken account with in this calculation.

The density of LNG is about 0.46 ton per m^3 (22). If one states that about 25 m^3 is bunkered three times per month, the ship bunkers about 405 ton per year. To make LNG less expensive than diesel, about 123 ships of the 110 meter length class need to be powered by LNG. Or other barges, like RoRo, ferries and other line service barges need to be powered by LNG.

It can be concluded that it is of great importance that LNG is used on a large scale to make it an attractive alternative to diesel. If the initial costs are bridged and LNG production is suitable for large scale powering of ships, LNG will, on the long term, be not only cleaner, but also a cheaper alternative fuel.

6 Measures to assure success

The necessary techniques to use LNG as marine fuel already exist. The challenge that is faced now is to make it is a success. In order to operate on LNG, the necessary infrastructure needs to be installed and ships must be equipped with suitable engines and systems.

Since the use of LNG would be new to the sector, ship owners and builders must be convinced of the practical use. To achieve this, decent information about the theme must be spread. This will not be enough to ensure the success of operation on LNG. To convince ship owners and builders to make the investment, the installation of LNG equipment on board of a ship will need to be stimulated. Along with this, the necessary infrastructure must be build to facilitate them.

Many ship owners will not install LNG systems on board until clear regulations are made.

6.1. Stimulation for installation equipment on board

The initial costs of installing an LNG engine and the necessary systems are large. Ship owners will need to be convinced of the benefits of operation on LNG. This can be accomplished on several ways.

A clear and simple cost/benefit model can be made. An estimate of when the initial costs are earned back will give ship owners an insight in the matter.

Still, the initial costs of the installation might be too large to pay at once. Authorities could develop a loan especially for sustainable initiatives. Low interest could be a trigger for ship owners to decide in favor of LNG operation.
Other ways to stimulate this development can be made by taxes. For example: sustainable options could have a lower tax fee than the less sustainable options.
There are many alternative ways to stimulate the installation of LNG equipment on board. Harbor dues could be reduced for ships that have low emission, each year a price could be given to the ship that has made the biggest emission reduction per kilometer, etc.

Several initiatives to stimulate the use of LNG as marine fuel already exist. The financial support that is given by the government is arranged in different ways. The situation for the Netherlands is discussed here below.

The Vamil and MIA are initiatives of the ‘Ministerie van Infrastructuur en Milieu’, a Ministry of the Dutch government. They have an ‘ecological list’ of all the investments for wich they can give financial support. MIA Offers a tax refund and Vamil gives the opportunity of choosing when to write of costs.

The EIA gives a reduction of taxes as well. The EIA is a tax service that the Dutch government has installed. The EIA has not yet included an LNG installation to its list of investments that come into account for the tax reduction, but this is probably a matter of time.

The green funds scheme makes investments in ecofriendly projects attractive. When the projects are financed with external money, it offers very low interest rates.

6.2. Stimulation for building the bunkering infrastructure

It's important that the building of the infrastructure that is needed for the bunkering of LNG is supported by the government. At the early stages of the transition period, it's likely that there will not be many customers for LNG bunkering, which will make it unattractive for investment companies to invest in LNG bunkering infrastructure. This will eventually scare investors from sailing their ships on LNG. To break this spiral, a third party, most likely the government, is needed to support sailing on LNG for reasons of sustainability.

LNG provides a smaller emission of CO_2 overall, than the CO_2 emission of diesel. The amount of CO_2 that is saved by sailing on LNG is valuable on the emission trade market and can be sold. Another possibility is that other national industries are allowed to emit more, which can improve the national economic position.

The boosting for use of LNG of the government is only needed in the stage of transition from diesel to LNG. There is no need for long time subsidies of any kind. It is hard to say if the use of LNG will be economically viable for the government.

6.3. Clear regulations

Without clear regulation it is very difficult to attract investors. When regulation has been made regarding engines powered by LNG and LNG bunkers, ship owners and investors can research opportunities of powering their ships by LNG or building a bunker station. At this stage, there are not yet regulations made specifically for the use of LNG as marine fuel in inland shipping. The design process is delayed substantially and is very costly.

7 Conclusions and recommendations

Norway has proven that it in fact is possible to have ships operate economically powered by LNG. The future will show how long the newly developed LNG powered engines will last, but it is expected that there will be no major setbacks. Norway is an excellent example for the Netherlands to follow. LNG is cleaner and can even be a cheaper alternative to diesel. With upcoming tier III regulation, and even more strict regulation to be expected in the future, an alternative to diesel has to be found.

With low emissions and the opportunity to create LNG out of used material, LNG is environmental friendlier than diesel made out of crude oil. Emissions of NO_X can be lowered by as much as 90%, CO_2 emissions can be lowered, SO_X emissions reduced to virtually none and soot can be reduced as well.

Initial development costs for ship design and infrastructure will be high at first. Important to note is that these costs only have to be made one time. When the infrastructure for LNG flow has been created, the proper regulation has been developed and barges powered by LNG are sailing inland, the costs will lower over time until a breakeven point is reached. After this point, LNG powered inland barges will even become less expensive to operate.

The payback time of the investments made by ship owners is relatively short. Depending of the difference in diesel and LNG price, the investments, which are usually about 15-20% more than the usual diesel powered ship, will pay back in a few years.

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Literature

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List of figures