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M.Sc.THESIS

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LNG as fuel in global trades for Höegh car carriers	14.06.2011
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Abstract:

Environmental challenges, high fuel prices and technological development of natural gas production and handling have made LNG an interesting subject for a future fuel. The planning and building of regasification and liquification plants shows signs of a future LNG network that can be utilized for ships as well as the traditional industry consumers.

The purpose of this work is to get familiar with the developments in relation to this situation, and determine the various influences and players in the market. In addition, future regulations will also play a part in global shipping as various areas will have limitations in the types of fuels being allowed. In addition the all the external factors, Höegh Autoliners operate a fleet of 60 car carriers in a global network with a dynamic route schedule. The LNG fueled alternative must also fit in the ship owners operation and management in order to be a choice.

By the sum of these factors, I have found it to be possible for Höeghs vessels to operate their ships with LNG as fuel. The different configurations, being either dual fuel or purely LNG, are dependent on several future factors, such as fuel prices, utilization, freight rates and range requirements.

The work has been very informative and has opened for finding new solutions in relation to shipping and future challenges.

Keyword:

LNG, HFO, MDO
ECA, Emissions
Fleet operation, Car Carriers, RoRo

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Master thesis

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Global warming, emission control areas and rapidly increasing oil prices has again turned focus towards new design and solutions within shipping. The candidate will in this work evaluate LNG as fuel in global shipping for the RoRo fleet operated by Höegh Autoliners. The following aspects will be the main content of the work:

Background study of LNG in order to clarify following points:

- Present status for LNG production
- Future development based on current trends and future outlook
- Global markets and supply of LNG
- Availability as fuel for ships in global traffic
- Feasibility of LNG as fuel, compared to the alternatives

Study the experience connected to LNG as fuel:

- Define and find risk aspects connected to LNG onboard.
- In general describe the development connected to LNG as fuel, both connected to ship types, engine types, tank and refueling systems, classification societies etc.
- Discuss other comparable practices and studies executed in order to evaluate LNG and how robust these studies and experiences are.

Analyze the environmental effect of LNG compared to fuel oil. Also study current and future status of emission.

Connect the findings up to Höeghs fleet of car carriers. Evaluate the conclusion on terms of the entire Höegh operated fleet, with these aspects in particular:

- Trade routes and demands
- Ship types and operation profile
- Aspects connected to ship management, down time and reliability
- Company strategy and other factors

Evaluate the solution using analyses and calculations:

- Optimization methods
- Risk analyzes
- System based ship design
- Financial and economical calculations connected to investments

Conclude on grounds of the results from the studies and the evaluations. Discuss this conclusion, define a solution, and give a final suggestion to the ship owner.

The study is formulated in cooperation with Höegh Fleet Managements Vessel Performance division. The main contact in Höegh is Hans Anton Tvete, who will also assist with computer tools and access to ship/shore reports and fleet data. The student will also partially be working on the task at Höeghs offices in Oslo.

In addition the candidate will be in contact with entrepreneur Terje Lade who is currently working on a new design in relation to car carriers, known as "Vindskip". The work will be of mutual interest to both parties.

NTNU
January 15th
2011

Stein Ove Erikstad
Teaching Supervisor

Preface

My objective with this thesis has been to cover the future regulations connected to ships machinery emission, understand the energy market in terms of the price of natural gas, and the possibilities for a deep sea Höegh managed RoRo vessel to operate on LNG.

The work has been written in co-operation with Höegh Fleet Services and Höegh Autoliners where I have also been working as a summer intern and written a project for last semester.

I have had access to ship-shore reporting systems and ship information through their in-house database. I have been at their head office at Skøyen, Oslo, for parts of the time during the semester. Technical supervisor at Höegh Fleet Services has been Hans-Anton Tvete, while project manager Knut Ljungberg had the idea of the possibility of a LNG fueled deep sea RoRo vessel. Tvete has been helping me with everything from meetings with coworkers at other divisions, to set up of computer and work space for me as well as guidance in the ship owners' data base.

I have also had parallel contact with Terje Lade during my work, who is working with a wind assisted RoRo design on behalf of Höegh, intended to be LNG fueled.

This study has been influenced by the first part being a literature study. This is because my project work before the master focused more or less on a separate problem. However, knowledge from the ship operation and ship specific information obtained in the earlier project has been used in this work as well.

I also want to thank Professor Stein Ove Erikstad, my teaching supervisor in the master program. He has been very helpful at defining a suitable thesis that is of high interest for both me and my contacts at Höegh.

Trondheim, 14th June 2011

Martin Wattum

Summary

LNG shipping is tracking back to the 1950s, and has for more than half a century been finding promising. It is not until the last years LNG has been taken into commercial shipping as a fuel, and more widely considered a future main source of energy. This is due to important factors such as shale gas production together with increasing oil prices and pressure for green fuel by states and authorities. Within the new 10 year period, several key harbor areas will have strict limitations in term of fuel being used by the ships.

There are various technical solutions on the market to reduce the emissions from an oil fueled engine. However, as the oil price is predicted to further increase a change of energy source could be profitable.

LNG has a lower energy density than fuel oil and requires also tank isolation to keep it at -163°C. Together with limitations in where it can be installed in the vessel from the class societies makes it less energy dense as similar amounts of bunker oil. This is considered one of the main disadvantages for it to be used in ships.

As found, there are solutions that can be used in order to overcome the downside of LNG being less energy dense than fuel oil. This can be as I have found, to either increase the number of bunkering operations, the governments can install offshore bunkering stations, and one can either take space from cargo decks, redesign ship volumes, or add configurations for removable LNG tanks onboard, used when sailing longer distances. Ongoing development in membrane tanks will also increase the energy density, together with changes in the classification societies rules and regulations.

From studying the ship operation pattern and engine loads, I found that the consumption of fuel oil compared to fuel oil volumes is relatively low. Today, the vessels have a capacity of sailing for about 2 months without bunkering. Still, I have seen and experienced that a bunkering operation is not an issue, and only requires some additional planning. On this basis and picture of the general arrangement and stability data I have found different solutions that will have different effects depending on several factors, such as future fuel price and operational pattern.

In the lean burn gas solution, the design would have to take a volume of 1.500 [m^3] from the cargo space to be able to reach between the longest sea stretches, being from Japan to South America. The cost of lost opportunity will depend highly of the degree of utilization of deck 1. As long as it is under 65%, there will be no cost of lost opportunity. Utilization over this will give an added cost, depending of the freight rates and utilization degree. I found that this solution actually would be profitable as long as LNG is about 10% cheaper than HFO for assumptions regarding operation profile and the mentioned utilization and rates. Since the LNG 2-stroke engine is significantly decreasing in efficiency below 60-70% load, it is likely to be beneficial with shaft generators installed. The size of the main engine would again depend on load and operation.

Another solution is to add extra fuel tanks when crossing the pacific. This will not result in a cost of lost opportunity if the vessel is sailing in other trades. This concept would also be easily loaded and discharged as the tanks can be rolled on and off, with the ramp supporting 150 tons.

The other solution I found is that the existing bunker tank volume included in Höeghs ships is sufficient for the vessel to operate on a dual fuel configuration, with more than 400 tons LNG and

675 tons HFO onboard. If it is possible to add HFO in the volume underneath the LNG-tanks, the total volumes of the two fuels could be 500 tons LNG and 1900 tons of fuel oil. The dual fuel engines are said to be 4% less efficient from statement from engine makers, when operation on HFO mode compared to a pure diesel engine.

In conclusion, the dual fuel design is profitable if the LNG costs are between MDO and HFO-price, and the design will also add values that might also give motivation behind the choice, such as redundancy in the fuel system and a lower climate footprint. If the LNG price is lower than HFO, a purely LNG solution is found to be most likely economical.

Contents

Table of figures

Chart of tables

List of Acronyms

AE	Auxiliary Engine
ARB	California Environmental Protection Agency Air Resource Board
BOR	Boil-Off Gas Rate
CAPM	Capital Asset Pricing Model
CEU	Car Equivalent Unit
CNG	Compressed Natural Gas
DNV	Det Norske Veritas
FE	Far East
FPSO	Floating Production Storage and Offloading
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	Liquid Natural Gas
MDO	Marine Diesel Oil
ME	Main Engine
MGO	Marine Gas Oil
MARPOL	Maritime Pollution
PCC	Pure Car Carrier
PCTC	Pure Car Truck Carrier
RPM	Revolutions per Minute
SG	Shaft Generator

Introduction

Air pollution from the global merchant fleet is today a subject that has grabbed the attention from gouvernmenting forces, and has led to a large development from suppliers and other players in the shipping sector. This focus, together with high fuel costs has created a strong effort for developing new technology for ship propulsion with a new atmosphere for innovative solutions.

One of the solutions that might benefit these interests is a change of fuel in the merchant fleet. Bunker oil has been the obvious source of energy for ships the last century due to its low cost and high availability. This is now expecting to change, as we see a lower oil production on many regions together with high oil price.

Robinson West from the energy consulting firm PFC Energy summed it up in 2007 with the quote: "There are no easy barrels left."

The industry will continue to find vast amounts of oil on more remote regions and at deeper depths, but technology is costly. Together with the high demand for logistics and shipping, the resulting oil price is predicted to continue to grow.

A solution that will reduce emissions is natural gas. Natural gas is a mixture of various hydrocarbons, with methane as the dominating part with a share of often as much as 90-95%. The various mixtures depend on several causes; from where it's found, to if it's from crude oil reservoirs or separate wells If the mixture consists of 95% methane, it is some time characterized as dry or lean. Due to its chemical properties, it emits less CO2, NOx and PM compared to any petroleum product during combustion. It also contains zero sulfur, thus eliminating acid rain contribution from ships. Some of the additional physical properties of natural gas can be found in

When cooled down to under -162 °C, it will reach its atmospheric boiling point, and become a liquid. Liquid natural gas is colorless, non-corrosive, odorless and non-toxic and only 1/600 of the volume compared to gas state. As the technology have improved and demand for energy rises, we see a development in many areas concerning production, transportation and use of LNG.

Natural gas has been a fuel for ferries and a small part of the offshore fleet in Norway for about a decade, and the experience from this small shipping environment will be of importance when perhaps someday implementing it in a global scale for ships on the deep seas.

I will in this work try to find out if LNG is suitable for also deep sea ships, and especially interesting if suitable for a RoRo ship with relatively expensive cargo and high fuel use. I will use Höegh as the benchmark for the study, and answer from their situation regarding operation, routes and ships.

Historical LNG shipping development

Liquid natural gas onboard ship is not a new technology. Already back in 1915, a Godfrey Cabot patented an idea for handling and transporting liquid gas in America, on river barges. And in 1954, Dr. Øyvind Lorentzen had developed and obtained an approval from DNV for a spherical tank with a 17.000 ton capacity. The marine department of Shell in London initiated in 1955 a conceptual ship design study and material survey for finding insulation materials for the inside of a LNG tank. The first LNG taker was the Methane Pioneer. She was a converted cargo ship, and would take the role as a prototype LNG ship that would first prove that transocean shipment of LNG was safe. The first test with filled tanks took place in the fall of October 1958 with trials in the Gulf of Mexico. Following, in January 1959, she left Louisiana heading for U.K. with full cargo. When she arrived, having crossed the Atlantic Ocean, the complete success was proven, and many expected already now a rapid expansion with this new technology.

Figure 1. Methane Pioneer

The first commercial LNG ships where the Methane Princess and Methane Progress. The new build contracts were signed in 1962, with the customer being British Gas. The ships were built on time within the contract price, and the Methane Princess came into service in 1964. She sailed until 1997, and was scrapped in 1998. [17]

Today, there are about 350 pure natural gas tankers in operation in the world. It is currently a considerable boom in production of LNG carriers the last couple of years. The number has increased from a total of 200 vessels in operation in the end of 2005, to almost a double of that amount only during the last 6 years. This is the largest increase within this shipping segment in the history. [18] Where other markets and ships are suffering from an over populated fleet, we see the opposite in LNG shipping. One of the most important reasons for this is the increased demand for energy in fast developing countries such as China and India, where the need of a greener source of energy is a driving factor in the European Union. Another reason behind the increased number of LNG tankers is the fact that the biggest producer, Qatar, and the biggest importer, Japan, are 8000 km apart, and

Japan is increasing its volume of imported LNG. According to the president of Teekay Gas Services, Mr. David Glendinning, by 2020, TK will need another 100 LNG ships, and by 2035 the fleet has to double." [19] The Qatari shipping company Nakilat has pushed the development for large LNG tank ships. They have currently the world's largest LNG fleet in terms of payload capacity.

Figure 2. Large scale Q-type LNG tankers Source: [7]

The last few years Nakilat have increased their fleet with the total number of 25 new Q-flex and Q-max type vessels. These vessels have a nominal cargo capacity of 210.000 to 266.000 m^3, respectively. Such large scale developments are crucial in order to get the most economical situation in terms of a global network of bunkering stations for ship owners with gas fueled fleets. The effect of the large increase in LNG shipping in terms of the probability of natural gas as fuel for cargo ships is hard to determine as of today. One effect is however that this source of energy as is easier to provide in a global scale due to the large quantity of shipments. A large number of LNG-tankers available will hopefully help contribute to a market with high competition and low natural gas prices.

Figure 3. Illustration. Large quantities does not necessary equal large network.

Present LNG market

The present LNG market is a very interesting market in many ways. There is a large growth in technology regarding use of LNG as a source of energy in various industries, power production, vehicles and ships. Especially the coast of Norway is an area with more and more vessels being designed and built for LNG propulsion. As the situation is today, the main portion of LNG-tankers serve particular and large consumers with long term contracts. This is not beneficial for providing a spread network in terms of bunkering for ships. However, with a large tank fleet, more isolated and smaller markets without own production will be easier accessible for LNG tank ships in the future, with the current development and effect of large scale.

There is also an optimistic attitude in general towards finding solutions and possibilities regarding LNG. One specific example is a big player such as DNV, claiming that the age of LNG has arrived. With high oil price the market is strongly trying to find a better alternative. This may lead to further development and work for implementing LNG into shipping.

From the statistical review of world energy report in 2010, the global natural gas market had these key trade lines:

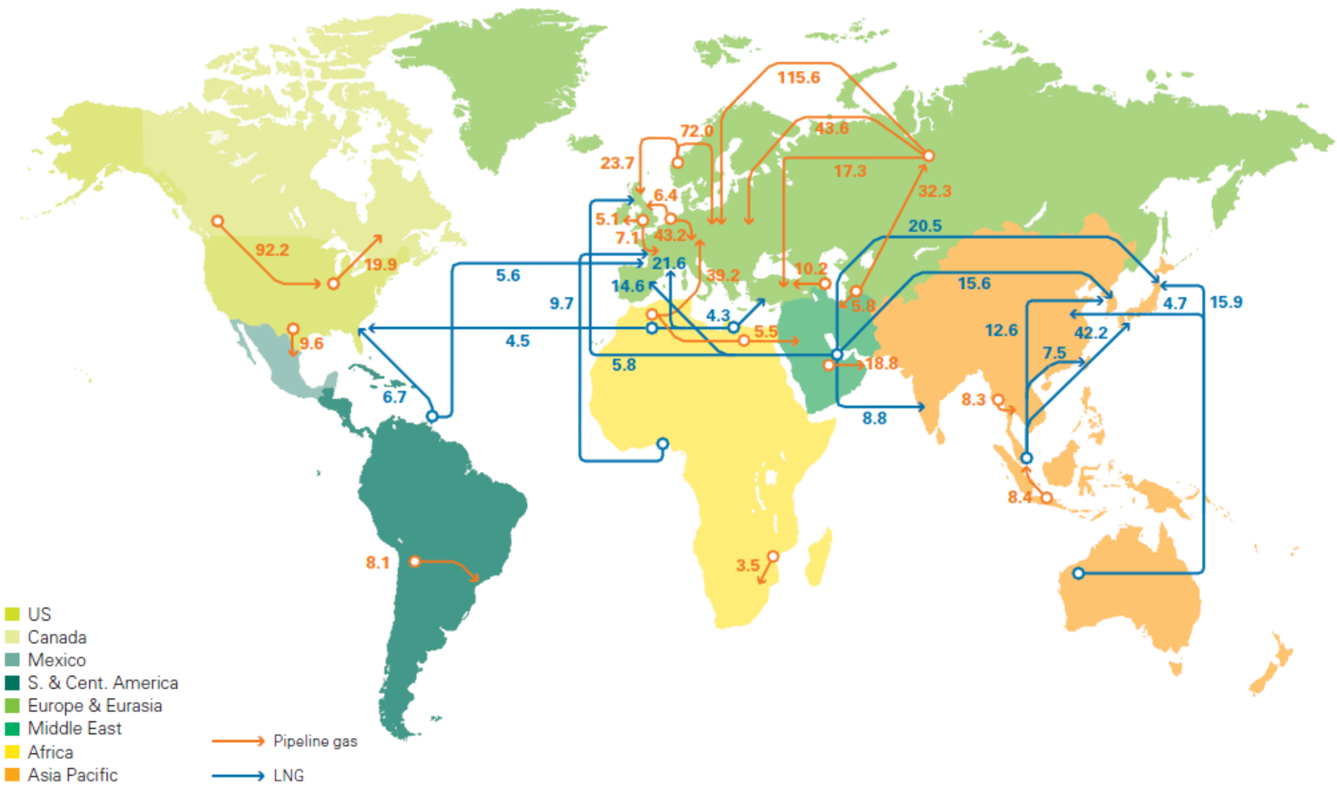

Figure 4. Natural gas trade. Source: [15]

A growth in technology when it comes to gas production in term of using shale drilling is opening for a significantly larger and economical production of gas in a vast part of the world. The typical natural gas founds are hard to characterize, but they are in general not very high in concentration, and is spread over a larger area. In other words difficult and require well stimulation or extraction to be able to extract large portions of the actual potential. In terms of shale gas, the shale is both the source and the reservoir for the natural gas. This production is also called unconventional gas. Recent wells are drilled horizontally on order to achieve a large borehole surface. This also requires artificial stimulation through manmade hydraulic fracturing, which is a drilling technique that creates cracks in targeted rock formations in order to increase the wells total production utilization. In the United States, there has been a rapid increase in production from shale gas due to the two mentioned techniques. [20] Here, the annual growth in production from shale gas was 17% from 2000 to 2006. From 2006 to 2010 the annual growth increased to 48%. This is due to the improved techniques and more economic ways of horizontal drilling and the use of water to make cracks in the shale. The market expects further increase in shale gas production in the US until 2035, with almost a threefold. There is of course a large degree of uncertainty in such predictions. [21]

The International Energy Agency (IEA) is a multinational organization that includes 34 member countries from almost all parts of the world with the larger portion from Western Europe and the western world. From their studies regarding natural gas we see interesting figures that gives us an overview of the current situation and future development. The effect of the financial crisis in 2008 had a large impact in this production and development as well. Figures from late 2008 are on a 2004 level, and IEA conclude that the gas market demand will be back to its high pre crisis level in 2012. The interesting part of the development, beside the future rise in gas demand, is the high rise of LNG capacity. This will grow be 50% from 2009 to 2013. The supply is however not following the larger liquefaction development, which only went up 5% in 2009. The increased production of gas in North America has also led to an oversupply in gas from 2006-2007. Former Soviet Union countries and also Canada and various African countries reduced their production. A few countries, such as Qatar and Norway faced still a growing output, and increased their production to meet the demand. This situation of an imperfect market, together with natural gas being discovered in many regions globally, it is very interesting if the situation with initiatives towards gas production also takes place in other regions. Because natural gas is a high potential source of energy, it has made several governments positive to further investments in production. We can notice this point in the graph below. Especially Asia and region Middle East have shown a large development of natural gas production the last years prior to the 2008 crisis. In Europe we have seen examples of problems facing production of unconventional gas, or shale gas. Local opposition, political resistance and also environmental issues regarding the production have played a role. One will have to be more systematical in appraising the resources in order to develop the potential in unconventional gas. The outcome of this situation is a gas glut that is according to IEA unclear to predict the outcome of in the various regions. Another factor to this glut comes from the situation that despite an increase in short-term contracts, the vast majority of natural gas is still traded through long-term contracts. This keeps it hard for industries to get the best and lowest energy costs, thus harder to exploit the energy source. So far we have seen the result of this gas glut turning into a system with two different price systems.

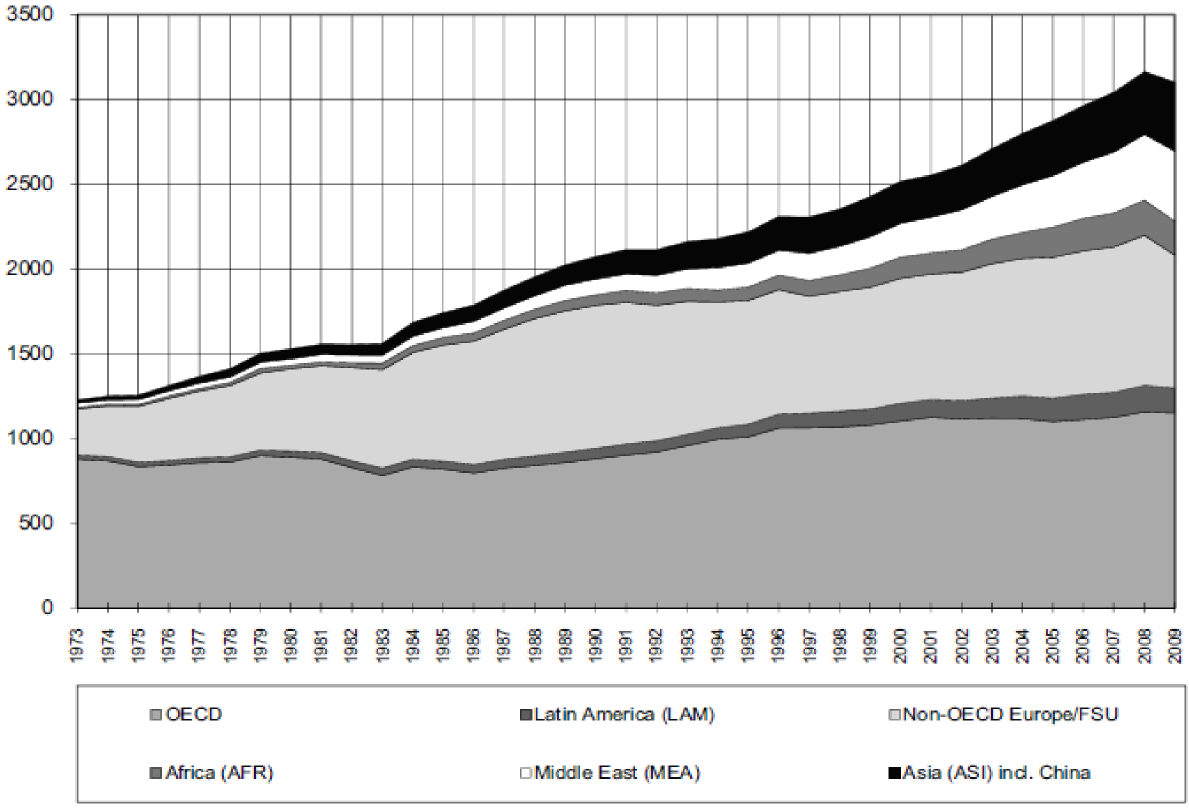

Figure 5. World production of LNG. Scale in billion [m^3] Source: [9]

The Henry Hub is owned by Sabine Pipe Line, and is situated in Louisiana, USA. This is a physical connection point for several pipe lines, with about 50% of all US natural gas production passing through or close to this system. The next day price of the natural gas from this point is documented and used for The New York Mercantile Exchange (NYMEX). The price includes a transportation cost, and is also after natural gas liquids are removed from the product. [22](Not to be read as liquefied.) For energy market analyzers, the difference between the wellhead price and the Henry Hub (HH) price shows the development in supply and demand.

The other similar system used for natural gas delivered in the UK is known as the National Balancing Point (NBP). This is however a fictive price statistic-system, not connected to one physical place as the HH is. Delivery is made equally each day throughout the delivery period, balancing out changes in the market between order and delivery. The variation in the natural gas price between these two countries shows some of the differences in the market just on each side of the Atlantic Ocean. However, as all markets, the natural gas market is a product of supply and demand. Logically, gas production, import, storage and extreme weather conditions such as hurricanes and tropical storms, and political climate, will affect the supply of gas. Cold winters and hot summers will be a factor in the energy prices, which again is directly linked to natural gas consumption. This will influence the prices in either positive or negative way. Some of these conditions will be directly connected to the oil price, with a significant dynamic in the price difference between the two, as other influences will be isolated from the oil or coal market. As an example, higher oil prices will influence the demand for gas, as many heavy industries and large consumers such as power plants, can switch between different sources of energy.

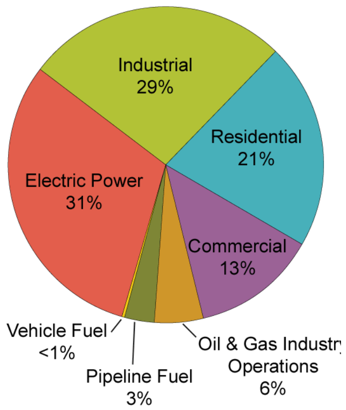

Figure 6. Natural gas consumers in the US in 2010. [21]

When oil prices rise relative to natural gas prices, there will be some consumers capable of switching from oil to gas, leveling out some of the difference in price development. However, in the 2011 Annual Energy Outlook (AEO2011), the results from IEA analyses conclude that the Henry Hub Spot Price will stay between the current 5 US$/ MMBtu, and about 9 US$/MMBtu until 2035, in 2009 dollars. In comparison, I find it unlikely that the oil price prediction for the next 25 years will be at todays level. The various results are a consequence of the differences in the degree of utilization of the shale gas resources in the American region. [9]

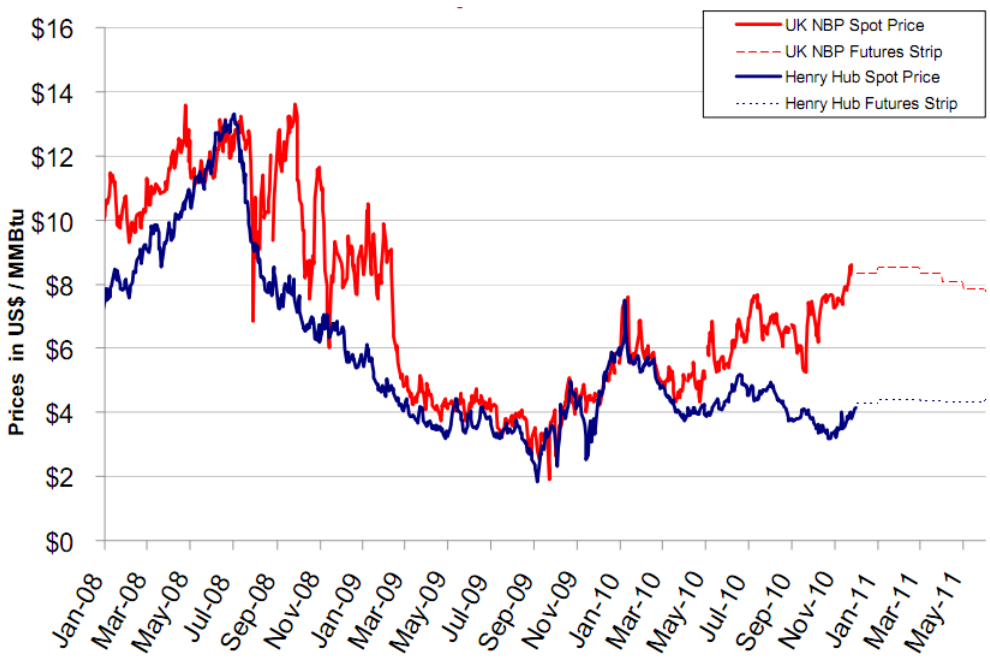

Figure 7. US and UK natural gas last 2.5 years spot prices. Source: [16]

The graph below is the prediction of the future gas price between the UK market, and the HH spot price. The variation is quite large compared to the shown 2.5 year historical connection to the two markets. The most recent figures shows a continuous trend after the larger separation of the two prices, happing in the area from late 2009 and early 2010, which are converging in that period of time.

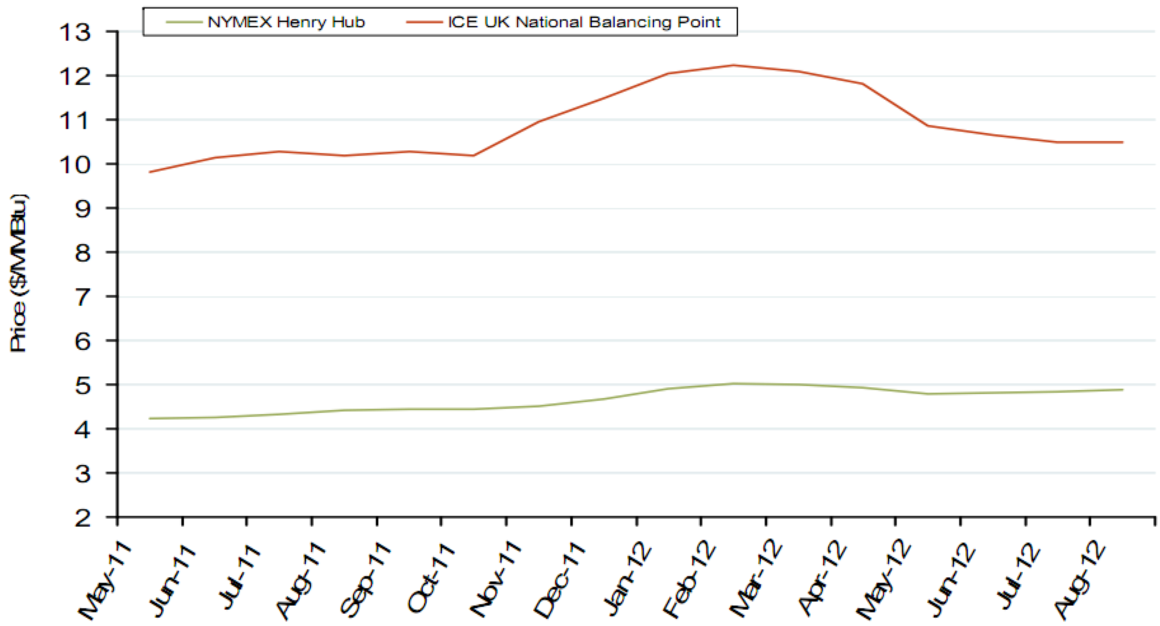

Figure 8. Future prediction of the natural gas prices in the US and UK. Source: [16]

This graph illustrates the strange price differences for the same product.

The figures below shows the prices of imported LNG to Japan and Korea the last previous seven years. The sources of natural gas into these two nations are a mixture of several exporting nations, such as Australia, Nigeria, Qatar, Trinidad, USA and Malaysia. All these countries have again a quite fluctuating price difference, showing the many large differences in the LNG market as of today. As an example of the variances, in 2008 the average price of shipped LNG into Japan was 12.64 [$/MMBtu], with the highest price came from Trinidad with as much as 16.40 [$/MMBtu], while the most cost efficient exporter was USA with an average cost that year of 7.79 [$/MMBtu]. Different qualities regarding fuel value and other factors are not being clarified in these statistics from IEA, but the statistics illustrates the situation the LNG market is in today. [23] The second graph is also interesting in relation to the experienced raise in LNG prices into Japan and South Korea. The combination of higher cost linked to a high demand for LNG will be one of the factors that will influence the process of LNG production on the domestic region for the countries used in this example. Today, 100% of the LNG consumed in Japan is imported trough long terms contracts, having a resulting end user price of the LNG at about 3 times the price of natural gas in the US. The LNG situation in Japan and South Korea is important since they are both included in one of the main Höegh trade pattern. [2] This will make the cost of LNG in this area in particular very important to operational costs for a LNG fuel ship in these waters.

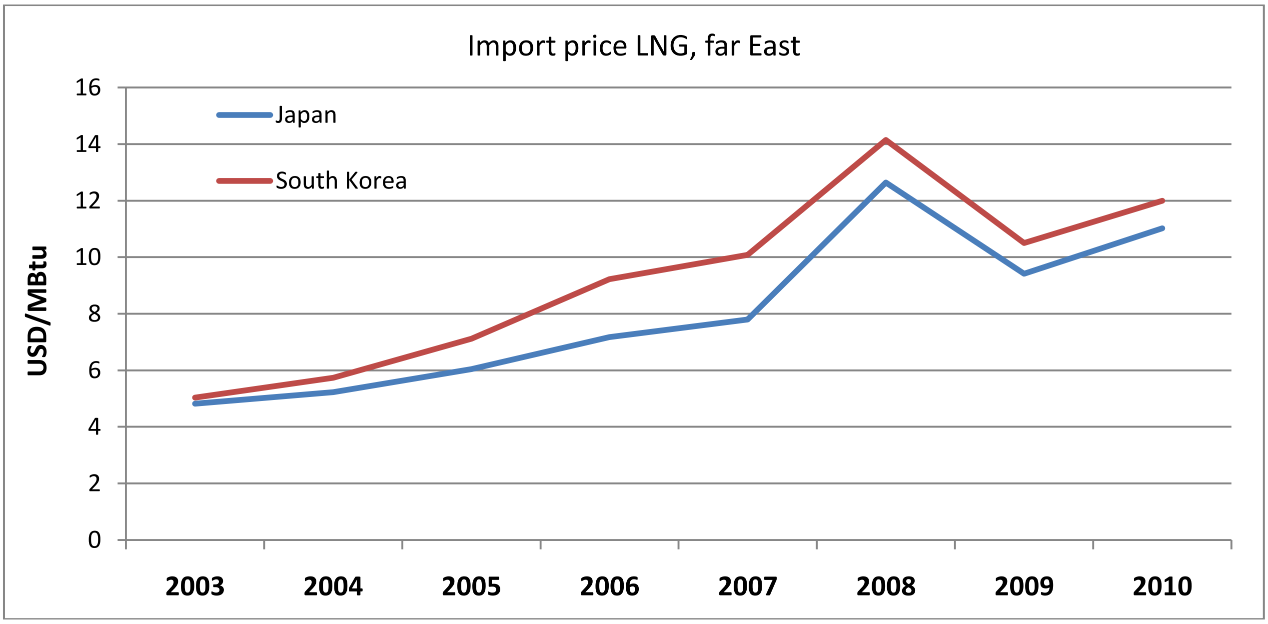

Figure 9. LNG prices Japan and South Korea import. Based on data from: [23]

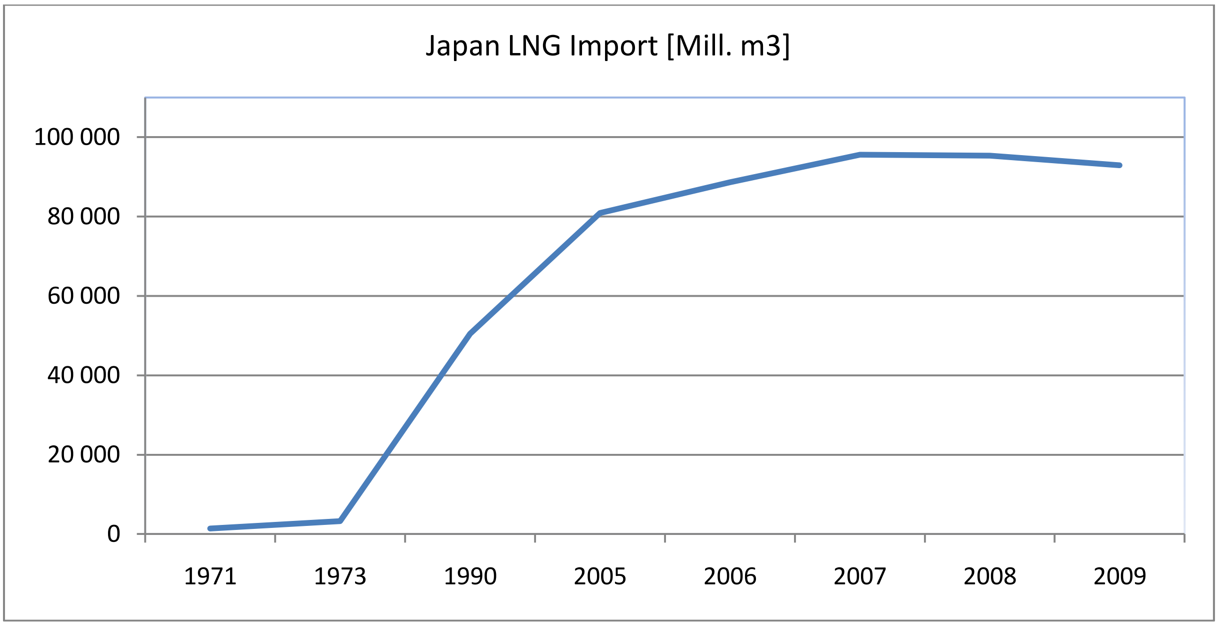

Figure 10. Volume of imported LNG to Japan. Data from: [9]

Future natural gas production and availability

In 2002, 12 countries shipped 113 million tons of LNG to 12 LNG-importing countries. This is an increase of about 35% from 1997, where we shipped 85 million tons in the same countries. [24] This is now less than what Japan, the largest importer, imports solely today. The new technology in shale gas production is interesting because it can be the reason for why LNG might grow further and be a source of energy for ships. A study conducted by the EIA, released in April 2011, shows how shale gas is spread globally, and in enormous quantities. The shale gas has been known to oil and energy companies for several years, but due to the high production cost in relation to the advanced shale rock-drilling, it has not been of interests until the later years. From assessments of 48 shale gas basins in 32 countries or 14 different regions outside of the United States, we see the availability in a world wide scale. The study concluded that the countries assessed had a total amount of 5.760 trillion cubic feet, or about 163 trillion [m^3] recoverable shale gas with existing technology. In addition, the US alone has a total of about 24 trillion [m^3]. Where conventional natural gas production is quite stable and firm in the US, the production of shale gas has increased from 0.39 [Tcf] to 4.87 [Tcf] in 2010, or about 138 billion [m^3]. The consequence of this rise is both bringing the US to a situation where it can be a net exporter of LNG, and it can also have an impact on both regional and global LNG prices. Other studies of technically recoverable shale gas resources include few of the ones addressed in the study mentioned. These estimates count a total of about 16.000 [Tcf], or about 450 trillion [m^3]. In total we are dealing with as much as more than 600 trillion [m^3]. We also see in the report that this figure is quite conservative since it excludes several potential large shale gas resources, such as major producers as Russia and the Middle East. The study also puts some of the covered countries into two groups that have two different reasons for finding LNG production attractive.

The first group consists of countries that are currently importing large quantities of LNG, but actually have large shale gas resources. They include France, Poland, Turkey, Ukraine, South Africa, Morocco and Chile. Of these countries, France, South Africa and Chile are often visited by Höegh vessels in trading routes. [2].

The other group of countries produces already larger amounts of natural gas, and they have large shale resources waiting. These countries are Canada, Mexico, China, Australia, Libya, Algeria, Argentina, Brazil and the United States. Most of these will also be considerable countries for the Höegh fleet in terms of fitting into typical trade patterns.

Especially the US is a much discussed producer when it comes to natural gas, and is considered as the country that might have the biggest influence on the current natural gas situation. The role of being a huge consumer, both from large domestic and regional production, as well as an international importer, makes the US important. In addition, the current Obama administration is also interested in reducing GHG and has set a green image, with LNG in mind as one of the solutions for a sustainable future development in regards of energy.

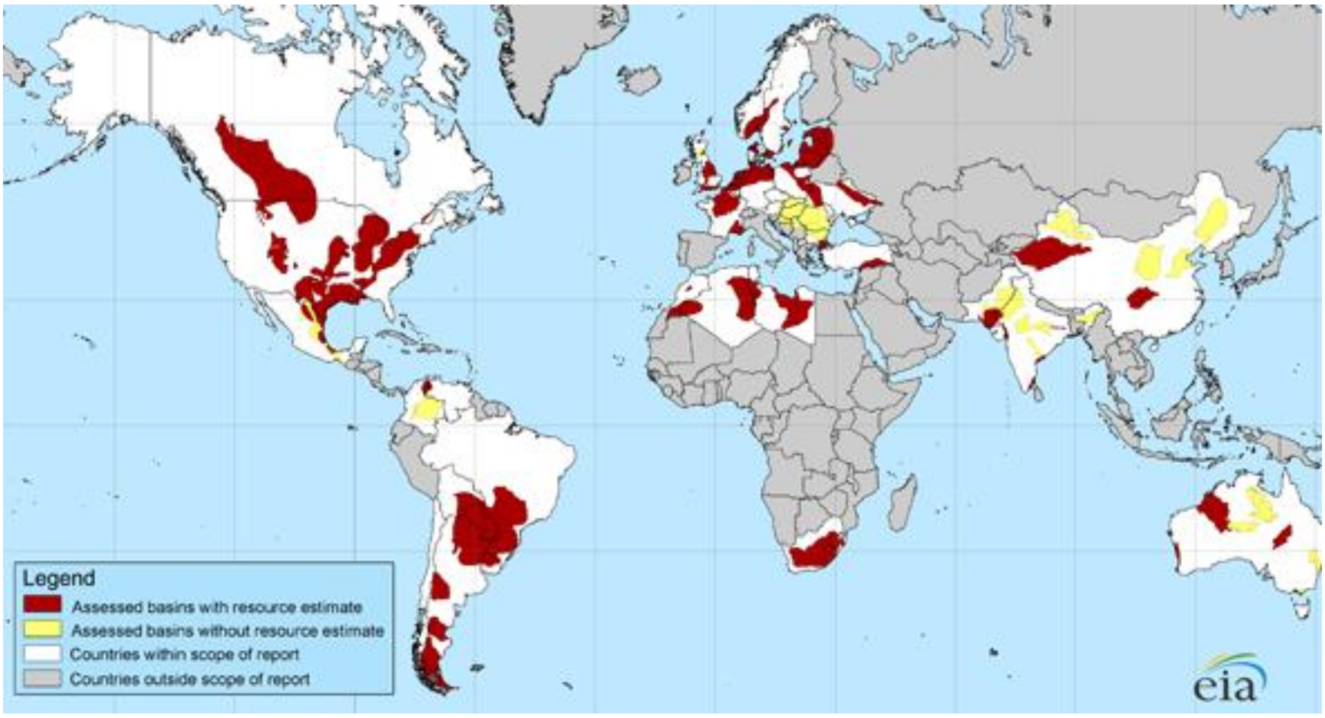

Figure 11. Overview of some of the global shale gas reservoars. Source: [13]

- *Red colored areas represent the location of assessed shale gas basins for which estimates of the 'risked' gas-in-place and technically recoverable resources were provided.*
- *Yellow colored area represents the location of shale gas basins that were reviewed, but for which estimates were not provided, mainly due to the lack of data necessary to conduct the assessment.*
- *White colored countries are those for which at least one shale gas basin was considered for this report.*
- *Gray colored countries are those for which no shale gas basins were considered for this report*

Source: EIA.gov

LNG supply

As we see, the amount of natural gas available and possible for production is not the limiting factor, but the main opportunity. In order to be able to use LNG as an addition or alternative to ordinary HFO, we must have a situation where LNG is better in so many ways that the risk and investments needed to implement it still doesn't stop the development. DNV had in the summer of 2010 a student project that involved LNG for fuel in a tank vessel fleet in the Baltic Sea. In their report, they conclude on some of the problems and opportunities in this region. From their study, there is no reason for why an LNG export terminal not should function as a bunkering terminal also for LNG carriers, or in this case LNG fueled ships. The fuel needed is also a very small percentage of the terminals capacity. [25]

This is in general the picture of how small the scale of fuel needed for a shipping company is, compared to the enormous daily consumption from the existing users. The solution could be many with available technology. Scenarios with bunkering direct at major terminal sites, or smaller stations/ offshore bunkering facilities in the loading/discharging ports, could be feasible in the various ports and regions where they have LNG production. The situation today in Norway, is that the LNG used as fuel by ferries or other coastal or offshore vessels has a much higher end user price making it difficult to work as a good alternative at the time. From DNV the summer project in 2010, the end cost of LNG per metric tons was found to be about 900[$]. The high end user LNG price is due to the situation with few suppliers, little or no infrastructure, with the LNG being transported by trucks to the ferry bunker stations in low scale. At that time, the price of HFO was about 450 [$/mt], and bunker diesel about 675 [$/mt]. The following table shows a momentary relation between the costs of energy between the different types of fuels:

Table 1. Amount of energy per dollar.

Type of fuel	Cost in July 2010	Heat value	Convert into MJ	MJ/$
HFO	450 $/mt	42,9 MJ/kg	42900 MJ	**95**
Bunker Diesel	675 $/mt	44,5 MJ/kg	44500 MJ	**66**
Average natural gas price from HH and NBP	6 $/MMBtu	1055 MJ/MMBtu	1055 MJ	**176**
LNG cost Delivered for vessels, Norway	900$/mt	53,6 MJ/kg	53600 MJ	**60**

This table illustrates that the price of LNG can be written as:

Cost of small scale LNG = Market based gas price + Cost of supply logistics

This is an indication of the challenges in order to make LNG a suitable alternative for ship owners. The cost of LNG for the end user in the transportation sector in Norway was higher than the cost of diesel oil, and the difference in price between spot market prices and end user price for LNG in a factor by 3. We see also later in this work that there has been a clear correlation between the diesel distillate and the heavy fuel oil price, as one understand.

The correlation between LNG and oil is of interest when choosing between the various fuels in this work. If the cost of LNG and H.H., always stays at the same ratio compared to each other and the oil price, one can with a larger degree of certainty calculate the likeliness of reduced operation costs when choosing a possibly cheaper source of energy. In 2005, there was a study conducted by the Energy Information Administration (EIA) together with the Department of Economics at George Washington University in order to use statistics and probability-theories in order to create a scientific answer.

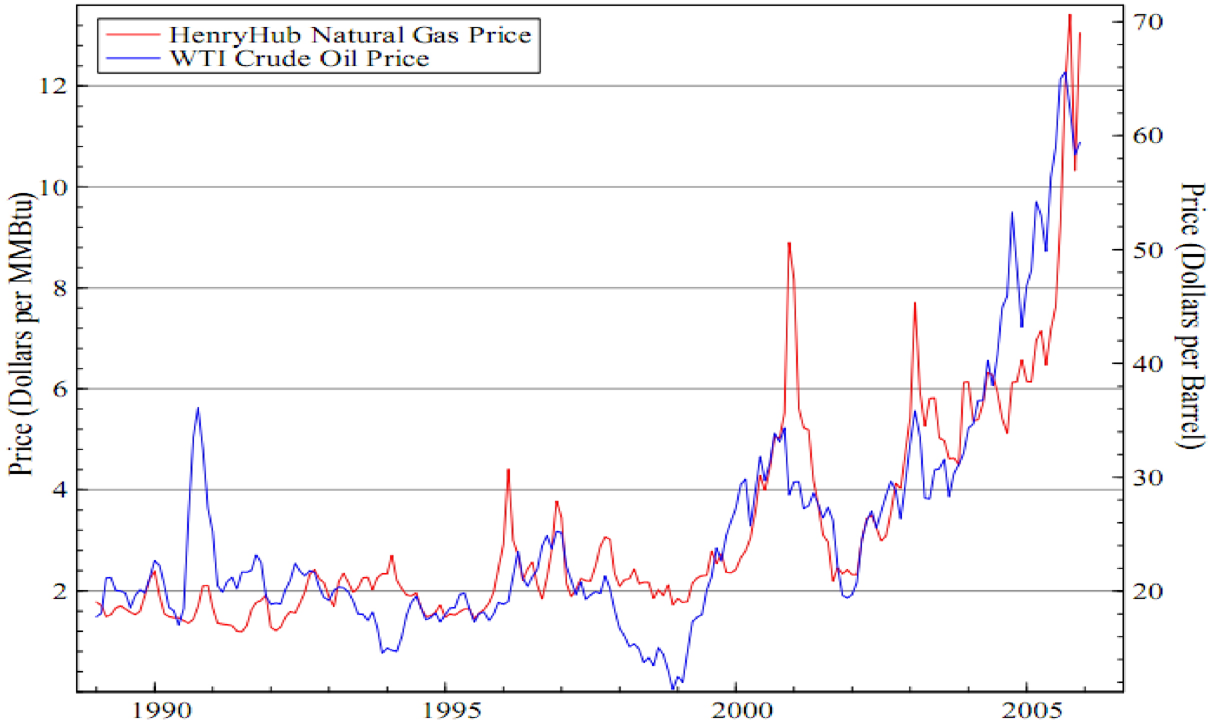

Figure 12. Natural Gas (HH) in correlation to Crude Oil. (WTI). From source [14] Note different scales on the two Y-axis.

They studied historical gas prices out of Henry Hub together with the figures from West Texas Intermediate (WTI). This is a reference as Brent and North Sea oil prices, connected to the oil market. Historically Brent and WTI have traded closely. The figured used where data from 1989 to 2005, which covers many peaks and sudden changes such as the oil price spike in 1990 following the invasion of Kuwait, significant supply shortages in cold winters and the big increase in natural gas prices starting in 2001. From the several statistical methods used, they concluded in their abstract that there was a relationship relating the Henry Hub and WTI prices. The study also concluded on several relations in regarding of the dynamic between the two trends, said to capture the relative demand and supply effect over this 16 year long period. Also, a significant stable relationship between the two series was identified. They found that the WTI oil prices are influence the long-run development of natural gas prices. In addition, some long term gas contracts, that was normal in 2005, where being priced on background of the current oil price. This is clearly directly linking the two markets closely together.

As we see, the development from 1990 till today is a rapid development in both markets, showing a pattern best described as erratic, as the energy market has been in this historical period. However, the last movements in the energy sector are that natural gas and oil will increase in price difference. Rules and regulations benefiting the use of greener natural gas, large increase of LNG tanker fleet capacity and much more economic production of natural gas are all fairly new influences that will change the trends. From EIA data the last year, together with long term future prospects, the following ratio figures are being presented:

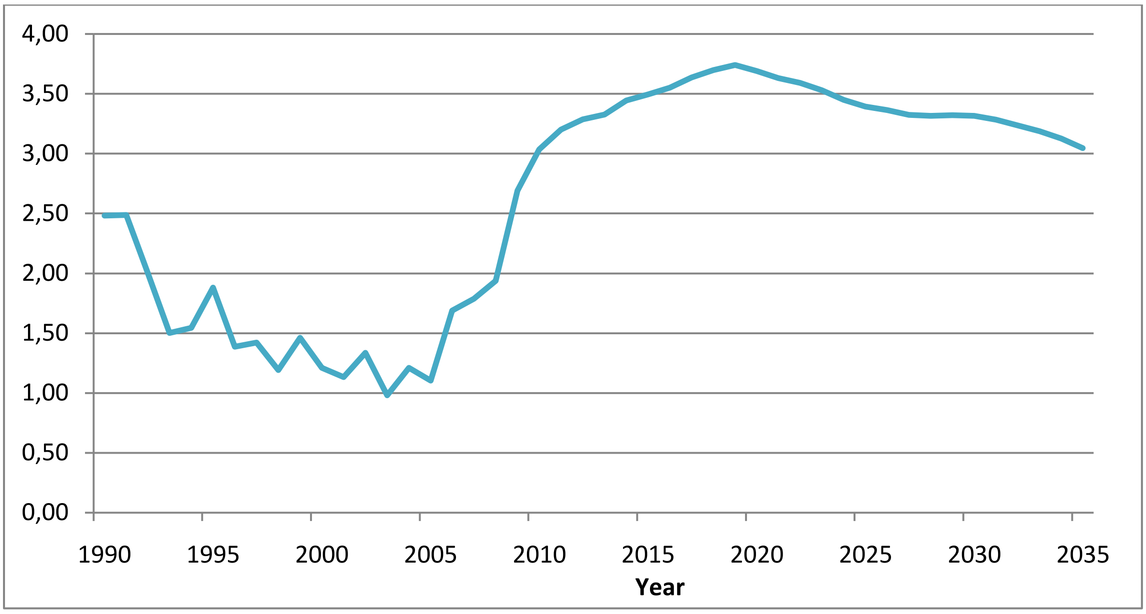

Figure 13. Ratio of low-sulfur crude oil vs. HH natural gas price. Source: [21]

It is also important to be aware that this relation between the Louisiana Henry Hub price and the WTI distillate index is only showing the situation on the US. It will be different from the relation between LNG and light sulfur oil in all other markets as seen from the variation of natural gas prices. As large consumers turn from crude oil to natural gas, the demand for natural gas will increase, and also the price of natural gas and LNG. I find this likely to happen as the development continues, and we see today examples of industries changing from coal to crude to gas as the markets develops and the rules and regulations creates demands for the different energy source.

A study done by students at NHH, Norway, concluded that there is a clear relation between crude oil and other oil distillates from the historical five years period they noticed, where the LNG price is not as directly connected with a smaller delta value for changes in crude price. The prices are based on Norwegian LNG and oil prices from Bergen port. This is in general the same conclusion as we see from the earlier sources above. Their regression analysis had the following values in relation to the oil price. Source: [26]

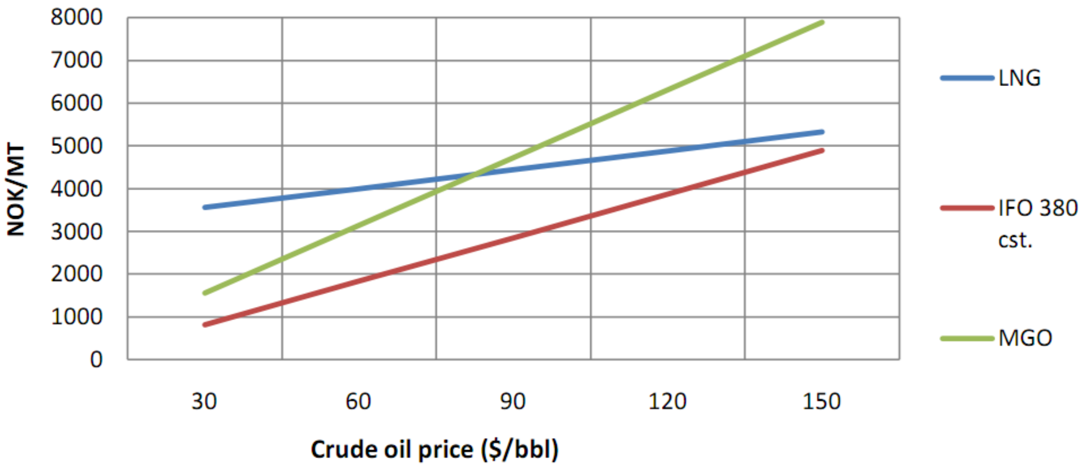

Figure 14. Price relations from a past study from NHH students.

As of today, the Henry Hub price is only about half of the price compared to the gas price in South Korea, Japan and the UK market, based in general on long time contracts. To be able to have LNG as an option or preferred fuel for international shipping, the Henry Hub price must be the global benchmark for natural gas. The process from natural gas to delivering LNG must be cost effective in order to be competitive. In order to have such a competition, the market is dependent on a broader globalization within the LNG market. I can conclude on the grounds of the trends described above, with the expanding tanker fleet, development in shale gas technology, and the global spread of gas resources, that we are in the starting phase of such a fundamental globalization.

The UK market is as seen currently somewhere in between the two markets. For the ship owner, the price of the LNG fuel will depend on several factors of uncertainty as we see in the various differences between the global regions. In a scenario with a global network consisting of the economical shale production, where LNG is traded on short term contracts, the market price will have a potential of being significantly lower than the price of crude oil as seen from the H.H. figures. As we will see, the many technological solutions in terms of LNG tanks, bunkering opportunities as well as exponential increasing tanker fleet, makes the vision of a global LNG network highly probable. Beside these, the LNG price will be influences by the dynamic in pricing between the various energy sources. Major consumers such as industry and power plants can change between gas and oil as well, making the demand rise together with the prices. From figures established in the MAGALOG-project [27], the difference between low and high cost of supplementing the user with LNG, derived from natural gas, is quite high. The prices are given in Euro and [MWh], and after transformation into $/ton LNG, we have the following prediction between high and low supplying cost:

Table 2. Supplement cost for LNG per ton.

Supplement costs of LNG from MAGALOG	
High [$/ton]	400
Low [$/ton]	120

Looking back to the regional price gives us the following possible prices for LNG in todays market:

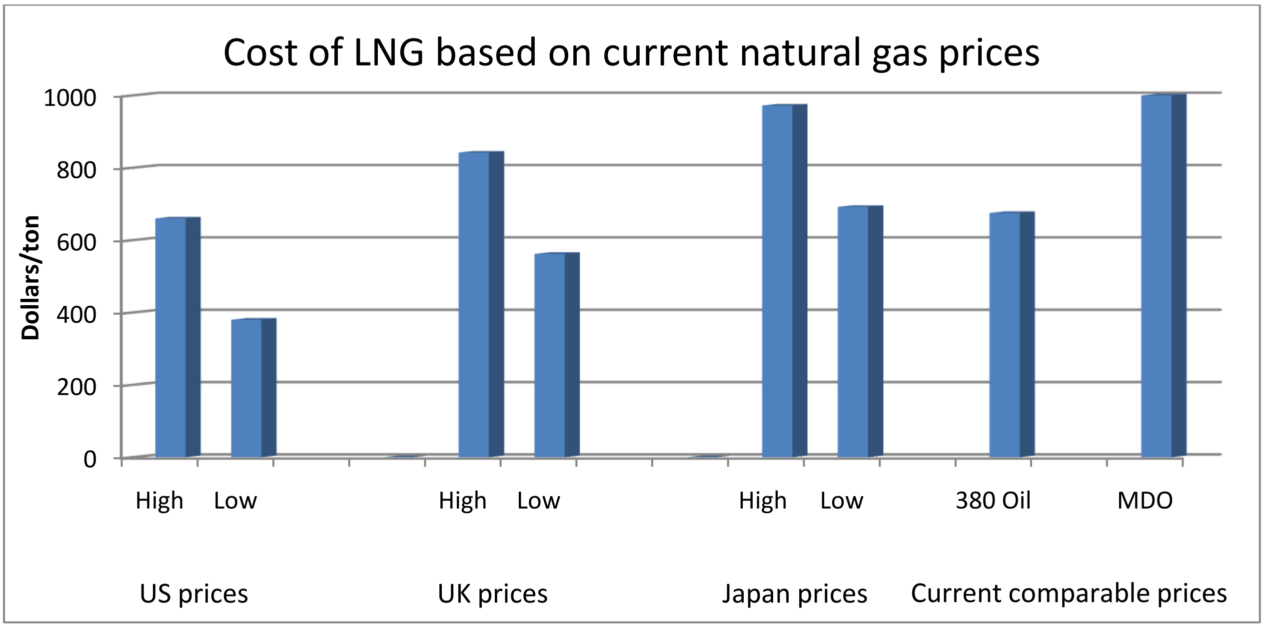

Figure 15. Possible LNG prices after handling.

Table 3. Energy relations.

Energy per ton	
Fuel value LNG/MDO	1.17
Fuel value LNG/HFO	1,25

Based on these figures, LNG has a potential of becoming cheaper than 380 centristoke oil quality even if used the high limit value for liquification. The market must however change from long term contracts to short terms contracts. Notice also that LNG has higher fuel values than both MDO and HFO.

The final question is as always when looking at future prospects "when will it be possible", and "to what extent will it be globalized". Those questions will depend on several relations, and is hard to predict as we are still in an early phase in the LNG market in many ways.

LNG-network

The common distribution of natural gas today is by shipping or pipe lines. The long term contracts mostly common for the large consumers, makes the network quite limited with few but strong direct links between producers and consumer. Two examples are the described LNG tankers sailing from Qatar to Japan, and the Russian gas pipes through Ukraine. To be able to use LNG as fuel for a merchant vessel in deep sea trades, there will have to be opening for short terms contracts to reduce the price, flexibility, and a larger network with relatively smaller quantities shipped to the various hubs. This can be realized either by onshore LNG tanks on the harbors, or offshore terminals as we already sees in use today for domestic energy needs in order to reduce the bunkering time if already waiting for port space. There have been many concepts that are designed with regards to offshore loading of LNG, that are technologically transferable to bunker loading in this case.

One example that illustrates the possible sizes of an offshore terminal that also is in operation today is the Adriatic LNG terminal, located 15 km off the coast of Italy. The terminal is a gravity platform, with storing, unloading and regasification plant for LNG, shipped from Qatar. It is also connected to the domestic network by pipes for distribution. The terminal is about 400 [m] in length and 100 [m] wide with a enormous tank capacity of 250.000 [m^3] [28]

Figure 16. Offshore loading. Picture: [10]

Smaller bunkering stations without regasification capabilities is a good option for creating a network for gas fueled ships. Such facilities as well as logistical chains have been in development for several years through various different initiatives. One example is the Azure R&D project finished in 2000. This project included nine European companies, including five oil and gas companies, in a study of how to design a fully floated LNG chain. This includes liquefaction plants, terminals and transfer systems. It was concluded that included all technical issues, such a design could be both safe and economically feasible through a concrete hull. [29]The similarities to the later Adriatic terminal are clear. The present development regarding global LNG regasification and liquification plants can be

Figure 17. Singapore LNG terminal. From Singapore LNG

found in Appendix XV. We see a large development spread all over the world. This development is vital in creating a network for LNG, needed to operate a ship on LNG. The terminal under construction in Singapore, with due date in 2013 is a highly interesting project. [30]This is both because of the technology, being both capable of regasificationof the LNG for the domestic market, as well as having exporting possibilities for various consumers, such as ships. The geographical positioning is for Höegh very important, as the FE markets is one of the key regions at the time.

Offshore or bunkering stations outside the ports are also possible. Aker Solutions prismatic LNG tank might be a future choice in a LNG network. The design can carry large volumes and withstand sloshing at any ratio of fullness. It can also be placed onshore as well, naturally. The challenges remaining to fulfill this design are approval from the classification societies in relation to the offloading at sea with a tandem solution. Such a system will be capable of bunkering even in higher wave heights than the existing systems. Also, approval of the design in terms of pressure limits is to be realized. [31]

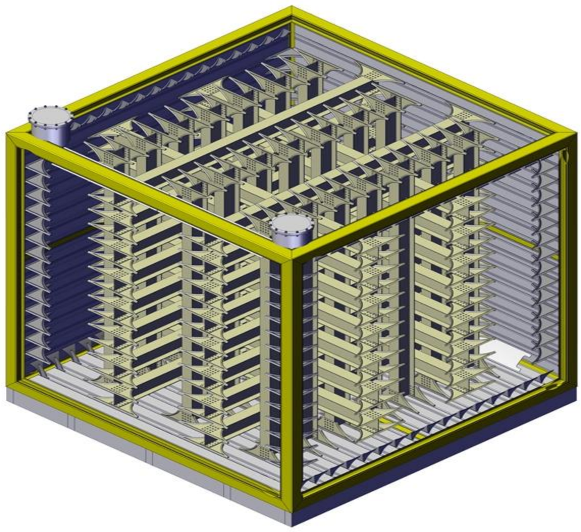

Figure 18. Design solution from Aker. Picture: Aker Solutions.

Emission regulations

Today the shipping mode transports about 90 per cent of global trade. It is also the most environmental friendly mode of transportation in order of CO2 emissions [ton/km]. In 2007 international shipping was estimated to contribute with 2.7% of all CO2 emission. However, to be able to reach the goal of no more than 2°C increase in global temperature since the industrial age to the year 2100, the shipping industry must be even more effective. The projection from the last years global shipping activity shows that by 2050, shipping will be responsible for about 12-18% of the total CO2 emission available, to be able to reach the 2100 goal. [32]

The illustration below is a picture of how many tons CO2 the various competitive transportation modes use on an average basis today. Factors such as sailing speed, degree of utilization and traffic conjunctions will have an impact. It still shows clearly that shipping in terms of CO2 emission, is a superior mode of transportation.

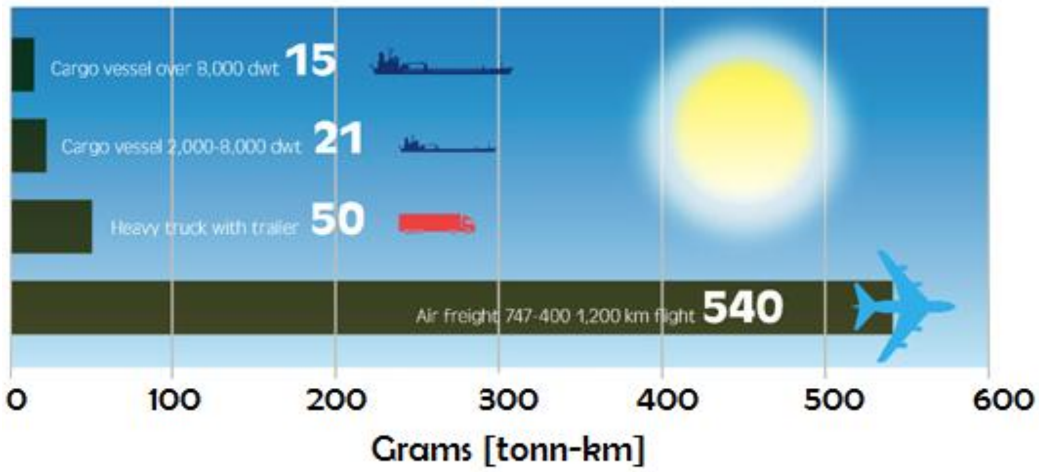

Figure 19. C02 emission for comparable modes of transportation.
Source: Swedish Network for Transport and the Environment

CO2 is not the only form of pollution from shipping so the total picture of what to be categorized as environmental friendly when it comes to transportation is more complex and difficult to determine. Shipping is found to contribute with about 4-9% of all anthropogenic SOx-emission, and about 10-15% of all anthropogenic NOx-emission [33]. These air pollutants cause serious harm to people and other living organisms in the local area. NOx is known to causes respiratory problems such as asthma, emphysema and bronchitis, and damage to lung tissue which will cause premature death. It is also a component in smog, and will also contribute to acid rain. [34] Studies shows that SOx has many of the same health impacts. [35]

Smaller quantities of stronger greenhouse gases and other hazardous pollutions such as chlorofluorocarbons (CFC), particulate matter (PM), volatile organic compound (VOC) and hydrofluorocarbon (HFC) will also have an effect, though some are phasing out. In addition, other impacts such as oil spills, toxic fouling and in the end scrapping is also a part of the overall impact to the environment. Studies published by MIT in 2010 concluded that the share of LNG in the energy market wills double the next decades, from todays 20% to about 40%. This is backed by the effects of shale drilling, as well as the policy for more environmental friendly energy form the state. Today, coal is a less costly source of energy, but will however most likely lose it share of the market for LNG due to the mentioned developments. On the other side, a switch to LNG will not have significant change in the CO_2 emission. As the goal is to reduce CO_2 emission by 80% until 2050, LNG alone will alone not reduce this number.

Road transport as a frontier

Shipping is as seen much more environmental friendly than competitive modes of transportation due to the large scale first and foremost. However, shipping must said to be a slow developer compared to other modes of transportation when it comes to emission regulations and the use of more environmental friendly engine technology. Comparing emission regulations with road transport, shipping is in some cases and areas decades behind. In the European Union, regulations concerning pollution have existed since 1988 in the Euro 0 standards regarding Large Goods Vehicles. Asia is also active when it comes to emission regulations for land transport. China with Hong Kong and India is especially rapidly catching up to European standards, and is currently at the Euro IV levels.

Table 4. Euro limits for Large Goods Vehicles. Source: [36]

Standard	Date	CO (g/kWh)	NOx (g/kWh)	HC (g/kWh)	PM (g/kWh)
Euro 0	1988–1992	12.3	15.8	2.6	none
Euro I	1992–1995	4.9	9.0	1.23	0.40
Euro II	1995–1999	4.0	7.0	1.1	0.15
Euro III	1999–2005	2.1	5.0	0.66	0.1
Euro IV	2005–2008	1.5	3.5	0.46	0.02
Euro V	2008–2012	1.5	2.0	0.46	0.02

In addition to the Euro standards, Japan has its own emission regulations with similar limit values. In America, the state of California has a leading role when it comes to emission regulations in the US, but many other states are adopting those rules. Also, the USA itself has stricter regulations for road transport on a federal level with its Tier program. In general, many non western countries are beginning to introduce the EURO standards, and more and more attention is brought on air pollution. As the trend shows in the western world and especially in Europe, the automotive industry is the first mode of transportation to be effected by new standards. Never the less, the shipping industry has been seen to catch up when introduced similar standards. Below is a table that shows the development in the emission regulations on heavy land transport and the various emission types.

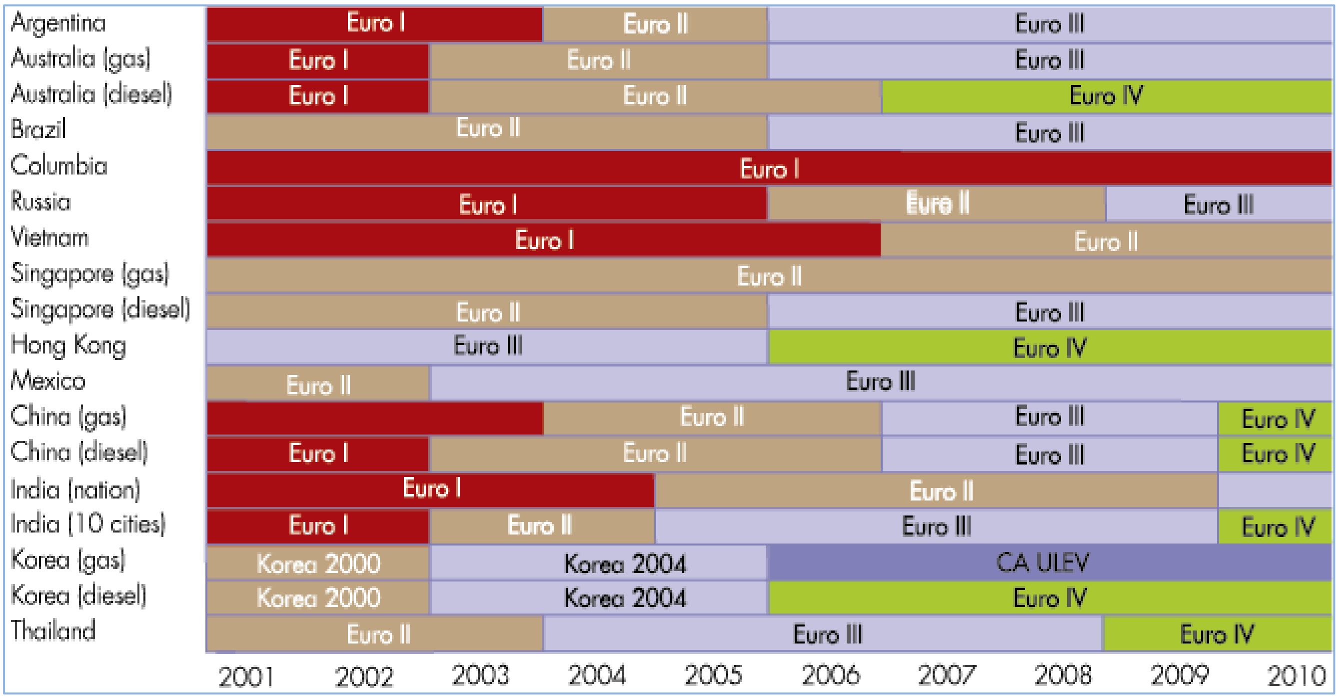

Table 5. Global emission standards for road going vehicles. Source: [4]

These figures are a benchmark for a world standard the latest years. This is an indication that other countries are following the air pollution standards for road going transport, brought in by the European Commission.

If this trend continues and is brought into shipping, today's ECA for the North Sea and the Baltic Sea might be applied at a global scale. The European Union is setting a benchmark that can be expected to be met or closely followed by other nations as the standard of living also improves.

ANNEX VI of the MARPOL regulation

MARPOL is the leading international convention regarding pollution from ships, as a part of the International Maritime Organization. (IMO) Through the first five conventions, sewage, harmful waste and other matters has been directed. The latest annex is known as Annex VI. This entered force in 2005, and now regulates SOx and NOx emissions from ships from almost 50 nations, and covers about 50% of the world's tonnage. Air pollution from ship machinery has now been under regulation for the first time. This causes ship owners, ship machinery and diesel engine manufacturers to develop and come up with new solutions and technology to meet the current standards.

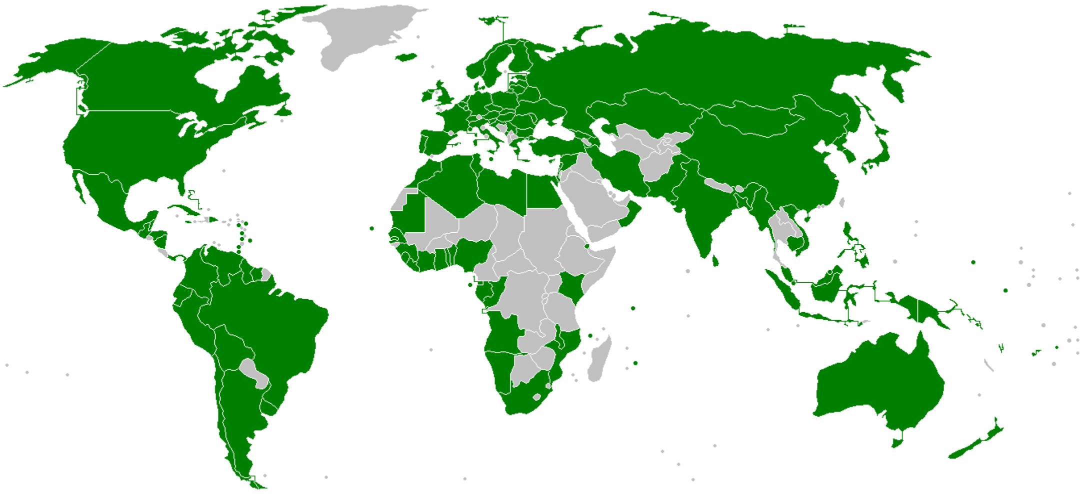

Figure 20. Illustration of MARPOL signatories. Source: [37]

Annex VI consists of several regulations that in detail describe the various demands and limits. The most interesting regulations in this case will be the following:

Table 6. Annex VI regulations.

Regulation nr. 13	NOx emission from ship engines
Regulation nr.14	SOx emission from ship engines
Regulation nr. 18	Fuel Oil Quality

Regulation 13 and 14 is defined in Tier I, II and III, introduced to the Annex VI in 2008. The various Tier regulations are thoroughly described and defined.

NO_X- regulations

For the NO_X regulations, the engine limits are directly given for the various engine RPM. Tier I introduced NO_X limits with the following defied area of application: A diesel engine which is installed on a ship constructed between 2000 and 2011 is prohibited, except when the emission of NO_X from the engine is within the following limits:

1. 17.0 [g/kWh] when n is slower than 130 rpm.
2. $45 \cdot n^{(-0.2)}$ [g/kWh] when n is 130 or more, but less than 2,000 rpm
3. 9.8 [g/kWh] when n is 2,000 rpm or more.

n is given as crankshaft revolutions per minute [RPM].

Tier II further narrows the emissions allowed by the vessels constructed from 2010 to 2016, and within the covers of MARPOL:

1. 14.4 [g/kWh] when n is less than 130 RPM.
2. $44 \cdot n^{-0.23}$ [g/kWh] when n is 130 or more but less than 2,000 RPM.
3. 7.7 [g/kWh] when n is 2,000 RPM or more.

The Tier III is a future limit value for MARPOL and IMO standards, taking place for ships constructed after 2016, and for ships operated in special Emission Control Areas [ECA]. I will come back to ECA later in this work.

1. 3.4 [g/kWh] when n is less than 130 RPM.
2. $29 \cdot n^{-0.2}$ [g/kWh] when n is 130 or more but less than 2,000 RPM, and
3. 2.0 [g/kWh] when n is 2,000 RPM or more.

All MARPOL Tier I to III limits from source: [38]

As we see, this calls for a much more dramatic change in the ships engine air pollution emission values compared to the typical vessel operating on heavy fuel oil. The development in NOx regulations can be shown clearly with a plot of the three Tier-limits:

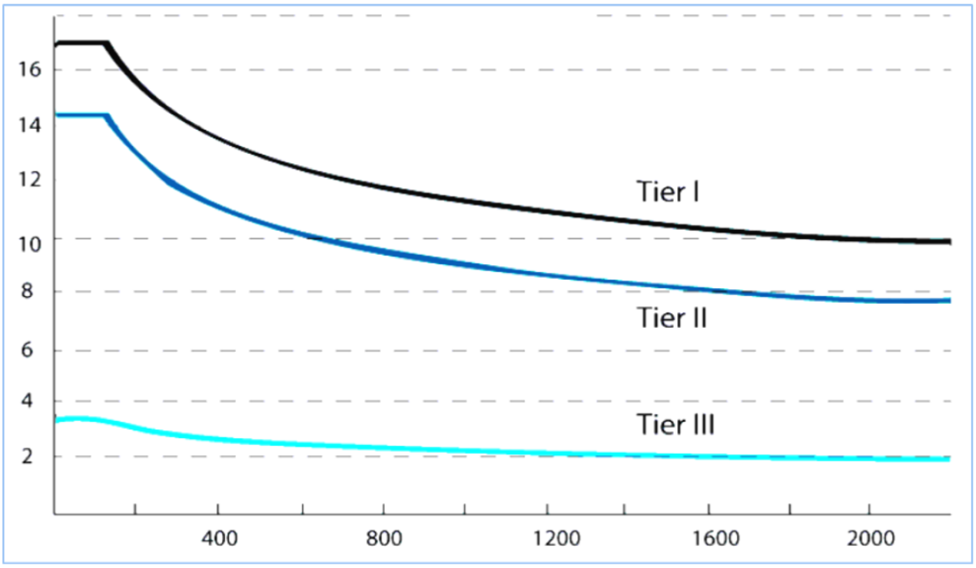

Figure 21. NO_X limits [g/kWh] related to the engine speed. [RPM]. Source: [39]

The engine producers are capable of delivering more or less the same engine as usual within the Tier II limitations. This is done without adding any additional systems, such as neither selective catalytic reduction (SCR), water emulsification, humid air motor (HAM) nor other additional NO_X reduction systems. From Caterpillar and MaK engine manufacturer, fine tuning techniques and adjustments to the following parts are mentioned in relation with their Tier II adjusted engine catalogue:

- Turbocharging system
- Injection system
- Combustion chambers
- Longer stroke
- Flex Cam Technology system. (FCT system)

The engine producer MAN operates with the same technology and solutions for their green engine technology. They also use electronic injection systems (Common rail) variable valve timing and variable turbine area in the turbochargers. [40]

Both manufacturers are capable of staying within Tier II using these relatively small adjustments. However, to be able to keep clear of Tier III levels, additional systems such as SCR, HAM etc would be necessary. The last and easiest solution used by many ship owners operating in Tier III ECA is the use of other fuels and lighter, expensive distillates.

SOx regulations

As for the NOx regulations, the development in sulfur levels in marine fuel oil can be described as modest at first, and strict in the latest phase. As the rules have been introduced, we see examples that the main difference between the current NOx and SOx regulations is that the NOx requirements are more or less an engine technology problem. This can seen to have been met for Tier II, through the various adjustments mentioned earlier. The SOx boundary causes the refineries itself to deal with the technological problem, and produce as cheap as possible petroleum products within the first two regulations itself. These limits are given by MARPOL and states clearly:

Regulation 14

Sulphur Oxides (SOx) and Particulate Matter

General Requirements

The sulphur content of any fuel oil used on board ships shall not exceed the following limits:

1. *4.50% m/m prior to 1 January 2012.*
2. *3.50% m/m on and after 1 January 2012; and.*
3. *0.50% m/m on and after 1 January 2020.*

The worldwide average sulphur content of residual fuel oil supplied for use on board ships shall be monitored taking into account guidelines developed by the Organization.

For ships operating inside the EMA, IMO has these requirements to the fuel onboard:

While ships are operating within an Emission Control Area, the sulphur content of fuel oil used on board ships shall not exceed the following limits:

1. *1.50% m/m prior to 1 July 2010.*
2. *1.00% m/m on and after 1 July 2010; and*
3. *0.10% m/m on and after 1 January 2015.*

Source: [38]

To illustrate the development in a similar way as the NOx regulations brought in by MARPOL through Tier I to Tier III, the step by step SOx-development will be as follows:

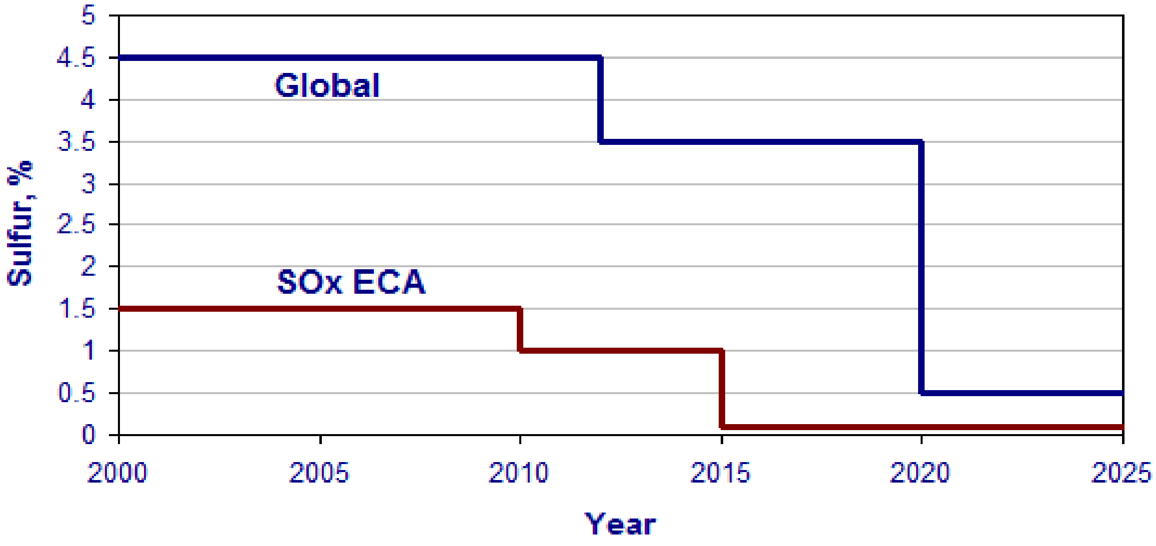

Figure 22. SOx regulations from ANNEX VI. Illustration: [41]

Studies performed by IMO and other indicates that the average sulfur limit in HFO is known to be about 2.8 – 3 weighted percent, which we can see is within the Annex VI regulations. [42] To be able to meet the sulfur standards inside of ECA areas, only petroleum products made from a finer or higher distillate, or has been chemically processed through hydrodesulphurization (HDS)[1] must be used. These petroleum products are of a significantly higher price than the HFO with higher levels of hazardous compounds. An interesting aspect is the difference in cost by using a HFO within the 3.5% sulfur level as being done today without the ECA, and the added cost of running on a lower level sulfur fuel within the 1% limit. From dialogue with Geir Inge Asskildt from Global Yield and Capacity Management at Höegh Autoliners, I learned that they carry large quantities of marine gas oil (MGO) to be used when sailing and loading in ECA areas, such as the much sailed ARA (Amsterdam-Rotterdam-Antwerp) region.

With todays prices, the added cost by using finer distillated can be seen from the historical prices between the distillates. Using bunkerworlds price, that differences will be as follows:

[1] HDS is a catalytic chemical process used to remove sulfur compounds from refined petroleum products.

Figure 23. HFO 380 (to the left), and BWDI[2] (to the left.). Source: [43]

As we see, the HFO with viscosity of 380 Centistokes and the combined distillates follows each other very closely, as one would perhaps expect. The price variation between the two fuels in percent of each other is also within a very little variance. The expected price for the distillates compared to HFO is almost fixed, and around 50% higher than the cost of the fuel with 380 Centistokes qualities. (Note the different scales of the y-axis) A characteristic with this percentage relation is that the price differential in [$/mt] between the two types varies as the price levels varies.

In competition with other refineries and energy markets, there is also a great concern for a downside of the MARPOL . Some of the skeptics argue that the increased production cost due to these regulations may cause some refiners to use cheaper blend products and components that will in the end result in bad quality fuel oil. In that way, the regulations itself will be met, but the overall goal of reducing the total amount of green house gases and hazardous emission will not be reached. [44]

EU directive 2005/33/EC

The EU directive 2005/33/EC limits the sulfur content of marine fuel oil used by vessels operation at member countries ports, harbors or inland water ways to 0,1%. The legislation came into effect from 1. January 2010. Marine gas oil with sulfur levels of more than 0,1% is therefore prohibited in the European member states.

Emission Control Area [ECA]

The hazardous pollution in relation to exhaust gasses from shipping has for many years been unattended as the consequences have been more or less unknown. As ships also operate at distances far away from populated areas and in international waters for the greater part of the time, this contributes to make shipping stand outside of attention and local legislation. The result of these factors has been noticeable in many coastal areas and major harbors, with pressure from states to implement emission controlled areas: Areas where there is a strict regulation concerning hazardous emission from ships in term of NOx and SOx, as it is of today. A strong example of the effect from shipping is seen in the Baltic Sea.

[2] Bunkerworld.com uses the BWDI notation, meaning Bunker World Distillates Index. The BWDI is the average of Marine Diesel Oil (MDO) and Marine Gas Oil (MGO).

The North Sea and the Baltic Sea

ECA levels have already been introduced to the North Sea and the Baltic Sea, with the following geographical limitations:

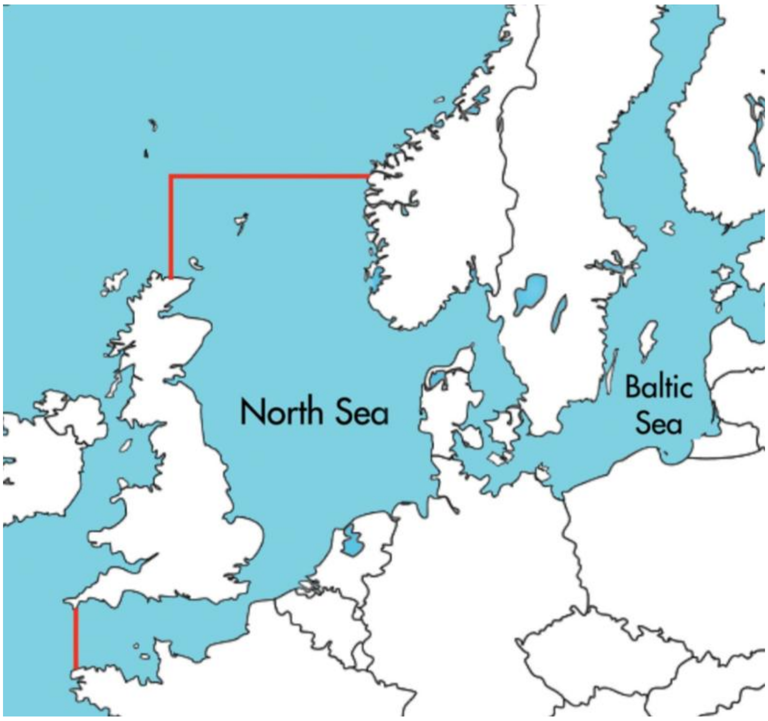

Figure 24. North Sea ECA. Source: [45]

This area covers some of the largest ports in the worlds, with the ARA-region, as well as several other considerable ports with a large per cent of the total worlds shipping activity. The emission regulation will have a significant result in terms of the air quality for a large portion of the population in the European Union, which borders to the North Sea area, as well as sea life and other organic life. Pollution from road going transportation and industries will still be a major source, but the planned reduction through Tier I to III will also play a considerable part of the hopefully increased air quality.

The Baltic Sea has been under heavily pollution from agriculture, ship emission and oil spills the last decades. As early as in 1974, a convention was arranged for the 7 neighboring countries to the Baltic Sea, with a goal of reducing the various sources of pollution into the sea. The convention came into force in 1980, and this was the first time a whole sea has been subject for a convention. However, large discharges, geographical and biological relations and other oil spills and emissions have made several zones of the sea to be been known as “dead spots”, without any form of biological life. From studies done by The World Wildlife Fund in the Baltic seaport of Stralsund and the German Federal Environment agency, the main reason for this uninhabitable situation is known to be from fertilizing, with leakage of nitrides into the sea, and from discarding of animal waste from animal farms around the sea directly into it. [46] Never the less, shipping is also a considerable part of the emission problems in the Baltic Sea, and from studies done by DNV, the impact from shipping has increased significantly the last decades, and will increase further the next decades if the trend continues and no initiatives are taken. [47]

North America and the Caribbean

California is a pioneer state in the US when it comes to legislations regarding air pollution from transportation. In 2008, rules for ocean going vessels where adopted by California Environmental Protection Agencys Air Resource Board (ARB). The implementation began in 2009, with the following two-phase local emission reduction implementation for ships main engines, auxiliary engines and auxiliary boilers:

July 1, 2009:

- use marine gas oil (averages 0.26% sulfur), or use marine diesel oil with a 0.5% sulfur limit.

January 1, 2012:

- use marine gas oil with a 0.1% sulfur limit, or use marine diesel oil with a 0.1% sulfur limit. Source: [48]

These limitations apply within a 24 nautical mile area off the coast. We can see that the ARB-levels are similar to the sulfur levels of the Annex VI restrictions. So, almost naturally, in April 2009, Canada and the United States sent in a proposal to IMO for introducing a Emission Control Area for the two states. Source: [49] One year after the proposal, and two years after the adoption of sulfur regulation for ocean going ships in California, ECA was introduced for the US coasts. In March 2010 the IMO introduced major parts of the North American coast as an ECA, in regarding to the MARPOL specific emission regulations. This area will become enforceable in August 2012, after then a two years lead time. This legislation was introduced after the United States and Canada earlier proposed the coastal areas as new emission controlled areas. France had also proposed certain territories and islands, Saint-Pierre and Miquelon, off the coast of Newfoundland, as future ECAs.

More detailed, the area in North America covers both the west coast, with the Pacific Sea, and also the East coast and the Atlantic Sea and into the Mexican Gulf. The area extends from the U.S, Canadian and French territories shore lines, and 200 nautical miles off the coast, except into other marine areas where other states have sovereignty or jurisdiction. The area will also cover the eight main Hawaiian Islands. In total, the North American region will have the following ECA, with full effect from August 2012. Source: [50]

Figure 25. North American ECA. From: [50]

I also found in the same article that the American Environmental Protection Agency (EPA) is currently continuing finding new regions where the MARPOL legislations will be of interest. The quoted American territories are the US Virgin Islands and in Puerto Rico. Other areas for consideration include the Pacific US territories, smaller Hawaiian Islands, and Western Alaska. As a result of these ongoing processes, I find it likely that more areas in addition to the ones shown on the map above will be a ECA in the future. One can then speculate if other North American (Mexico), Caribbean, or other South American regions also will follow the US. From the EPA website, questions regarding Mexico as a future ECA together with the US ECA are currently answered in a way that opens for interpretation. The quotation was dated January 2009. Source: [51]

"We have also had discussions with the Mexico National Institute of Ecology (INE) regarding inclusion of Mexico in the joint application. While the INE has expressed interest, there is concern that it will not be possible to perform the necessary inventory and air quality analyses in time for a submittal to MEPC 59. In addition, it is not clear if Mexico will ratify Annex VI in the near term. We expect to work with Mexico separately, if necessary to extend the ECA in the future."

EPA on question regarding joint application with Mexico

Future ECAs

According to different sources such as bunkerworld and DNV, other states and regions have interest and considering applying for ECA as the matter is being discussed. An outlook from DNV's "Greeener shipping in North America" shows the following map of possible new ECAs:

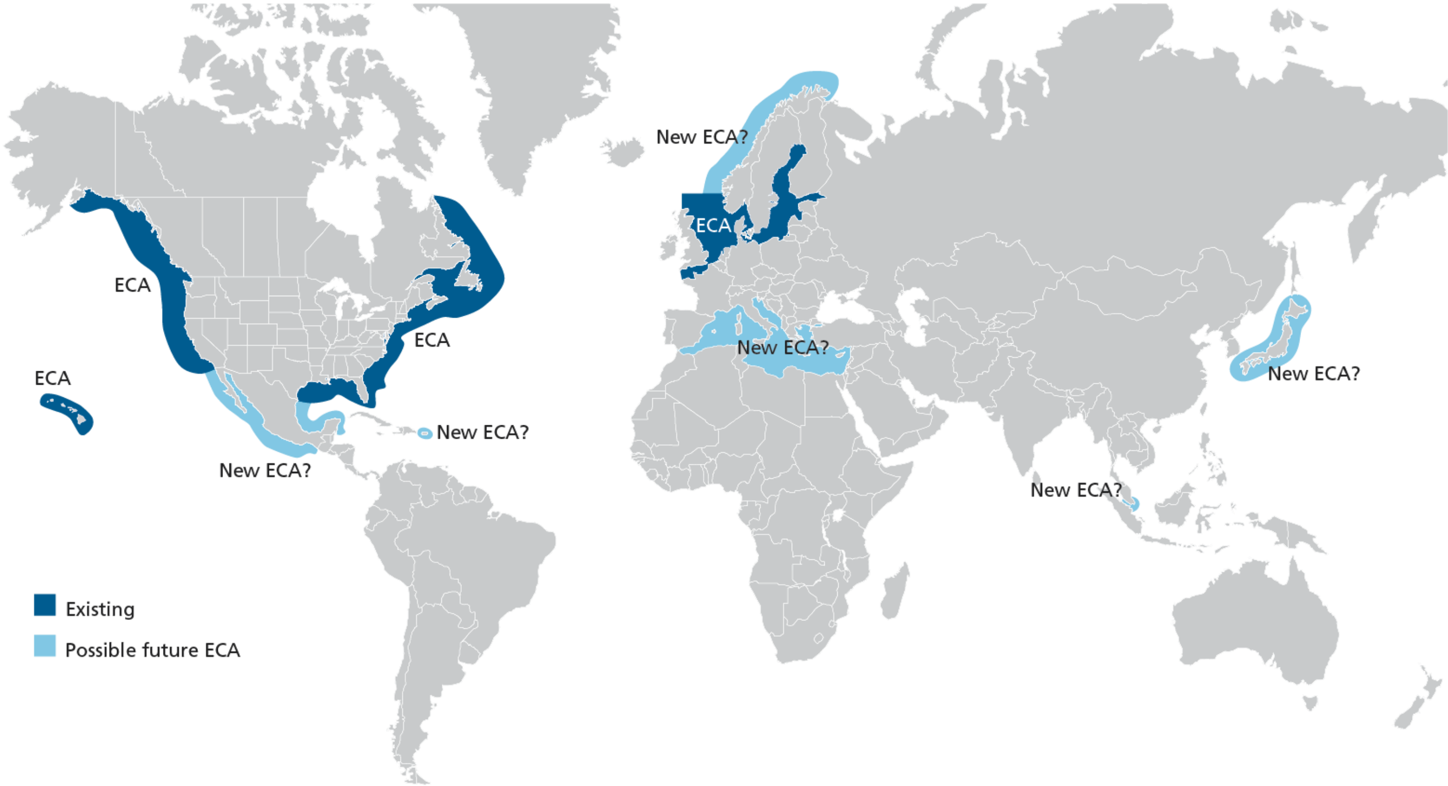

Figure 26. Possible future ECAs. Source: [3]

For a ship owner such as Höegh, with a global network of trades, areas such as Mediterranean, Singapore with the Malacca strait, and Japan is of high interest as these are highly sailed waters. Also the mentioned Mexican coast is of interest, even though a lot of freight is done by rail from Mexico into the US. It is hard to tell when the possible future areas might be under emission control. This will depend on regional decision making, and especially in the Mediterranean such decisions may have to postpone due to the political situation and instability in the region. However, within a period of about 9 years, depending on a future fuel study, MARPOL Annex VI regulations will be strict regarding sulfur limits and NO_X-emission on a global scale. Considerable modifications or change of fuel types must be done sooner or later, disregarding ECA or not. The TIER III limit will come either in 2015 in order to sail in an ECA, or around 2020 for rest of the world covered by the Annex VI. The sulfur levels in 2020 with a MARPOL level of 0.5%, and an ECA level of 0.1% from 2015, will call for new solutions.

Current LNG fueled vessels and future designs

In order to see the various solutions available today, or for the near future, it is of interest to study ships that are fueled by LNG and existing today – either on paper or in actual operation. Some of the ships sailing on LNG have broken down barriers, and created new opportunities for later ships running on gas.

Vessels in operation today

Present vessels fueled by LNG are mainly operating in ECA at the coastal areas around Norway. In this region, vessels sailing between two or more Norwegian harbors are affected by the Norwegian NO_X tax. This consists of a taxation of 15 [kr/ton NO_X] for machineries used for propulsion with an effect of 750 [kW] or more. In addition to this taxation, there is also a NO_X fund which stimulates companies and ship owners to invest in NO_X reducing solutions. By offering funding per kg saved NOx, ship owners are encouraged to invest in other technologies than ordinary diesel propulsion systems. One of these technologies is LNG as fuel. Today, one can receive as much as 80% in financial support, limited up to a maximum of 350 [kr/kg] reduced NO_X. [52] In addition to this, all gas fueled vessels are also exempted from CO2 taxes in the Revised National Budget from 2011.[53] With this frame, Norwegian offshore and ferry operators are ordering more and more LNG propelled vessels.

The number of vessels operating on LNG in Norway is about 30, with a large portion being ferries operating in populated coastal areas. Besides ferries, the Norwegian Coastal Guard is operating three dual fuel (LNG and diesel oil) vessels, and the Platform Support Vessel owner Eidesvik alone has currently a fleet of three dual fuel vessels, with two more for delivery in the fall of 2012. This will make them the largest LNG powered supply ship owner in the world. [54] The Norwegian offshore ship owner REM will also join the exclusive party of being a ship owner with a LNG fuel vessel in their fleet. They announced in May 2011 that they have ordered a PSV from Kleven yard in Norway for a 90m dual fuel vessel. [55]

Figure 27. Dual fuel offshore support vessel. Photo: REM offshore.

This trend and the special condition and legislations in Norway are not the situation for the current global shipping. The Norwegian situation has however given valuable experience with also a lot more to be experienced in the future. This must be said to have pushed the drive for new LNG technology further. Also the classification societies, with DNV as the prime driver, have gained a lot of empirical data from the operations in the Norwegian waters. Such experience makes the implementation of LNG onboard new vessels easier, as the strict regulations due to uncertainty regarding safety and hazards are slowly getting less restrictive. This can be seen in the development of the coastal LNG ferries in Norway. The first ferry, Glutra, went into traffic in the year 2000.

Figure 28. "MF Glutra". Notice the two separate machine rooms located on the top deck. Picture: vesseltracker.com

MF Glutra was built with gas-electric propulsion system, with the LNG fueled engines and fuel tanks placed on the top deck. This was due to many factors, such as explosion and fire concerns and lack of experience. It was also uncertainty connected to a scenario where LNG could leak and getting trapped under the ferry's decks. This was a concern, even though methane is lighter than air and would in that case likely rise up and spread out in the atmosphere, limiting the fire hazard. Also at that time, LNG engines was not cleared for direct propulsion to the propeller and had to be used together with generators and an electrical system. This made the new build price quite high compared to a mechanical direct drive solution. M/V Glutra must be considered as a pilot project for LNG fuel vessels. Challenges and experience regarding fuel delivery to the vessel and actual fuel use during sailing has been encountered. A result of this led to a rather embarrassing episode, with the ferry being taken out of traffic for the rest of the evening due to lack of fuel onboard. This is an example of the two most interesting operational challenges regarding LNG as fuel for ships: Distribution of LNG, and LNG's energy density. Source: [56]

A newer generations of ferries operation on LNG, together with MF Glutra, is the sister class consisting of MF Bergensfjord, Fanafjord, Raunefjord, Stavangerfjord and Mastrafjord. They connect Stavanger and Bergen, as a part of highway E39 in Norway. Compared to the RoRo vessels operated by Höegh, they have a few similarities. Where the majority of the Höegh fleet is equipped with a total of four engines, one main engine and three auxiliary engines, the MF Bergensfjord sister class have four main engines with diesel-electric propulsion system installed. The total amount of installed power is similar, with about 15.000 [kW] from the 2-stroke main engine installed in Höeghs vessels, whereas the ferries have a total of 12.300 [kW] installed.

Table 1. Comparing data between a LNG fueled ferry and a generalized Höegh vessel.

Vessel	Fjord 1 ferry, Bergensfjord	Höegh, C4 sister class
LOA	130	229
Built	2006	2000
Type of fuel	LNG	HFO
Nr. main engines	4	1
Power	12.300	15.000
Operating speed	21	18
Bunker capacity	250 m^3	3500 m^3

This newer sister classes of ferries shows the development in technology, and some of the changes in regard of limitations. We can see from the general arrangement that the LNG tanks are now fully integrated in the ship's hull, and the vessel can be designed with a better pay load optimization and more economical.

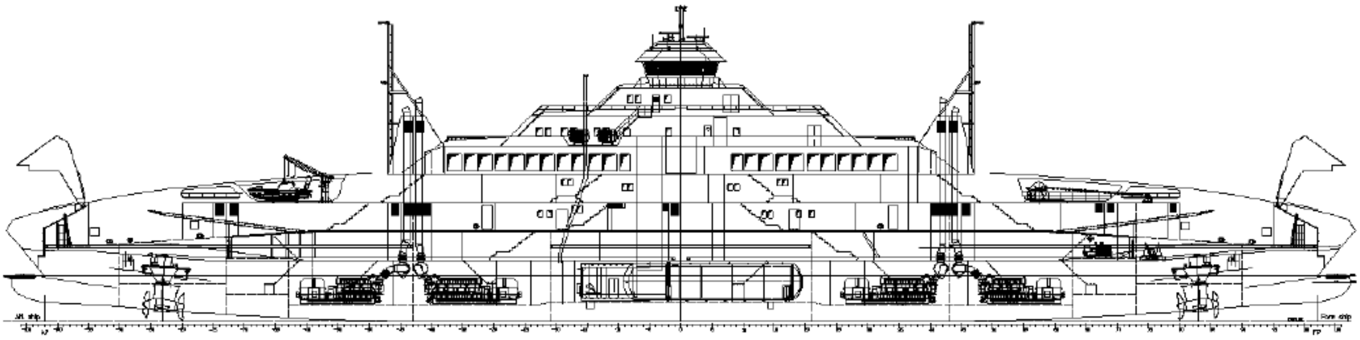

Figure 29. MF Bergensfjord. Courtesy MARINTEK.

The most significant difference is the operation pattern of the two different types of ships. The ferry has a very limited bunker capacity due to its designed short sea operation, whereas the car carriers have a very large range that utilized price differences in HFO to gain the ship owner. This will be the main challenge for LNG as a considerable option to diesel, and will be of essence later in this study.

Future LNG ships and designs

The two different ferries mentioned above, with MF Glutra and Bergensfjord also shows a leap in LNG development. Also, from experience from gas power plants, as the knowledge of LNG qualities and LNG-engines in vessels gets better; the regulations are no longer as strict. The new modern LNG vessels have a much better integrated LNG fuel system. This gives the naval architects possibilities to design a much more optimal ship for the various roles, as we know from conventional fuel oil propelled vessels. Another example of such vessel, that share similarities to a possible Höegh LNG RoRo ship are the coastal LNG-fueled RORO from Sea Cargo, and the LNG-fueled RoPax designed by Hamworthy.

The vessel has a direct mechanical drive with a reduction gear, and two 250m3 gas tanks located directly aft of the engine room, off-center to reduce the effect on the cargo capacity. The single main engine solution is identical to the solution onboard Höeghs ships. In the Sea-Cargo case, the propulsion system consists of a 5.000 [kW] Bergen 4-stroke engine with a reduction gear mechanically coupled to a controllable pitch propeller. The Höegh vessels use direct drive, low speed 15.000 [kW] 2-stroke engines with a fix pitch propeller[3]. In other words, the vessels have a quite similar solution.

Figure 30. Illustration of the Sea-Cargo LNG fueled vessel. From: [57]

The RoPax designed by Hamworthy is in some ways similar to the Sea-Cargo solution. The LNG tanks are on the double bottom with a total capacity of 1500 m^3.It is designed with a direct drive solution to controllable pitch propellers. In the Hamworthy set up, they have however two propellers and four main engines. Their design also includes additional 720 m^3diesel tanks, allowing the vessel to operate on gas, diesel or both with the ships duel fuel engines. [58]

Figure 31. Duel fuel RoPax design from Hamworthy.

[3] From experience during my summer internship,
I learned that the new Vinashin-built Höegh vessels will be equipped with controllable pitch propeller.

In the summer of 2010, DNV had a summer intern project called Frost, looking at possibilities for LNG as fuel for a fictive ship owner in the Baltic Sea. The result was perhaps more of an economical and logistical conclusion, compared to the ship design solution this part of the task looks at. Never the less, they concluded that by having a tanker vessel they would have no problems concerning stability, and could place the LNG tanks on the top deck. This design could not steal cargo space, and could also maintain sufficient range. The reason why this conclusion is of interest is that it might also help other shipping segments, such as ordinary bulk vessels or tankers, to choose LNG as fuel. That would help the development of global LNG bunkering stations and network.

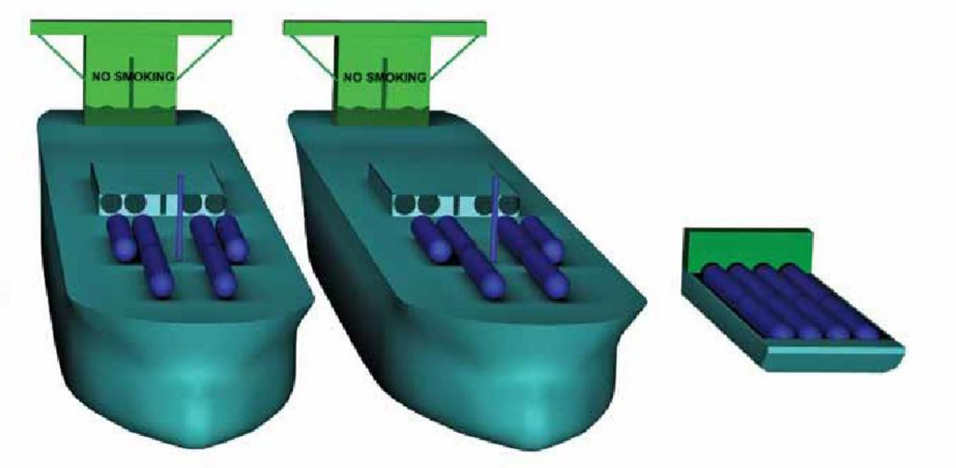

Figure 32. LNG on deck of tanker vessels, with bunkering barge as assistance. Source: [25]

The most interesting study done in relation to my thesis is however the Triality concept designed by DNV, together with participants from the industry. The Triality ship is a crude oil tanker concept that is designed to be fuelled by LNG. Just as the summer internship Frost project, in this case the LNG type C fuel tanks are place on top of the deck, outside. This is possible due to the mentioned high initial stability connected to this class of vessels. [59]

As we see from the illustration and understand from the concept, is that the possible fuel capacity for such a vessel is very large thus making it without concern of the possible range for the vessel. In this specific case, two C-type tanks with capacity of 13.500 m^3 LNG is installed, and is estimated to giving the ship a range of 25.000 nautical miles. Together with a ballast free hull, this vessel is from DNVs conclusion superior to the traditional supertanker when it comes to environmental factors and emission. It is also from DNVs estimates competitive economically compared to the traditional supertanker in spite of the added new build cost, due to overall lower operating cost mainly due to the difference in gas and fuel oil cost. [60]

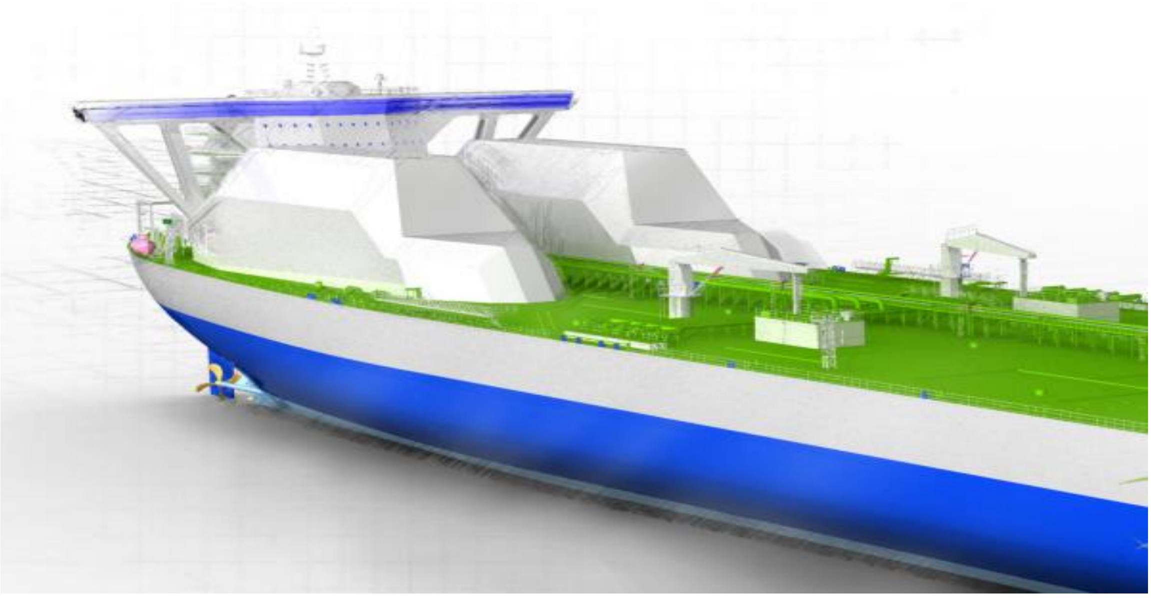

Figure 33. DNVS Triality concept. © DNV/Making Waves"

LNG engine technology

Current options regarding LNG engines are good with in terms of the four stroke engine, with several suppliers. The major engine makers have an increasingly large span of lean burn LNG, and dual fueled engines in various sizes and categories. The only operating marine engine on LNG is four strokes, medium speed engine with lean burn or dual fuel. This is found in the offshore vessels with the dual fuel edition, and the ferries as pure LNG, a design choice motivated by the different operation profiles and area. The switch between the two types of fuels happens without any interruption. The different engines delivered from Wärtsilä, MAN and Rolls Royce Bergen can be seen in the table:

Table 7. Examples of DF engines on the market

Type	Speed	Cylinders	Engine [kW]
Wärtsilä 20 DF	1200	6, 8, 9	1.056 - 1.584
Wärtsilä 34 DF	750	6, 9, 12, 16	2.700 - 7.200
Wärtsilä 50DF	500	6, 8, 9, 12, 16, 18	5.700 - 17.100
Bergen C26:33	900	6, 8, 9	1.460 - 2.430
Bergen B35:40	750	9, 12, 16	3.780 - 7.000
Man 51/60DF	500	6,7,8,9,12,14,16,18	5.850 - 17.550

The specific fuel consumption for these engines can be estimated to be around 180 – 190 [g/kWh] at optimal load, depending on many factors such as fuel oil quality, temperatures etc. This is also within the area given by Rolls Royce. [61] The way a purely LNG fueled engine operates compared to dual fuel engine can be illustrated by the following sketch from presentation by Einang, Marintek:

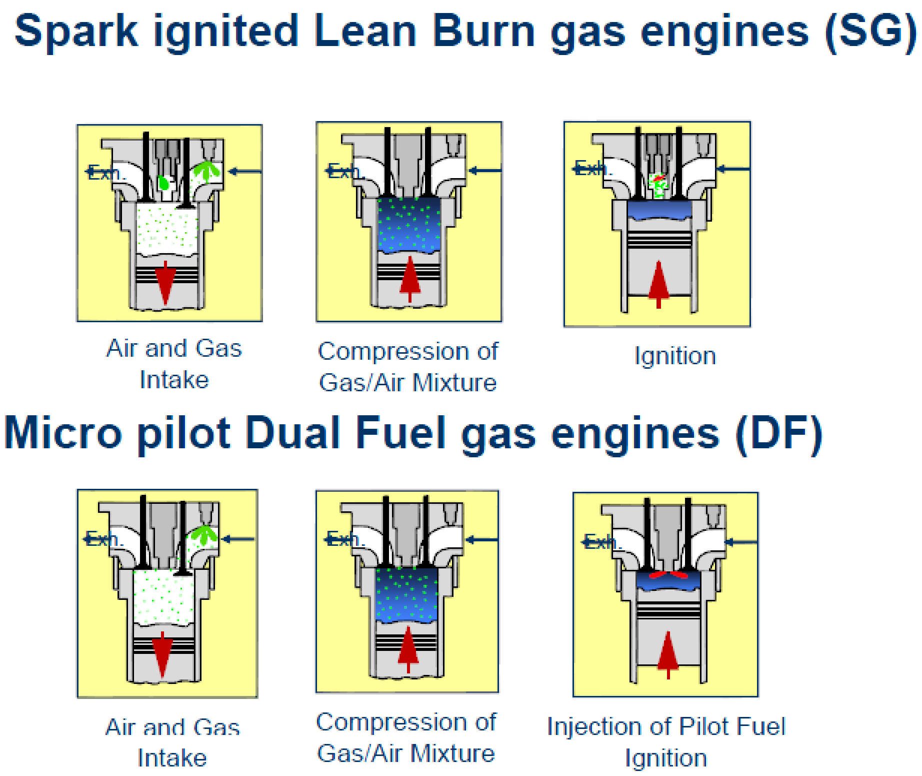

Figure 34. Lean Burn vs Dual Fuel. Source: [1]

When operation purely as a gas fueled engine, it will work as an Otto-cycle with an ignition spark to ignite the mixture of air and natural gas. The LNG being heated and regasified by the engines cooling water system before fed to the engine. These systems are today often seen integrated in the LNG tank, together with compressors, making the gas running automatically to the engine. A dual fuel engine operation in gas mode will have a pilot fuel, consisting of a small diesel injection, less than 1% of total fuel consumption from Wärtsila, in order to make the mixture ignite. The emission when running on LNG can be illustrated with the following sketches:

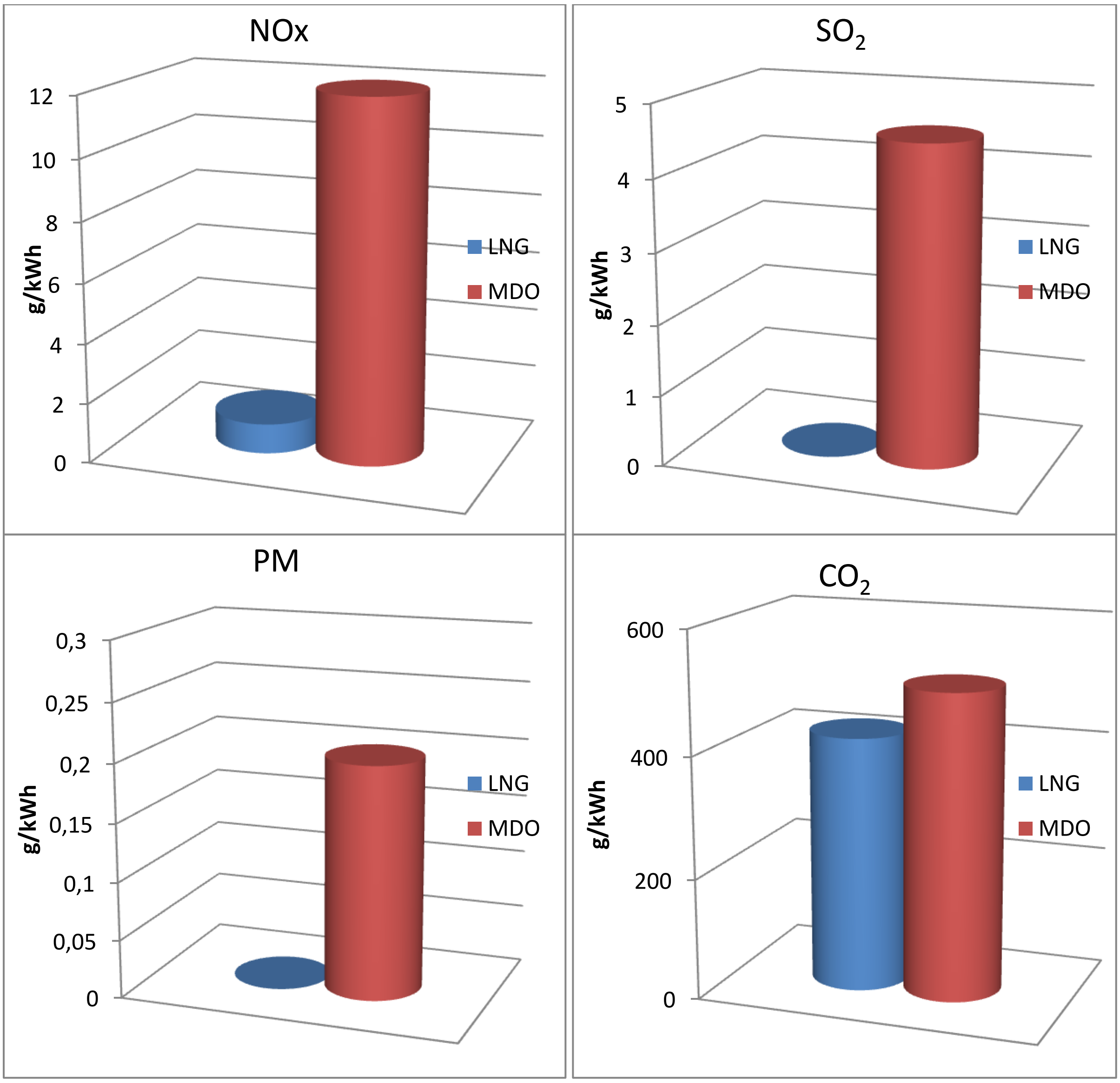

Figure 35. Emission from 4-stroke MDO engine compared to 4 stroke LNG. From [1]

These figures are not to be read as exact because of different fuel qualities and different quality of various distillates. There will also be variations from engine maker to engine maker, and in terms of speed of the engines. Notice that this is for 4 stroke engines. The difference between future 2-stroke engines on LNG compared to HFO is expected to be even larger, as HFO has higher concentration of sulfur, thus having higher SO_2-emission. LNG will still be sulfur free. The other scales are assumed to be quite similar based on how the engine works and the various fuel qualities. And educated guess is also that the difference in CO_2 will be a bit higher than the 20% shown, since HFO is not as energy dense as MDO. We also see that a LNG operated ship will be below all ECA values predicted in the coming periods. The efficiency of LNG fueled engines compared to diesel fueled engines is not well studied yet, but from a sketch from MARINTEK, the following basic differences can be shown, from the current standard engines:

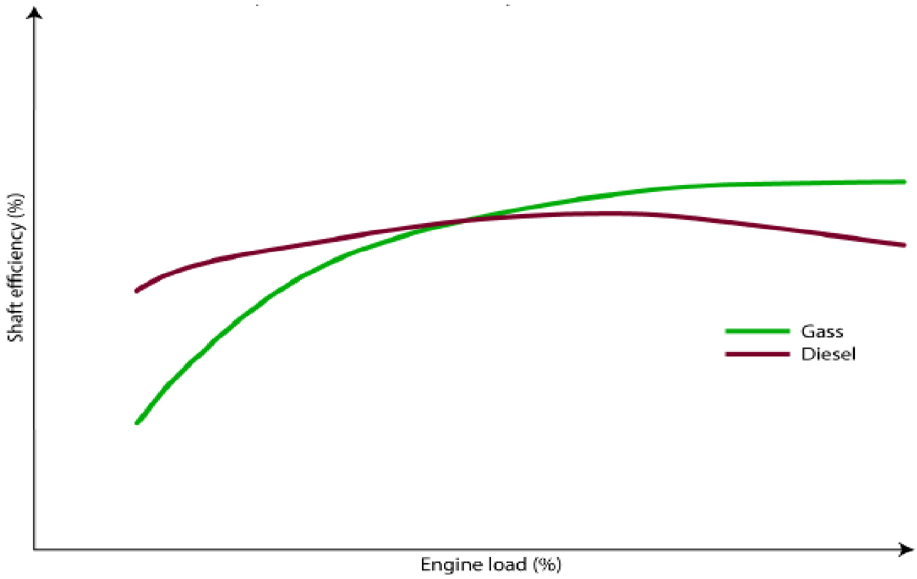

Figure 36. Illustration of efficiency of diesel vs lean burn. Source: [1]

We see from the sketch that a lean burn engine has an increased efficiency towards higher loads, but an exponential lower efficiency at lower loads, where the well known diesel curves peaks at about 80-85%, but with a relatively moderate development to each side. These figures are not to be considered as exact, and development in engine technology will influence the figures. It is however of interest in design of a vessel if the vessel frequently operates at load beneath NCR, or often at higher loads, close to MCR. These specific differences in the fuels are possible to implement in the design from study and assumptions from the operational profile. That will make the vessel running on LNG when most favorable, and switching to low sulfur bunker if at lower loads or at longer voyages. DNV had together with MAN Turbo and diesel the following solution for a dual fuel 2-stroke engine in terms of operation and fuel mode:

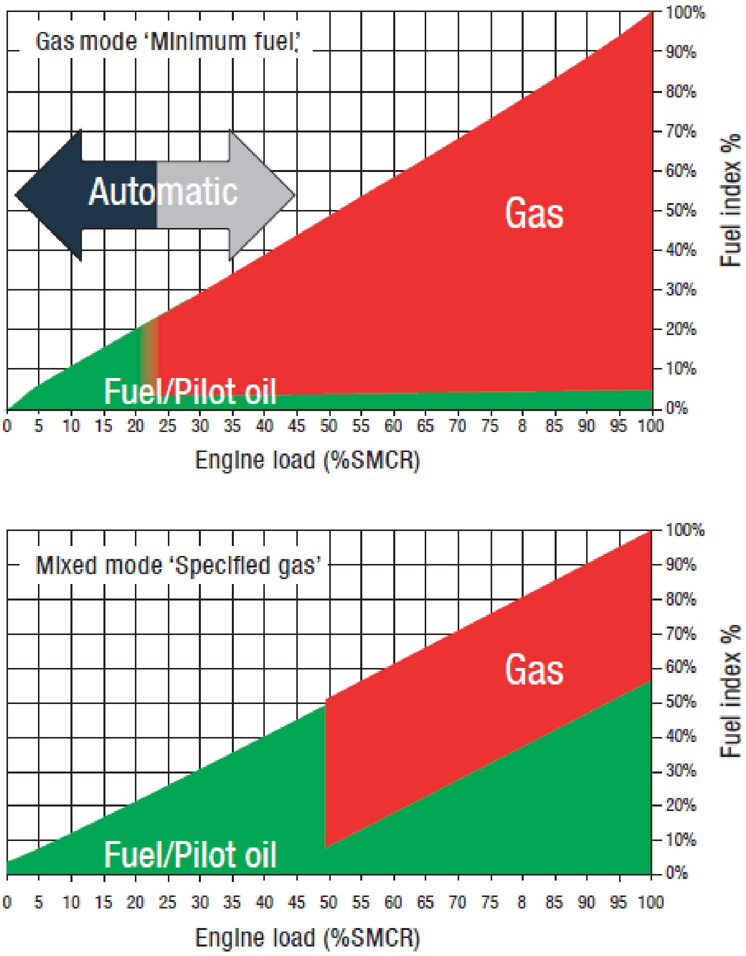

Figure 37. Duel fuel operation. Courtesy: DNV and MAN. [12]

MARINTEK have been researching medium speed LNG and dual fueled engines since 1984, with different engine models from both Wärtsilä and Rolls Royce. According to a presentation held by MARINTEK and Per Magne Einang from the course Sustainable Ship Design and Operation, LNG engines in a duel fuel set up may be suboptimal in some cases. MARINTEK, with the approval of Mr. Einang presented in a later report, concrete numbers connected to methane slip from the dual fuel engines due to leakage in the engine itself and from unburned LNG fuel. Source: [62] This is presented in the following table:

Table 8. . Methane emission from current LNG engines.

Vessel category (Gas operated)	Methane emission factor, ISO/IMO weighted	
Ferry (Currently lean burn engines only)	44 [kg CH_4/ton LNG]	8.5 [kg CH_4/ton kWh]
Offshore support (Currently dual fuel only)	80 [kg CH_4/ton LNG]	15.6 [kg CH_4/ton kWh]
Coast guard (Currently lean burn engines only)	44 [kg CH_4/ton LNG]	8.5 [kg CH_4/ton kWh]

These data are emphasize to be of a small selection of installations and are recommended to be further researched. Engine makers are also currently offering new engines that have limited these effects significantly, and are working on even better engines in terms of methane slip. LNG engines in commercial ship traffic is in many ways still a young niche, and since these problems are mainly connected to physical properties and the new technology, development within research will reduce the methane slip in the years to come, making newer dual fuels engines even greener.

From communication with both Wärtsilä and MAN engine makers, a lot is currently happening on the 2-stroke front. MAN is currently the coordinator of a venture newly started; a three year long project called Helios. Helios is a project within the EU's 7th framework program for research and technical development. This program has as goal to develop an electronically controlled 2-stroke low speed marine engine that operates on LNG or compressed natural gas (CNG). Source: [63] E-mail correspondence with MAN was of high interest. I was informed that they are currently testing and researching new parts in order to meet the high requirements concerning safety, and also in mind the complexity concerning LNG as fuel. Together with a defined large bore, two stroke engine, given to have a bore range between 350 and 980[mm], the other result of the program is to develop a basis for the possible retrofitting of existing two stroke ship engines to gas operation. From the Quantum project together with DNV on designing a container vessel operated on LNG, a new two stroke GI-engine is also presented. [12]

Wärtsilä is also currently developing two stroke LNG fueled main engines at this moment. From e-mail communication with Dionysios Antonopoulos at ship power for merchant vessels, they are currently testing and tuning two stroke LNG engines, and the results are not available until this thesis is due, as it looks today.

Together with this interesting information, he could also inform me that their dual fueled gas engines are optimized for gas operation, so a pure gas 4-stroke engine will in fact have the same efficiency as the dual fuel when both are operating on gas. His example was the 4-stroke 50DF (dual fuel) engine that has 49% efficiency in gas mode, and 45% efficiency when operating on diesel mode. In general, it looks as if the market will be served with competitive 2-stroke LNG and dual fuel engines that will

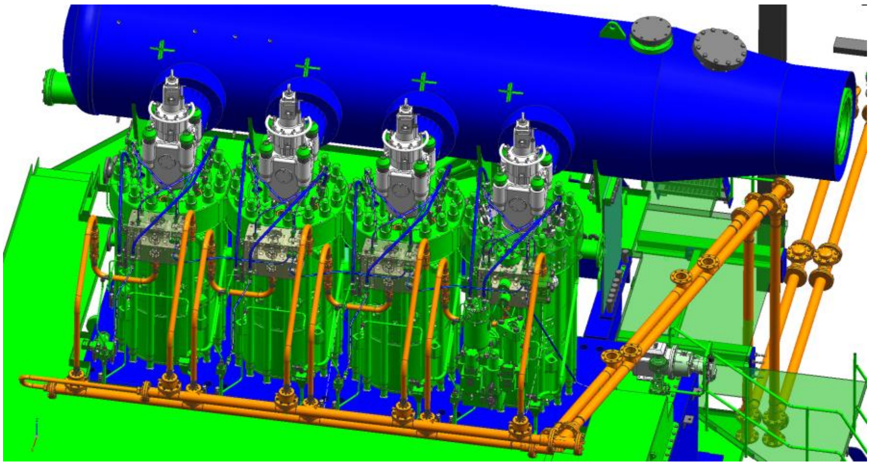

Figure 38. Two stroke gas fuel engine. Illustration from documents given by MAN.

have the same efficiency as the existing diesel powered engines when running on LNG. The price to pay in terms of the flexibility from a dual stroke, to switch between HFO in addition, is a lower efficiency compared to both the current pure diesel and the duel fuel operating on LNG. This makes the final choice complex due to many solutions at hand, such as regional LNG and bunker prices, voyage distances and consumption, ECAs etc. If selecting a future dual fuel setup, one would have to include in design the optimization that LNG will, from the research by Antonopoulos, be more efficient than HFO. This is a key factor when designing and locating space for the two bunker fuels. It would in the end result in a relatively larger volume for LNG tanks than if the two fuels would be similar in efficiency.

LNG tanks

The development of LNG tanks has been continuous as the marked for LNG tanks has increased, and the type of vessels or installations carrying LNG has varied. LNG being about 1/2 of the energy dense per [m^3] compared to marine diesel oil is one of the main drawbacks for using it as fuel onboard ships as this will reduce the vessels operation range. In addition to this, thermo tanks and equipment to handle the liquid natural gas makes the total volume factor compared to HFO about 3-4 times the volume per kg, dependant on LNG tanks utilization of the volumes onboard. In addition, regulations from classification societies have been an important design factor for the tank arrangement possibilities, and selection of tanks. Today, there are several types of LNG tanks suited for ships in all kind of operations and with various requirements. The two main types used by LNG tankers are the self supportive Moss-type spherical aluminum tanks, and the more membrane-type tanks. The trend shows that spherical Moss tanks are less chosen in LNG shipping, as they require a lot more space and a larger vessel per volume capacity compared with membrane tanks. This is due to the spherical shape of the tanks not exploiting the vessels hull shape, whereas the membrane tanks can be built in the same shape as the ship hull. In that way, the hulls volume is better utilized in a membrane LNG tanker. One of the main drawbacks with this low exploitation is the extra costs when sailing through the Suez channel, where the fee is connected to vessel size. A RoRo with cargo holds being exploited by LNG tanks will have a total added price per volume of cargo in that was as well, in addition to all the other direct costs connected to a ship. Membrane thanks are on the other side more vulnerable for sloshing when sailing in rough weather, where the spherical tanks are very robust and more suited for these conditions. However, there are a lot of efforts being put into design of membrane type tanks that can withstand sloshing impact loads. The boil-off gas rate is similar for the two types, with about 0.14-0.2 % day.

Figure 39. Illustration of a Moss type spherical tank (left), and picture inside of a membrane type tank. (right). Illustrations: [64] and [65]

Tanks suitable for bunker tanks onboard a merchant vessels, are from the current situation a bit limited but evolving. The tank must resist sloshing forcers when sailing with half full tanks, and they must be as compact and trustworthy as possible in terms of safety and operation. With today’s technology, the space saving membrane tanks will not be safe enough as a bunker tank due to sloshing in high sea. The conclusion is that the only possible choice as of today must be a self supporting tank that is strong enough to operate as a bunker tank with possibilities for sloshing forces. DNV have been researching such technology since 2004, and the mentioned Aker Solution offshore tank is one of the newer developments in design. This will be coming in the future.

The two appropriate choices at the market now for a Höegh ship is the IMO type-B LNG tank and the IMO type-C LNG tank. The two different tanks have these qualities and specifics:

Table 9. Suitable LNG tanks for merchant vessels.

	Type B LNG tank	Type C LNG tank
Shape	Diamond, rectangular or prismatic	Cylindrical or bilobe
Pressure	Atmospheric	4-5 bar
Boil off [%/day]	0,14-0,21	0,21 – 0,23
Main advantage	Freedom of shape	BOG-reduction, no maintenance

From studies done by DNV in the Quantum ship design, and results from other LNG fueled ships such as the Sea Cargo RoRo, the advantage of being able of implementing the BOG-system within the LNG tank in the C-tank set up, is of so large importance that it makes the C-type the most promising solution in those cases. When the tank is already under a pressure of about 4-5 [bar], one can collect the BOG within the tank. This opportunity will both benefit the fuel costs and the total emission from the ship during operation. This seems to be the best solution for the car carriers as well. There are several makers that offer various solutions for such a configuration, and one example from TGE shows the technical equipment connected to LNG tanks and engines.

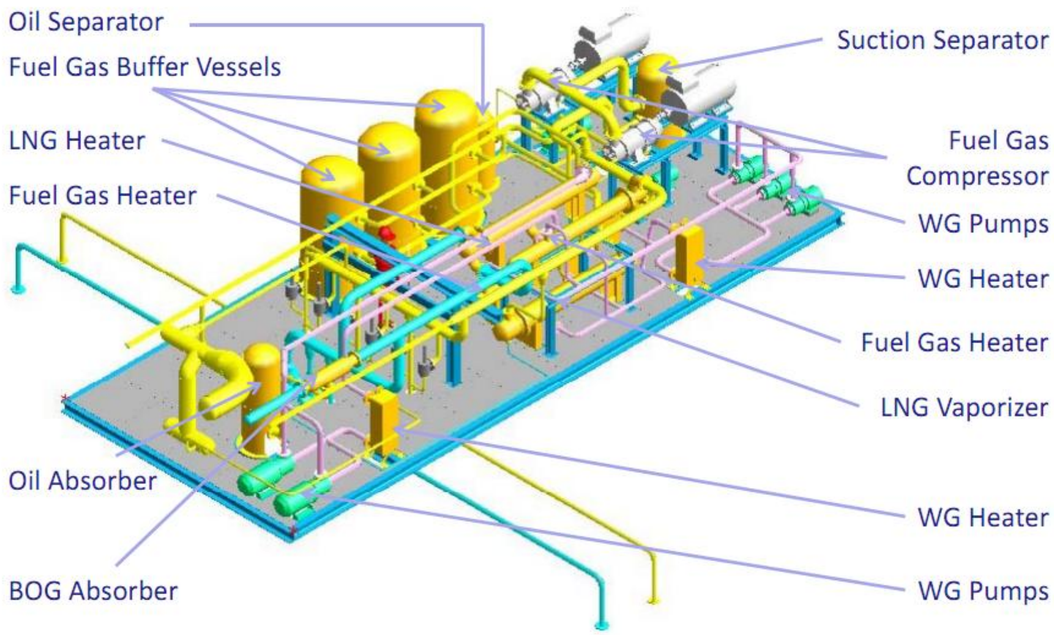

Figure 40. Technical equipement for LNG tanks onboard ship. Source: [11]

This setup is design for a vessel with a power of around 10.000 [kW], which is very similar to what the Höegh ships deliver. This system has also a BOG absorber that will prevent the loss of boil off gas, and it is also possible to fit on any C-type tank. In conclusion, various well suited LNG systems for larger marine engine exist today, and are available on the market. In the same brochure where this configuration was found, they also had a proposal consisting of three 300 m^3 LNG tanks connected to the system. This is also a good solution for being able to cross between the larger intercontinental markets, but as they also mention in the same brochure, there is a total of 160 different type-C tanks available from TGE alone, so the configuration itself is very flexible, and can be mixed in many different ways. We must also keep in mind that if the ship is designed to run on gas and gas alone (lean burn), DNV demands a tank arrangement of two or more tanks with approximately the same tank size. Source: [66]

The vast variation in sizes of LNG tanks, as well as development in this market in general, creates playground for solutions regarding bunkering and building a global network of possible LNG is refueling installations. An example of existing products for helping such steps taking place can be found from Chart Ferox. They deliver LNG solutions designed for places also without a LNG pipeline network or other gas infrastructure. Both Norway and Finland have these stations placed off the coast. The largest cylindrical tanks have a total volume of 1000 m^3, but they can also deliver flat bottom tanks with volumes up to 3000m^3 each. Source: [8]. These satellite LNG stations can be used to create a fueling network, which is considered of high importance of allowing the LNG to be competitive compared to HFO in terms of logistics.

Figure 41. LNG satellite. Picture from [8]

Rules and regulations

Today, DNVs role as a classification society is of large importance. They have followed the shipping of LNG since the first LNG tankers and especially by studying the development of LNG fueled ferries and offshore vessels in Norway. By introducing new requirements, and in addition contributing with new solutions in terms of the Frost summer project, and the Triality and Quantum designs, and also taking a close part in the development and setting up standards in general. From the DNV rules that came into force as of 1. July 2010, there were some adjustments to various aspects with handling gas as fuel for ships. In general we see a trend toward this being easier to implement onboard vessels. This can also be looked upon as a natural development, as the technology improves and the classifications societies experience and risk understanding are clearer. As examples of this, we read in the updated version of the rules that material requirements on compressed natural gas tanks are “less strict for low pressure and piping with working temperature above zero”. [66] Also compressor rooms can be below open deck if arranged as tank rooms with some special regulations.

The regulations connected to LNG tanks installed on board are B/5 from the ship sides, but for ships not made for passenger traffic less than B/5 can be accepted based on case to case. If located over the weather deck 760 mm is accepted for non passenger ships. It must also be the lesser of B/15 or at least 2 [m] above the keel and not less than 760 [mm] above the shell plate. This is found in part

G402 from [66] Double bottom hull is not necessary in the case of LNG as main fuel, as long as the LNG tank is within the acceptable range from the bottom. The tanks can also not be filled more than 98% in case of expansion. By contact from DNV regarding implementation of LNG tanks in or around pay load areas, there are no specific demands or defined rules jet as far as my person of contact knew. Martin Wold at DNV would think that it would have to be decided from case to case. I cannot find any regulations regarding HFO or other distillate tanks in arrangement to LNG fueled tanks from the current DNV rules. [67] An option could in such a case consist of a small deck or plate separation between fuel oil tanks at the bottom of the hull, and the possible LNG tanks 2 [m] above the hull and at least 760 [mm] above the shell plate.

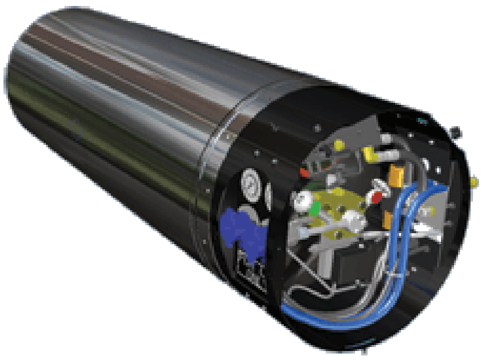

Figure 42. Illustration of cylindrical LNG tank with piping and equipment. Courtesy Cummins-Westport.

Risk aspects

The risk of having LNG as fuel or cargo onboard vessels are related to the gas being flammable if presented with sparks or other forms of heat sources. For us, risk is by definition:

Risk: an evaluation of hazards in terms of severity and probability. - S. Kristiansen *[68]*

It can be expressed as:

$R = C \cdot P$

The factors consequences (C) and the probability of occurrence (P) are functions of various parameters, such as human factors, operational variables, engineering factors etc. However, the perception of risk will be a subjective interpretation which will depend on factors such as knowledge, experience, external input and much more connected to each ones feelings and mindset.

Natural gas in its liquid state/in high concentration cannot burn and is thus not explosive and more or less harmless. It must be mixed with air and then ignited. If it is mixed within its flammable range and ignited, it can create explosion and fires. In order to identify probable hazards that could turn into accidents, it is useful to conduct a preliminary hazard analysis (PHA) for LNG onboard a vessel.

Table 10. PHA of LNG onboard ships

Hazardous element	Trigging event 1	Hazardous condition	Trigging event 2	Potential accident	Effect	Corrective measures
LNG onboard	Leakage from a broken pipe	Methane gas in technical rooms	Ignited by spark or heat	Explosion, fire	Fatalities, severe damages to ship	Gas detectors, piping integrated in the tank, separate rooms with increased safety
LNG onboard	Fracture in LNG tank	LNG spilled, vaporizing, hazardous gas	Crack or openings releases the gas out of enclosed space.	Leakage of climate gas, fire, explosion, global warming effect	Hull damage, environmental impact, fatalities	Tanks fitted away from collision areas, tanks in enclosed volumes with detectors
LNG onboard	Engine room fire	LNG tanks heated, failure in extinguish systems	Fire spreads out of the engine	Natural gas expanding in tanks, explosion of fuel tanks	Damages on structure and cargo, hull, leakage of fire hazardous gas, fire	Cofferdams, LNG tanks with safety systems, pressure release valves, CO2 systems

The table above is not exhaustive and will have added triggering events and more hazards. The point to the reader is however to see that the risk connected to LNG can be analyzed and further reduced through different design solutions and through experience in a later stage design and in a detailed work.

From the DNV regulations at the present time, LNG bunker tanks are not to be placed near the ship bottom or deck sides, making the event of cracks in LNG tanks or other damages to the LNG tanks from collision highly unlikely. As the consequences of the tanks having a leakage or failure not necessary turns into a fire or explosion, the total risk of LNG onboard is therefore assumed to be very low. Preventions for having an engine room fire would be of attention to the designers of LNG fueled vessel. Since this is of high importance for heavy fueled ships as well, I will assume that fire risk connected to the main engines is at low as reasonable feasible, thus making the risk of LNG tank explosion due to fire from engine room fire low.

When it comes to bunkering of LNG, this is described by Mr. Eingang [1] at MARINTEK as a safe operation. The standard today with the ferries operation in Norway is refueling every 4-5 hour with an isolated hose connected to the ship side and bunkering systems. Since natural gas is not flammable in it liquid state, regulations connected to leakage of the gas is of the most concern. The bunkering capacity in [m^3/hour] should also be of little concern as long as the fuel is kept liquid.

Figure 43. Bunkering of LNG from fuel truck to ferry. Courtesy MARINTEK.

There has been several risk studies for similar types of operation and cases as this, and from the study of LNG fueled ferries and merchant vessels off the coast of Denmark from 2010, [69], the report concluded that in their case both compressed natural gas (CNG) and LNG vessels can be designed so that the fuel doesn't give a added risk. From this Danish study, there are also general risk reducing measures that can be implemented and be appropriate for this case beside the rules given from classification societies in relation to design:

-Quality management systems in the supply chain, including inspections and audits in the respective phases of development, implementation and operation

- Procedures for operation and maintenance

- Inspection programs

- Emergency shut-down systems for sectioning of the installation

- Fire and gas detection systems, as seen in the PHA.

- Special programs for shut-down, maintenance and replacement of installation parts

- Safety instructions and work permits

A study regarding spill of larger amounts of LNG at sea, conducted by Sandia National Laboratories for the United States Department of Energy's National Nuclear Security Administration [70], resulted quite similar to the Danish Ministry's report. This report was firstly based on spills from LNG tanker. However some of the key findings were that the risk from LNG spills on the sea due to accidental collision is small and manageable with current standards. If there should be a spill of LNG, the most hazardous area would be in the very proximity of the spill. As LNG vaporizes into gas, it will in a various distance from the spill, depending on many factors, mix into the atmosphere, being no longer of any fire hazard. Also additional management procedures and security systems and inspections will reduce the risk of LNG significantly. These two reports add more trust to the conclusions as they result similar, even though LNG is still a fuel we have relatively little experience from. The technology has developed and there are few historical accidents to take understanding from. In that way, the variance between the results will vary as the assumption used are based on a limited set of experience data, stated in the study.

Höegh Autoliners

In order to evaluate LNG as an alternative for Höegh, we must clarify the various trades, ship and consumption they operate with today, and what the future fleet would have to deal with. It is also of interest so cast light over other aspects that might be of interest when looking at possibilities for the specific company.

Höegh Fleet

Höegh Autoliners and Höegh Fleet Services operate and manage about 50 pure car carriers in a global network, with new-build joining the fleet during this year. Of these vessels, 41 are owned by Höegh, and 11 are on long time charter. In 2010, Höegh vessels made almost 3400 port calls. The fleet is spanning from about 2300 [CEU] to 7800 [CEU] for the deep sea trades. The larger part of the fleet consists of vessels of 199 [m. loa], and also a newly lengthen part of the fleet, consisting of 229 [m loa] ships. These ships operate with three auxiliary engines, and one main engine, a B&W 7S60MC two stroke, slow speed engine, which is directly connected to a fixed pitch, 6.6 [m. diameter], single propeller. This setup makes the fleet very dynamic in terms of trades and capacity management. The engine setup is also designed to be as economical as possible, in terms of high efficiency if the main engine is operated at designed speed. The installed machinery is also known to be very reliable, but as the system as no redundancy from, and including, the main engine to the propeller, you are dependent on the single parts being of high quality.

Table 11. Summary of an average Höegh ship from Oracle B.I. at Höegh FS.

General information of a Höegh operated ship	
LOA [m]	199-229
Draft [m]	9
Breadth (MLD) [m]	32.3
Main engine model	B&W 7S60MC (or similar)
NCR [kW]	17.500 @ 101.5 RPM
Ballast tanks approx. [tons]	8000
HFO capacity approx. [tons]	2500- 3500
Range at 85% load with 18 knots and 50 [tons/d][4]	30.000nm/70 days
Auxiliary engines	3x 1000 [kW]
Cargo ramp capacity [tons]	150
Cargo capacity [CEU]	2300 - 7800

This possible range has also been verified by Mr. Asskildt at the capacity management at Höegh. Further, we can also notice how flexible the cargo space is, with liftable decks, making it possible to adjust the deck height depending on the various cargos. This is a key factor when operation in the

[4] Typical average figures from experience during summer internship.

RoRo segment, to be flexible enough to handle the fluctuating “high and heavy” demand, which is a lucrative part of the total shipment. An overview of the general arrangement with ship side view, and tank top overview is found in the appendixes. We can notice the large spaces used for bunker and ballast water, as well the high degree of utilization of available volume for cargo holds. As the decks also are moveable in vertical direction, the different heights of the cargo can also be best possible implemented into the loading operation. The following drawing and the drawing in the appendix are from the lengthened sister class vessels build in 2008.

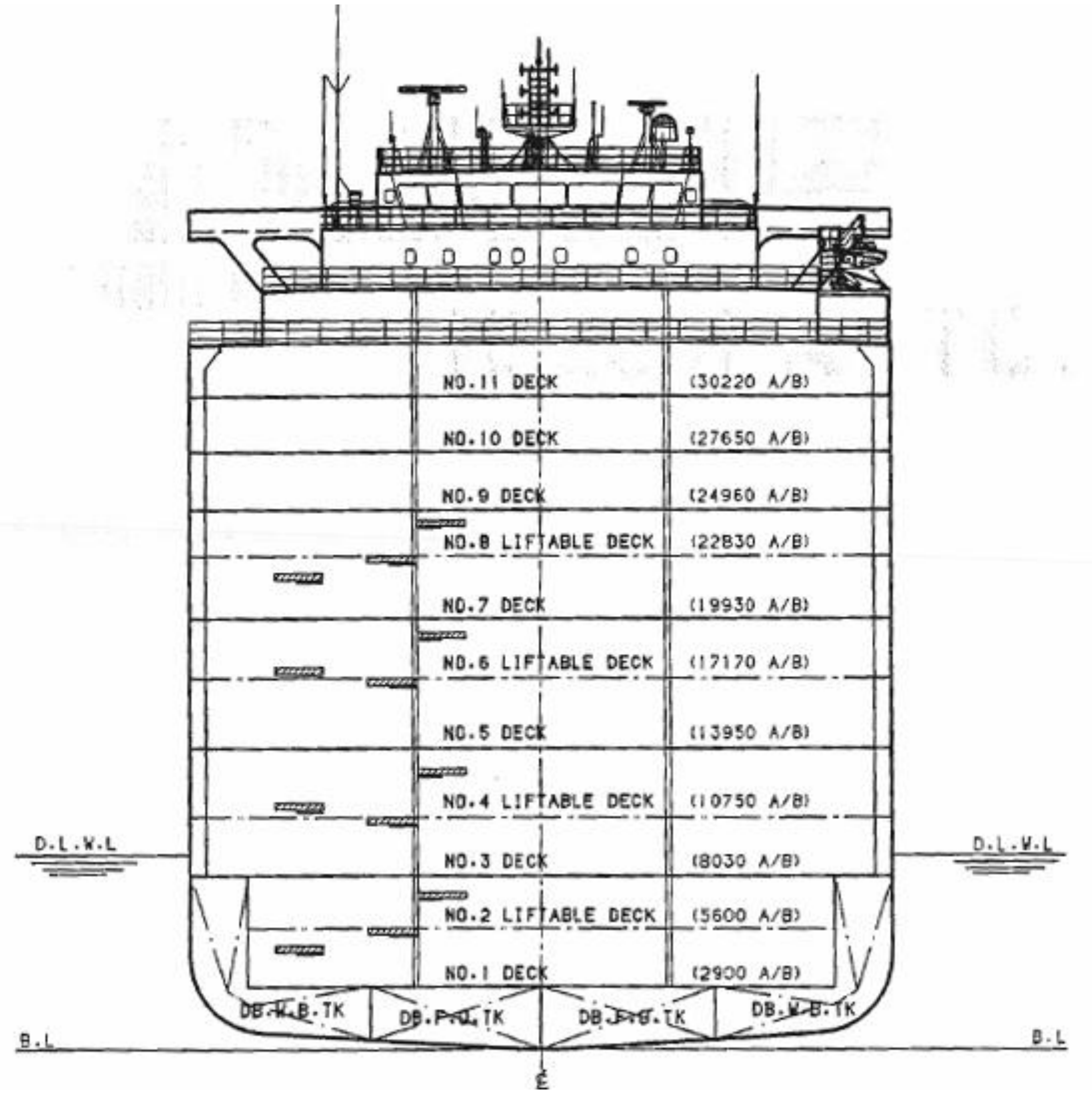

Figure 44. Midship section drawing of a Höegh PCTC.

The entire RoRo fleet today consists of about 600 vessels, making Höeghs capacity to be about 10% of the total market. The majority of the vessels operating in this segment today are off-the-shelf-ships based on standard designs from the major ship yards, with a rather small variance between the vessels in the fleet. This situation creates a smaller space for new development and solutions from the ship owners, as the ship builder have its own solution with small room for changes outside what is given in the design. In that way, the initiative for building RoRo ships fueled by LNG would have to be strong in order to change the ordinary market. The development can come from the major ship builders itself. However, such development from ship yards have not shown any signs outside the smaller offshore yards in Northern Europe, and it would likely have to be a great demand for such vessels for the key yards, such as the main yards in South Korea, to spend resources on research and development. Such a development would probably make LNG fueled ships quite low cost due to the effect of large scale, but it would have to be a development ahead in order to build up such a market. The other solution, and arguably the most likely, is that the design and need must necessarily come from the ship owners. Through cooperation with ship design offices that have the required knowledge regarding LNG-systems, and yards that offers competitive prices and experience from building merchant ships, the first steps could be feasible.

In the end of 2006, Höegh together with DVN, the Finish design office DeltaMarin and the Vietnam Shipbuilding Industry Group, Vinashin, started the development of a self designed new Pure Car Truck Carrier of 6900 TEU, with intentions of building a sister class of four vessels. The motivation of starting this project is several. This choice would give the ship owner several benefits that the common and major ship yards have little interest of offering. Some of the aspects mentioned by the COE of the time, Thor Jørgen Guttormsen, were to gain access to other sources in addition to the existing yards. The design incorporates technology to be as fuel efficient and green as possible. This includes optimal hull design for the operations, controllable pitch propeller, and aerodynamic bow shaped section with enclosed bridge wings also for safety aspects for the crew. [71] Having extensive experience from RoRo operation gives the ship owner a very good starting point for developing own ships. However, a PCTC is a quite complex and the project early faced challenges. The delivery time for the first vessel was originally set to 2009, but will not be completed until mid 2011. There have also been several issues during the construction phase, and it has not gone as well as initially hoped. The contract now only includes two vessels in total.

Fuel consumption and operation profile

The ship-shore reporting systems used by the Höegh fleet allows us to study a large amount of key data such as the past operation profiles and engine load from any single vessel. If we add it up, we can see a fleet level average from a chosen past period. From experience during my internship and understanding by the system, data’s before September 2009 are known to be a bit inaccurate as the system has been under constant improvement, and the reporting has been more stream lined through the years. In order to not be influenced by other factors, such to me unknown seasonal changes or other uncertainties; I chose to look at the fleets load profile from April 2010 to April 2011. It is off course highly discussable whether or not this specific time period will act as a good ground for future engine load. That will anyway be highly uncertain to predict as it is linked to many factors.

In this time period, the vessels operated half of the time at medium load, about 25% at lower loads and only 15% at high loads. The “unknown” is a variable reporting, often known to be maneuvering or at lower loads. This represents 10% of total time spent by the fleet as the graph shows. Mark that these figures below are the running hours, not the amount of fuel spent.

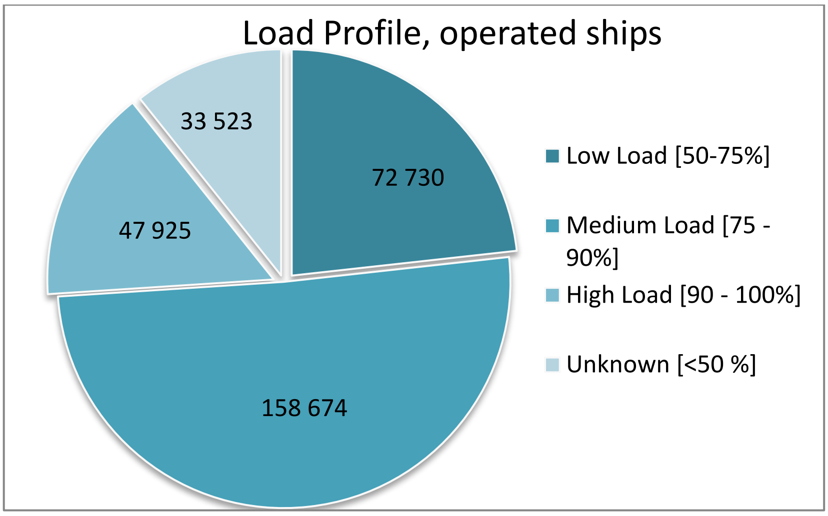

Figure 45. Load profile of Höegh operated ships. From ship-shore reporting April 2010 to April 2011.

With these data, we also include vessels that is on time charter or other vessels that have not reported daily numbers or accurate data. By filtering out the vessels that have less than 4000 hours of ME running for that period, which is less than half of the hours in a year, one can with better confident discuss the remaining vessels. These have been reporting daily during the entire year. This still gives us the majority of the fleet, with similar results as the one presented above as the small amount of vessels also had a small amount of operating hours, naturally. As seen earlier from the sketched efficiency between lean gas and diesel in relation to load, it is of interest to see the statistics connected to high load operation. The 45 vessels with more than 4000 registered engine hours are operating on normal or high load at 67% of the time the last year. The top third vessels in terms of high load have a significant average percentage of 83% on normal or high load, with normal load being the dominating state. In other words, 15 of the vessels operated sailed at 75% load or more for 83% of the time. The fuel consumption for the vessels in the three different profiles is as follows:

Table 12. ME consumption at various loads from 2010 to 2011.

Main Engine data from one year of operation, at fleet level.	
Load	Average fuel oil consumption per day
LOW	34,0
MEDIUM	41,0
HIGH	53,6
Significant value (top third) at high load	58,3

These numbers are of importance when calculating needed tank size, and will be used later on.

As seen in the facts box for the average Höegh ship, RoRo-vessels have a large power demand with three 1000 [kW] auxiliary engines installed. This is besides supplying the ship with electricity during voyage, as the main engine or shaft has no power outtake, also to handle a number of ventilator fans for the cargo decks during loading and discharge in ports. It is also supplying other systems operating at port, such as thrusters. If the vessel is harboring in an emission control area, these engines must run on low sulfur distillates in order to meet the regional regulations. As the number of ECA hasn't yet spread out worldwide, we see from the April 2010 to April 2011 data, that the most common fuel for auxiliary engines is marine heavy fuel oil. As discussed earlier in this study, this number will increase for the next years to come due to the increase in ECAs.

Table 13. Auxillary engine consumption.

Auxillary engine consumption, April 2010 to April 2011, fleet level	
HFO consumed by AE 1 to 3.	56 249 [tons]
MDO consumed by AE 1 to 3.	7 803 [tons]
Total consumption of auxillary fuel	64 052 [tons]
Per vessel per day	4 [tons]

The total consumption of fuel oil for the fleet can be found in Appendix , together with fuel oil statistics for the fleet from the past four years, illustrating the effect on fuel consumption in relation to a market dip or change in demand.

Höeghs trading routes and strategy

The trading network covered by Höegh is best described as global and dynamic, with a rather large number of port calls. From information given on the Autoliners webpage, the following standard routes are presented:

Table 14. Höeghs trading routes.

Caribbean Short Sea Service
Europe to East Asia and China
Europe to Middle East and India
Transatlantic Westbound
Europe to Africa, Indian Ocean and Oceania
East Asia to Europe
East Asia to South America
East Asia to US
East Asia to Oceania
USA and Mexico to Europe
USA to Middle East
USA to Africa
Middle East and India to Africa

We notice the numerous port calls within the range of routes. The east bound route, from the US, to the Middle East and continuing to Asia, covers a great distance and would need a vessel with large range if it was to sail the whole passage without bunkering underway. As the sailing schedule is highly influenced by numerous loading and discharging ports, the distances between ports are reality relatively short. This is also one of the main tactics from the ship owner. Höegh is functioning to be able to serve various regions between the main ports in order to pick up high and heavy cargo and have a large amount of cargo transported both ways between the markets. This also makes better possibilities for shorter bunkering intervals.

The opposite strategy is to ship directly between the two ends in order to get as much as possible high paid cargo from one region and high steaming back to the origin.

In the following two examples presented, the Höegh vessels are seen visiting the following harbors, respectively:

US, Middle East and Asia

Load ports:

- Jacksonville, FL
- Baltimore, MD
- Wilmington, DE
- New York, NY
- Charleston, SC
- Galveston, TX
- Providence, RI

Discharge ports:

- Valencia, Spain
- Misurata, Libya
- Beirut, Lebanon
- Aqaba, Jordan
- Jeddah/Dammam, Saudi Arabia
- Muscat, Oman
- Jebel Ali/Abu Dhabi, UAE
- Shuwaikh, Kuwait
- Mina Salman, Bahrain
- Doha, Qatar
- Mumbai, India
- Singapore
- Hong Kong

East Asia to Europe

Load ports:

- Shanghai, China
- Pusan, Korea
- Inchon, Korea
- Masan, Korea
- Kunsan, Korea
- Kawasaki, Japan
- Yokohama, Japan
- Kobe, Japan
- Kanda, Japan
- Hitachinaka, Japan
- Mundra, India
- Singapore
- Dalian, China
- Quingdao, China
- Tianjin, China

Discharge ports:

- Alexandria, Egypt
- Tripoli, Libya
- Djen Djen, Algeria
- Barcelona, Spain
- Beirut, Lebanon
- Genoa, Italy
- Livorno, Italy
- Koper, Slovenia
- Larnaca, Cyprus
- Limassol, Cyprus
- Piraeus, Greece
- Le Havre, France
- Amsterdam, Netherlands
- Antwerp, Belgium
- Zeebrugge, Belgium
- Bremerhaven, Germany
- Newcastle, UK
- Southampton, UK
- Rotterdam, Netherlands

In the selected routes, the longest sailing distances between ports will be from the Mexican Gulf, crossing the Atlantic Ocean to Europe, the Persian Gulf to South-Africa and probably form the Persian Gulf/ India, to Singapore, both ways. These stretches are vital for the line operation, and must be well within range of a vessel operated within the Höegh network. The distances from port to port for this route in particular will be approximately 5200 [nm] from Texas to the Mediterranean, 5000 [nm] from the Persian Gulf to South Africa, and less than 5000 [nm] from the Persian Gulf to Singapore.

Figure 46. Trading route US - ME – Asia. Illustration from [2]

These voyages are in other words the limitations when it comes to minimum range requirement for the vessels operation in these trades. It must naturally be able to cross these waters between the ports in any speed, and thereby fuel consumption, in order to be as flexible and efficient as the fleet must be in order to stay competitive as of today. However, as the fleet operators are dependent on mixing routes and vessels in order to meet the necessary demand for transportation, the larger parts of the fleet must be able to sail any possible trade. Everything from market development, disasters, dry dockings and sudden change in production from car and truck manufacturer, will alter the routes being currently operated. As of today, the furthest sailing distances between possible refueling ports are the vessels crossing from Japan to South America. Dependant on the harbors planned to visit along the legs, also the route from Europe, through the west coast of Africa, and then crossing from South Africa to Oceania, will have considerable distances between possible refueling options. Illustration of these two routes can be seen beneath, included and manipulated into the same map:

Figure 47. Two different trade routes with long range requirements for the vessels. Source: [2]

The distances in this case will be approximately 5500 [nm] from South Europe to South Africa, and less than 5000 [nm] from South Africa to Australia's west coast. (Fremantle being the first discharge port in Australia) For the route from Japan to South America, the minimum requirement in terms of range will be about 9500 [nm].

As we have seen, the range for these vessels are many times these laps, but the actual intervals between bunkering is not given on terms of the possible maximum number of sailing days between the need for replenishment.

Operational strategy

The operational strategy is dependent on the market in terms of ships sailing speeds. A good market with a large demand causes higher sailings speed, whereas a tight market in addition to higher fuel prices will create slow steaming.

Bunkering tactic is chosen regarding the various price differences between trading regions and the future operation pattern of the vessel at hand. If a vessel is coming from a low fuel cost area, typically in Rotterdam and Antwerp, bound to sail in a more costly region, fuel wise, it will bunker up maximum before trading in this region if possible. It might need to add smaller volumes of fuel along the route. In general, it will bunker fully up again when it is back to the low cost area. There are off course exceptions, but the main point is that a large range vessel will operate on general low cost fuel, thus being more cost effective than a short range vessel, as a LNG fueled ship will be. Examples of the variation of bunkering intervals are possible to find form the daily ship-to-shore-reports and from the capacity management division, supervising the bunkering operations. Below are some examples from past sailing schedules.

Example 1: In the start of 2011, Höegh Trooper served on a route that is not described from the routes found on the web page. The journey started in Europe, sailing down the west coast of Africa, and crossing over to Singapore followed by a round trip up to China and Japan, and back to Singapore and to the Middle East and Europe. This in itself shows the concept of flexible trade routes and demands on ship capacity in terms of range. This voyage is mapped bellow:

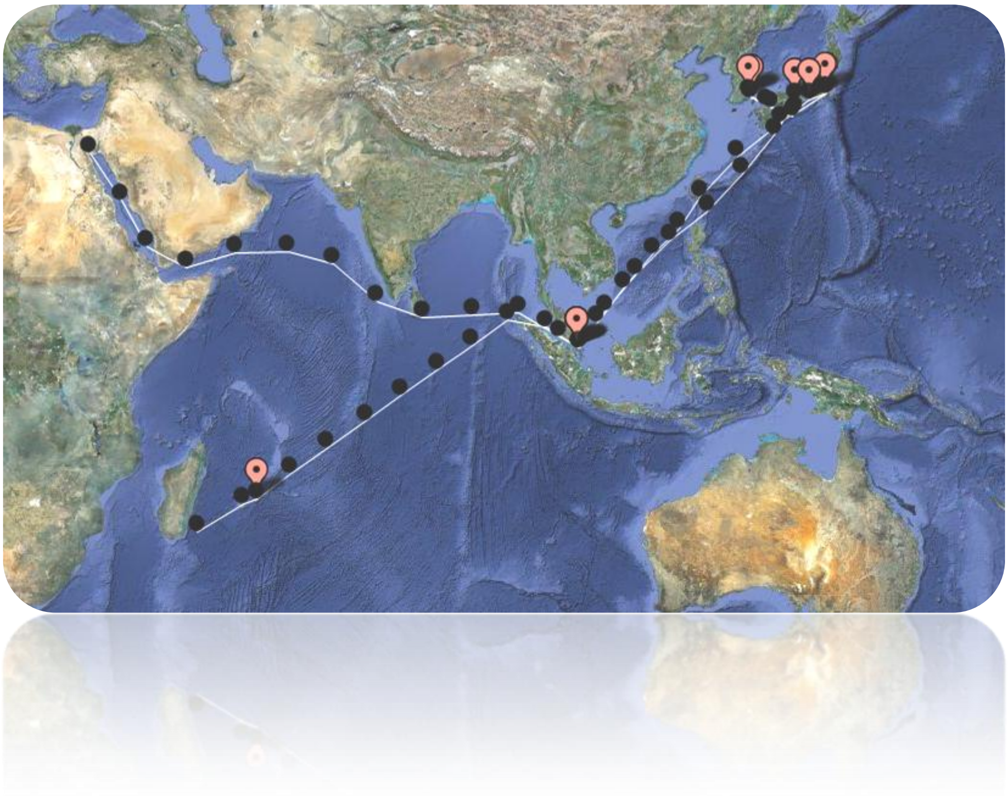

Figure 48. Höegh Trooper log.

The bunkering process in this trade was as illustrated in the next page. The figures are found from the noon reports obtained by the fleet management. Similar examples were found also for other vessels. Höegh Asia bunkered less than 300 tons in Barcelona, just to bunker almost 3000 tons in the ARA one week later, with still 700 tons remaining onboard. This illustrates that even though the vessels have a large range, they often bunker relatively small volumes during the voyage.

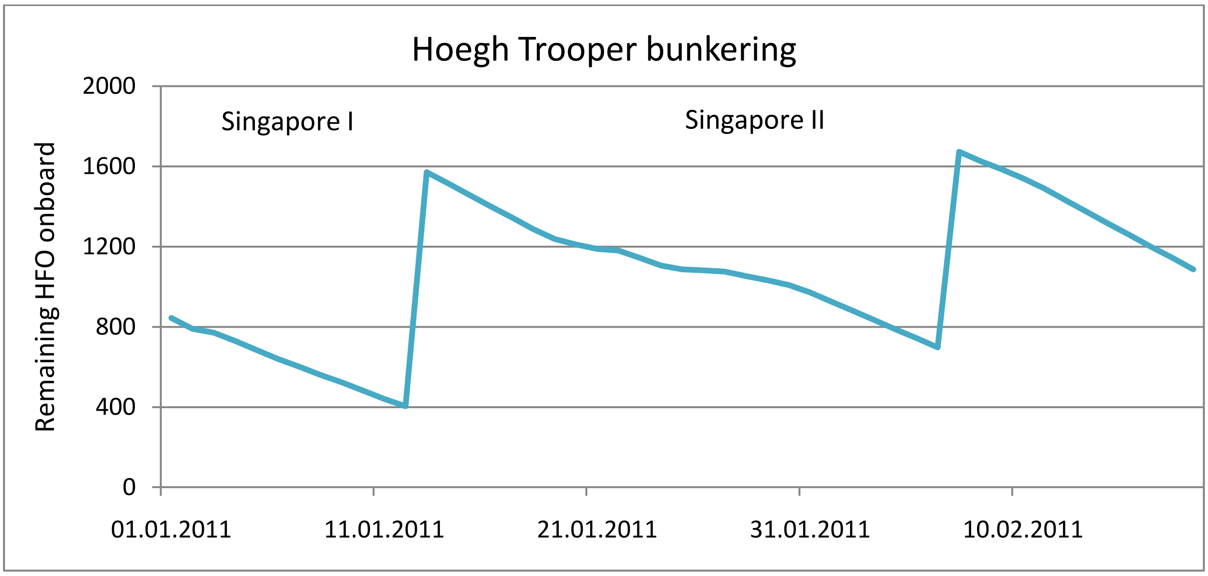

Figure 49. Trooper bunkering, start of 2011. From Oracle BI at Höegh, Oslo.

The ship bunkered sufficient amounts of fuel to be able to reach Singapore with good margin. She only bunker for 1000 tons in Singapore, making it necessary to bunker again in Singapore after having completed the port calls in China, South Korea and Japan, before heading west bound. We also notice that the vessel has double the fuel capacity on board compare to what it actually utilizes in this case. As mentioned above, the average fuel capacity is in the region of 3500 [tons] for these ships. This adds confident to the fact that these vessels in general have a very good range compared to the intervals between bunkering. From an operational point of view there is not a problem to bunker on ports of loading or discharging, and this is being utilized as we can se.

Other challenges concerning bunkering of fuel oil are the aspects of combination diverse qualities of fuels, in addition to regulation of fuel quality and quality testing.

When bunkering fuel oil today, a smaller sample from the fuel is being tested and examined by in Höeghs case, the DNV fuel division. This is of importance due to regulations and engine operation reliability. An issue with the fuel in relation to sulphur content or other errors connected to the different quality of the fuel could lead to a de-bunkering or a protest from the ships master. In case of a protest from the ships master, one would have to call in a broker and representatives from HFS in order to come to an agreement and further actions. If the numbers of bunker operations increases, one can assume that the probability of episodes that might lead to a de-bunkering would also increase.

Figure 50. Debunkering 1640 tons from a RORO. Source: [6]

If we would have a marked with identical fuel price among the various regions, a conduct of bunkering in every port that has on and off-loading would be possible. The challenge would mainly be a question of logistics, and would call for more planning ahead than today's operation, where the ship only bunkers once every two months.

Another aspect that might be of interest when taking a stand towards LNG as fuel are sudden changes in small, local regions fuel policies. A LNG fuel vessel would depend on continuous stable source of gas on its voyage due to range limitations. From earlier situations, ship owners have experienced cases where local ports has sold a larger portion of its fuels to harbouring ships, leaving a too small portion left for the domestic market. The outcome of this has been unforeseen price development. This causes a sudden halt or throttle regulation in the port, leaving the available fuel price to rise significantly. Such random episodes will be a larger problem for a vessel with shorter ranges, more dependent on being able to refuel in a given port.

Höegh LNG

Höegh LNG is a separate, independent company within the Höegh group, together with the mentioned Höegh Autoliners and Fleet Services, and other companies and investments. Höegh LNG operates a fleet of seven LNG tankers, and is a fully in-house shipping company with ship management. Höegh LNG is also one of the most experienced LNG shipping companies, with almost 30 years of operation with the vessel Höegh Lady, delivered in 1973. Beside this they develop new LNG solutions and technology connected to LNG FPSO-units, regasification and deepwater ports projects. The situation with a technology company as Höegh LNG within the same group with the same owners puts Höegh Autoliners in a good position when it comes to the possibilities of being a leading company within LNG-fueled merchant fleet.

HÖEGH AUTOLINERS

HÖEGH LNG

HÖEGH FLEET SERVICES

LNG solutions

From an overview of the numerous systems that has to be fulfilled by a RoRo vessel design, one can categorize the various parts of the vessels into a function overview in order to clarify which functions that are possible to manipulate or redesigned. For a Höegh ship and a general car carrier, the sketch below is an illustration of the common systems included in the ships:

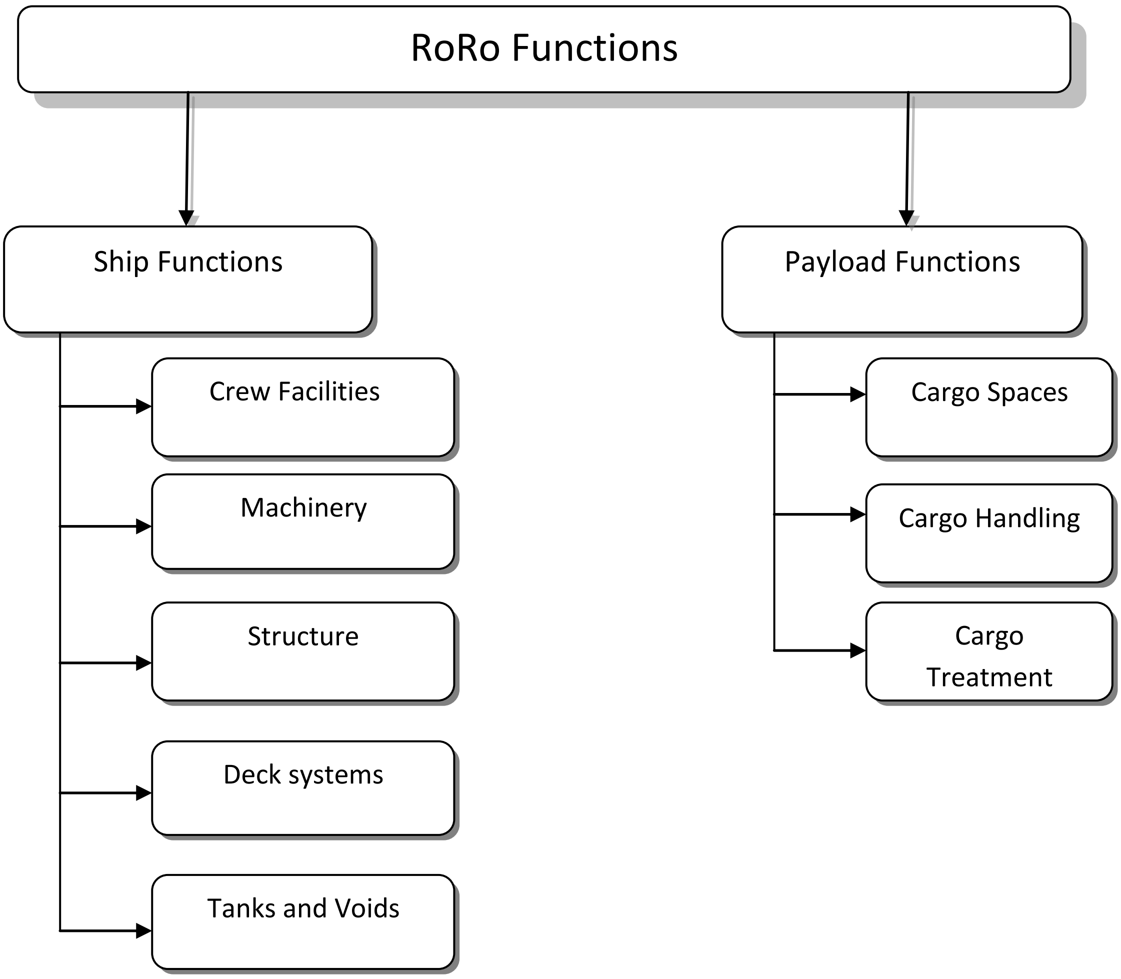

Figure based on System Based Ship Design. Defined by: [72]

Based on operation and fleet strategy findings from earlier, I state that if LNG should be feasible the ship must be able to be as functional and dynamic when it comes to trade routes as the current operated Höegh ship. This is motivated by reasoning that the ship has to be managed efficient during its lifetime so it can fulfill the ship owner's strategy. That will leave us the following requirements in terms of fuel capacity in order to stay within the feasible region:

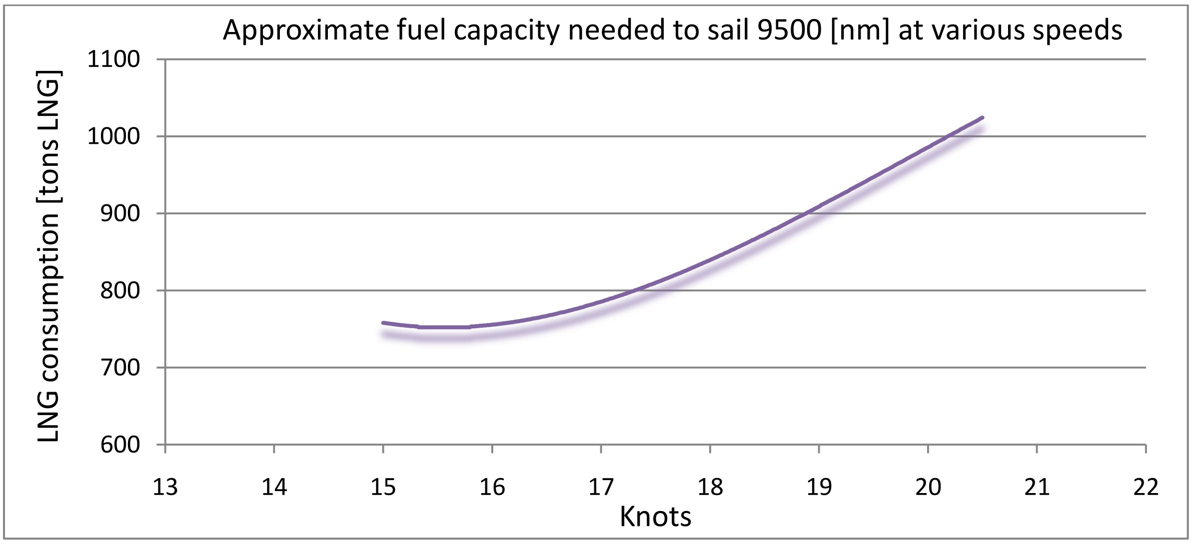

Figure 51. Tank capacity.

The graph is based on figures from the last year's operation with approximations taken. In addition, experience from summer internship in relation to maximum and minimum operating speed and consumption is used as I made a fuel calculator for the vessels operated in the fleet. The consumption also includes fuel for AE as well, assumed to have a daily consumption of 4 tons MDO, independent from weather, main engine speed or other factors. The range 9500 [nm] is the current longest leg, from Japan to America, as seen earlier.

2-stroke Lean Burn Concept

As seen, all of the vessels operated by Höegh are of low speed, 2-stroke, direct mechanical drive configuration with three auxiliary engines of 1.000 kW each. (Table 11) This configuration is in general a very cost and fuel efficient choice from figures in Appendix. These engines however operate most efficient in a limited area of load. We have also seen from the sketch illustrated by MARINTEK that a lean burn gas engine has an increased efficiency at higher loads, but exponentially worse efficiency at lower loads.

A solution to have both a cost efficient propulsion system and minimizing fuel costs related to the described low efficiency at low loads could be to install a power take off [PTO] installation in the propulsion system in terms of a shaft generator. From operation figures, the engine operating load can be modeled into a Weibull distributed graph. In this case, the unknown values from the operation profile are taken out due to uncertainties of the load during this operating range. If the load at "unknown" is distributed similar to the rest of the data, the resulting operation profile will be the same. From engine efficiency figures over various engine models, the differences between a 4-stroke engine and 2-stroke engine in terms of overall efficiency (thermo and mechanical) is shown in the following diagram. The figures are based on a number of engine models with given efficiency:

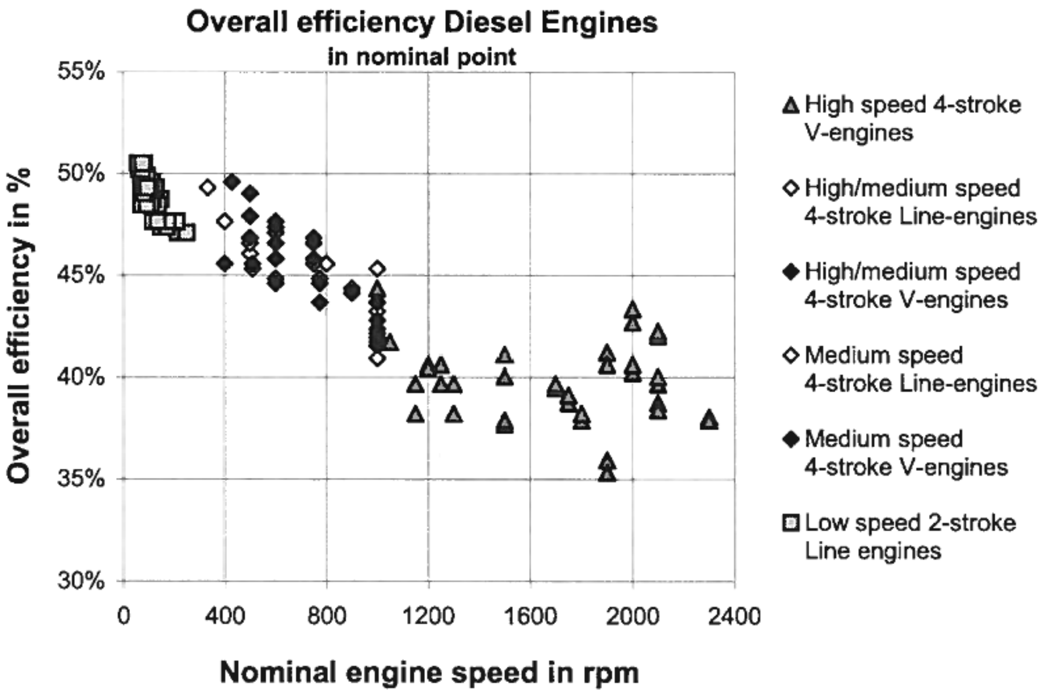

Figure 52. Overall efficiency of diesel engines. From [73]

Assuming that the total amount of propulsion preferred being 15.000 [kW], and the AE being 1000 [kW] to be able to operate the ventilation systems when in port, we can sketch an arrangement for the propulsion system with shaft generator installed. The size of the 2-stroke engine will depend on the operational profile multiplied by the total efficiency of the machinery, being the efficiency of both the 2-stroke ME and the 4-stroke auxiliary engines. From the information at hand, the lean burn 2-stroke engine is not yet developed and tested so the efficiency is not precise, only a sketch. The efficiency of the medium speed system, consisting of the 4-stroke engine, generator set and shaft generator, can be calculated:

$$\eta_{el.prop} = \eta_{AE} \bullet \eta_{Gen.} \bullet \eta_{S.G}$$

$$\eta_{el.prop} = 0,42 \bullet 0,95 \bullet 0,95$$

$$\eta_{el.prop} = 0,38$$

The efficiency of 42% is based on values from the overall efficiency table above. 0.95% efficiency in the two components is motivated by figures from the compendium in marine technology 4. [74]

In our case, the efficiency of a system consisting of a 2-stroke LNG engine and additional auxiliary 4-stroke engines with shaft generators installed will be

$$\eta_{tot} = (P_{tot} - P_{AE}) \bullet \eta_{el.prop} + (P_{tot} - P_{ME}) \eta_{ME}$$

where the parenthesis notates the percentage of power from the AE and the ME. From this relation, we see that the smaller main engine we install the larger part of the propulsion power when operating at higher loads will come from the AE system. As we see, with an efficiency $\eta_{\text{el.prop}}$ being lower than the efficiency of the 2-stroke engine at high loads, this solution will only benefit if we often operate at lower loads as well, this having a large spread in operation profile. By installing a smaller ME we will have better efficiency when sailing with a lesser amount of propulsion power, since this will be a relatively high load for the smaller 2-stroke engine, thus increasing its efficiency. In addition, in this setup the ME will also be capable of producing electricity to the ships systems when sailing. The effect is both that the electricity onboard will be cheaper since the ME is more effective than the AU, and it will also increase the load of the ME, making it operate at the efficient higher loads, as being optimal for LNG fueled engines.

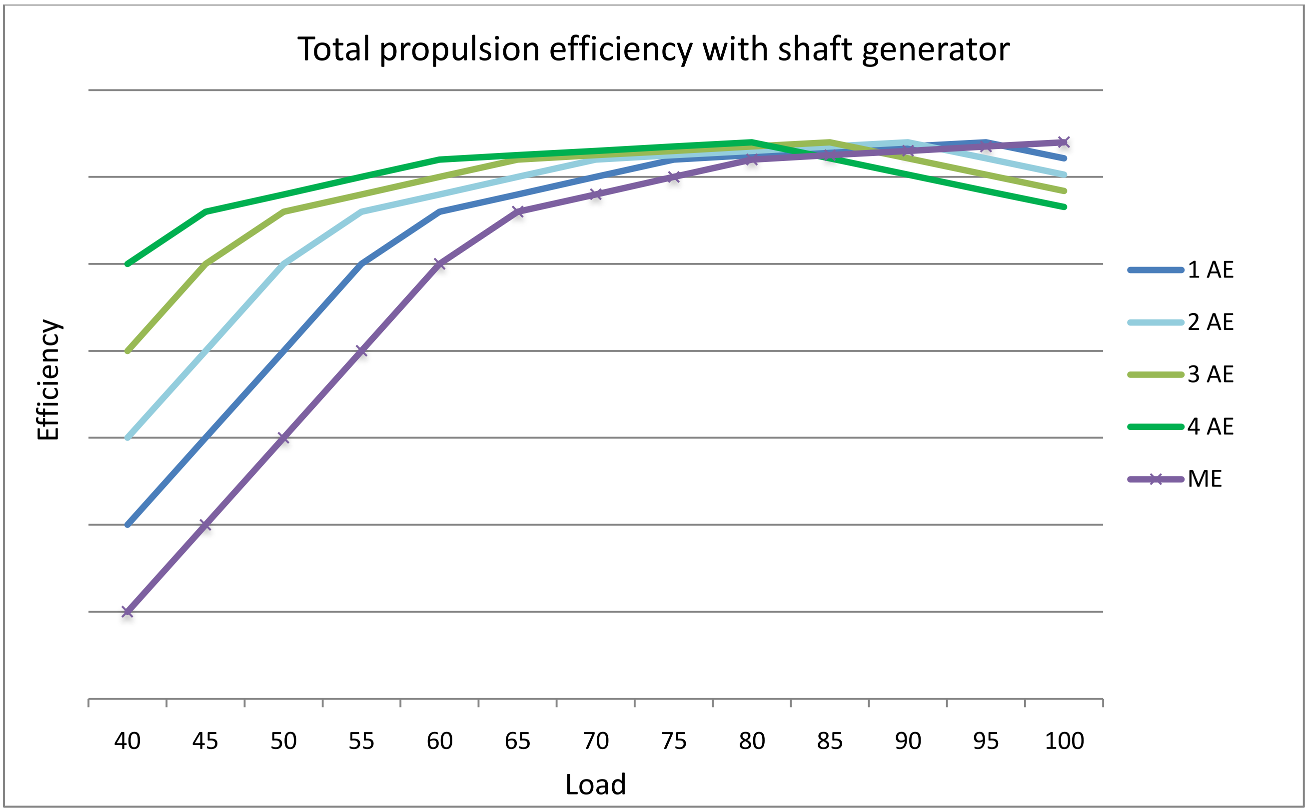

Figure 53. Efficiency of a shaft generator system.

We can see in this sketch a dip at the higher loads. This is due to the situation where the AE is a part of the power production of the ship, thus reducing its total efficiency. At lower loads, only the ME is running.

Not included in this illustration is the fact that the ship now also can operate on AE alone at smaller loads, such as maneuvering in port. The efficiency at these loads will then be the 38% stated earlier. An additional value in this setup is the redundancy in propulsion of the vessel, since it now can maneuver even with the ME malfunctioning.

Dependent on how often the vessel operates at the various loads and the efficiency of a 2-stroke LNG engine, one can calculate the optimal effect of the ME and number of AE and power. The solution described above has not been installed in the vessels as of today. This is probably due to the 2-stroke HFO engine being more effective than a 4-stroke engine even when operating at lower and higher loads, as we see its load graph being relatively flat. (Figure 36)

Tanking arrangement and capacity

From GA drawings Figure 44 and stability reports from the vessels found in Appendix , we can see that the VCG for the fuel oil at the bottom is about 1.5 [m] above the keel, and the tanks are more than 1/5B from the deck sides. As found, with todays classifications rules, the minimum distance from the keel for the LNG tanks are 2 [m]. If the LNG tanks would be fitted at the space between 2 [m] from the keel, and up to underneath deck 1, the available volume would be only 1/3 of the current volume available for LNG fuel tanks with today's design. This is when we assume that the fuel oil tanks in the vessels are symmetrical around the center of gravity.

In other words, the available bunker volume for installation of solely LNG tanks with the current design of deck 1 and fuel oil volumes is:

$V_{LNG} = V_{F.O\ TK}$ – DNV voids
$V_{LNG} = {}^{1}/_{3}\ V_{F.O\ TK}$

From the same stability data and earlier information from the capacity management, the total bunker oil capacity can be determined to about 3500 tons HFO, or a volume of 4500[m^2] as HFO has a density of about [0.8 tons/m^3] from appendix I. In the LNG tank study, we found that LNG requires 3-4 times the space per. ton fuel. That leaves us with the following maximum capacity for LNG in the Höegh vessels:

Table 15. Bunker capacity for lengthened Höegh vessels.

	HFO, currently	LNG, after DNV limitations
Volume available [m3]	4500	1500
Fuel Capacity [tons]	3500	500

In order to meet the 1000 [tons] demand stated earlier, to be able to access all markets, one would have to take up space from the cargo decks in the volume of 1500 [m^3] in order to hold 500 [tons] LNG. From stability data, it is also likely the only appropriate deck for having fuel as well, with the deck being about 3 [m] over the keel. From dialogue with Mr. Moen at Market Analyses, the first deck is the common to be the least utilized deck and the deck with the lowest freight rates. He could also inform me that the difference in price from the highest to the lowest rates is about double in today's market. (Minutes of meeting in the Appendix)

Table 16. Freight rate variations.

Route	Rate in relation to each other
Far East - Europe	1
Europe - Far East	1/2
Europe - Australia	2/3

These relations will fluctuate as the various regions develop its markets. I will not try to predict which markets will be most trafficked by the Höegh operated vessels in the future, so the change in sailing pattern or future rate relations will not be further studied or examined in this thesis. The figures are of interest to see the different relations between various areas. If we further assume that there is a relation between freight rates and utilization, related to supply and demand, the total cost of lost opportunity by claiming 1500 [m3] of the first decks total volume of about 4800 m^3 from GA, will have an exponential form with estimated values based on current rates, in the scale of:

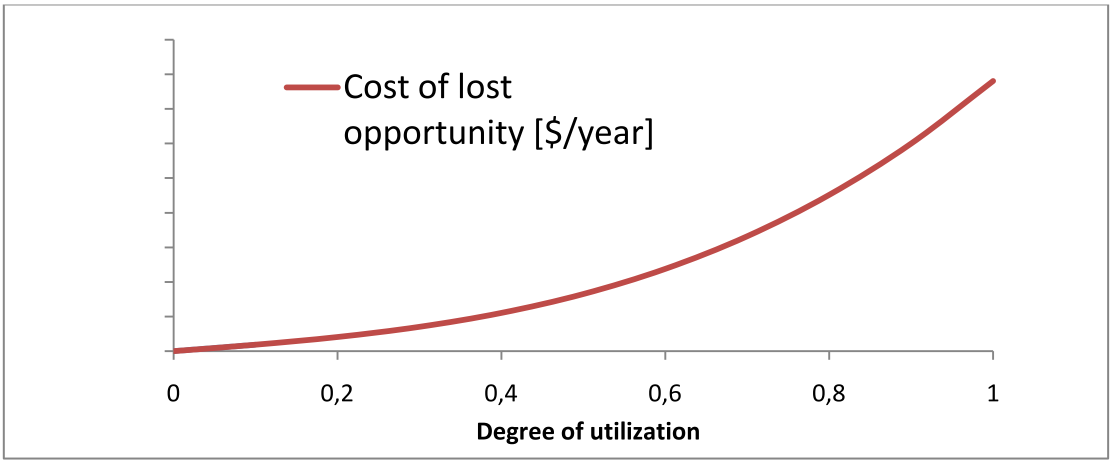

Figure 54. Lost cost of opportunity.

As long as the degree of utilization stays below 2/3, as the added LNG tanks will claim about 1/3 of the volume, there will not be any cost of lost opportunity. As the utilization increases, and the prices raises, the cost of utilization is modeled to increase exponentially. Depending on how often the ship sails with a utilization of more than 65% on deck 1, it is possible to calculate the costs of lost opportunity, depending on freight rates at these scenarios.

$$C_{lost.opp.} = \overline{r}_{u>65\%} \bullet \overline{p}_{u>65\%}$$

cost of lost opportunity is based on average rate when having more than 65% utilization of deck 1 multiplied by average lost shipped volume due to tanks. If we have a market where the vessels operates in a pattern between three markets, with 30 days at sea between each trade, making 12 trips each year. With the average price per m^3 being 50$ per trip, that will end up in 600 $\$/m^3$ per year per m^3.

Depending on the routes operated, rate fluctuations and degree of utilization, the total cost of lost opportunity can be given in the following scale:

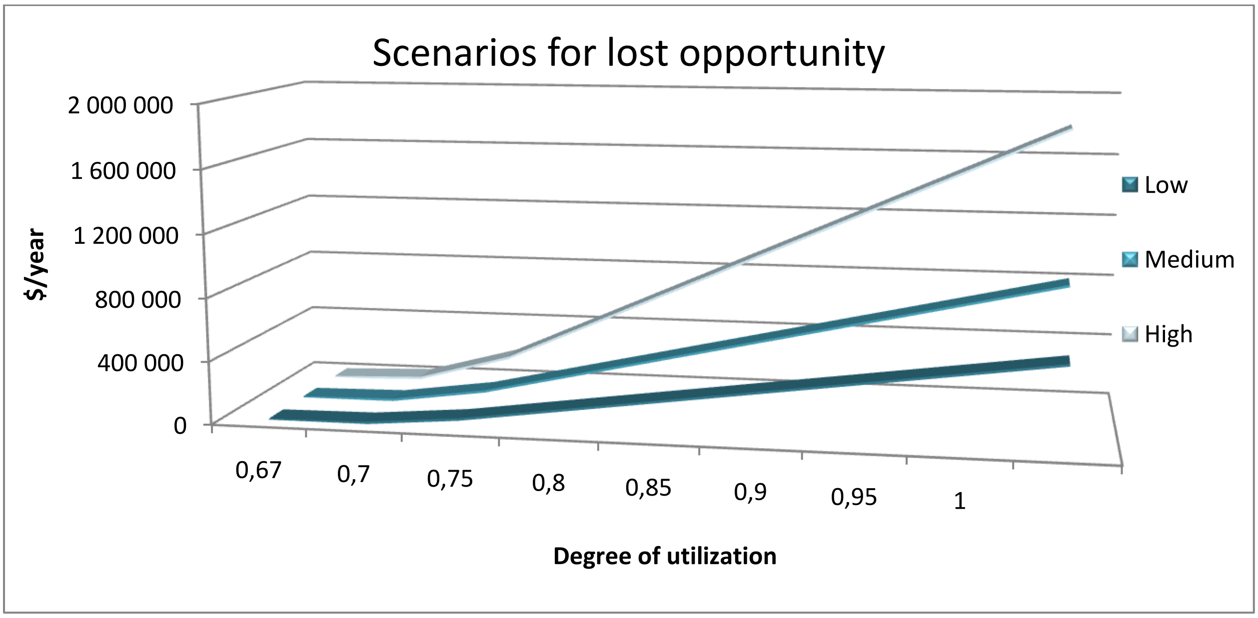

Figure 55. Lost income due to LNG tanks.

The worst case scenario would be the LNG fueled vessel operating in a high rate market that has a (unlikely) utilization of 100% the entire time between all ports. That would lead to a yearly loss of income of about 1.8 [mill/y]. The needed difference in fuel oil price between LNG, HFO and MDO would for the high freight rate and 100% utilization be:

Table 17. High rate and 100% utilization.

High Rates, 100% utilization	LNG price [$/tonn]											
HFO [$/ton]	450	500	550	600	650	700	750	800	850	900	950	1000
450	-1,52	-2,30	-3,07	-3,85	-4,62	-5,40	-6,17	-6,95	-7,72	-8,50	-9,27	-10,05
500	-0,72	-1,49	-2,27	-3,04	-3,82	-4,59	-5,37	-6,14	-6,92	-7,69	-8,47	-9,24
550	*0,09*	-0,68	-1,46	-2,23	-3,01	-3,78	-4,56	-5,33	-6,11	-6,88	-7,66	-8,43
600	*0,90*	*0,12*	-0,65	-1,43	-2,20	-2,98	-3,75	-4,53	-5,30	-6,08	-6,85	-7,63
650	*1,70*	*0,93*	*0,15*	-0,62	-1,40	-2,17	-2,95	-3,72	-4,50	-5,27	-6,05	-6,82
700	*2,51*	*1,73*	*0,96*	*0,18*	-0,59	-1,37	-2,14	-2,92	-3,69	-4,47	-5,24	-6,02
750	*3,32*	*2,54*	*1,77*	*0,99*	*0,22*	-0,56	-1,34	-2,11	-2,89	-3,66	-4,44	-5,21
800	*4,12*	*3,35*	*2,57*	*1,80*	*1,02*	*0,25*	-0,53	-1,30	-2,08	-2,85	-3,63	-4,40
850	*4,93*	*4,15*	*3,38*	*2,60*	*1,83*	*1,05*	*0,28*	-0,50	-1,27	-2,05	-2,82	-3,60
900	*5,73*	*4,96*	*4,18*	*3,41*	*2,63*	*1,86*	*1,08*	*0,31*	-0,47	-1,24	-2,02	-2,79
950	*6,54*	*5,76*	*4,99*	*4,21*	*3,44*	*2,66*	*1,89*	*1,11*	*0,34*	-0,44	-1,21	-1,99
1000	*7,35*	*6,57*	*5,80*	*5,02*	*4,25*	*3,47*	*2,70*	*1,92*	*1,15*	*0,37*	-0,41	-1,18

The figures are based on the relation between fuel costs for the vessel using HFO and MDO, or using LNG and having a cost of lost opportunity. In other words:

$$x = Cost_{HFO+MDO} - Cost_{LostVolume} - Cost_{LNG}$$

If x is positive, the original fuel costs by sailing with marine diesel and heavy fuel oil is larger than the fuel cost by sailing with LNG as fuel and the cost of lost opportunity. In this case, I have used the average daily fuel oil consumption from Appendix of 42.5 tons/day. This includes also auxiliary fuel. For a vessel operating on fuel oil, the total fuel oil price will consist of the MDO and the HFO. As seen earlier, the average consumption of the auxiliary engines are 4 tons/ day. We assume that this is finer distillate such as MDO. From the ECA study earlier and the trade routes, I further assume that the vessel will be operating in a future ECA for a period of 10% of the time. The total use of MDO or low sulfur oil will in such a situation be 20% of the total consumption.

$$Cost_{HFO+MDO} = (0,8 + (0,2 \bullet 1,5)) \bullet Cost_{HFO}$$

As seen earlier from the correlation between MDO and HFO, MDO have a steady correlation with about 50% higher costs than HFO. That motivates my (0,2·1,50) term in the equation.

As we see in the table above to make such a lean burn LNG ship to be profitable in the given trade, we will be able of having more than 10% lower prices of LNG compared to the price of HFO. This illustrates also the relative high fuel costs RoRo ships have, as we see from the figures. A loss of 1/3 of the cargo capacity on the lowest deck will in todays market, assuming 50[$/m^3] per trip, and 12 voyages a year, amount to 900.000$. This loss can be covered by a reduction of about 10% in the fuel costs.

From dialogue with market analyses added in the Appendix, I understood that the first deck seldom has full utilization. It also seems logical that the bottom deck has some spare volumes as it is difficult to reach for some parts of the cargo due to height limitations and practical questions when on and offloading. A change in the degree of utilization to 75% leaves us in a situation where it will be profitable as long as LNG is not more expensive than HFO. The freight rates must also be seen as very high in this scenario, leaving us with a safety margin in terms of the investment.

Table 18. High rates and 75% utilization

High rates, 75% utilization	LNG price [$/tonn]											
HFO [$/tonn]	450	500	550	600	650	700	750	800	850	900	950	1000
450	-0,17	-0,95	-1,72	-2,50	-3,27	-4,05	-4,82	-5,60	-6,37	-7,15	-7,92	-8,70
500	0,64	-0,14	-0,92	-1,69	-2,47	-3,24	-4,02	-4,79	-5,57	-6,34	-7,12	-7,89
550	1,44	0,67	-0,11	-0,88	-1,66	-2,43	-3,21	-3,98	-4,76	-5,53	-6,31	-7,08
600	2,25	1,47	0,70	-0,08	-0,85	-1,63	-2,40	-3,18	-3,95	-4,73	-5,50	-6,28
650	3,05	2,28	1,50	0,73	-0,05	-0,82	-1,60	-2,37	-3,15	-3,92	-4,70	-5,47
700	3,86	3,08	2,31	1,53	0,76	-0,02	-0,79	-1,57	-2,34	-3,12	-3,89	-4,67
750	4,67	3,89	3,12	2,34	1,57	0,79	0,02	-0,76	-1,54	-2,31	-3,09	-3,86
800	5,47	4,70	3,92	3,15	2,37	1,60	0,82	0,05	-0,73	-1,50	-2,28	-3,05
850	6,28	5,50	4,73	3,95	3,18	2,40	1,63	0,85	0,08	-0,70	-1,47	-2,25
900	7,08	6,31	5,53	4,76	3,98	3,21	2,43	1,66	0,88	0,11	-0,67	-1,44
950	7,89	7,11	6,34	5,56	4,79	4,01	3,24	2,46	1,69	0,91	0,14	-0,64
1000	8,70	7,92	7,15	6,37	5,60	4,82	4,05	3,27	2,50	1,72	0,95	0,17

Added or removable tank solution

One alternative design solution besides closing parts of the total volume of deck 1 to implement LNG in the vessels could be that the cargo holds are designed to be exploited by adding extra LNG tanks when needed in order to reach the America – FE trade. As found earlier in the trade route part, the vessels are actually seldom sailing distances in access of 5000 [nm], this having sufficient range if only using the current bunker volume available for LNG tanks. However, exploiting cargo spaces and roll-on and-off fuel through the main hatchway will give an added risk in terms of safety in both the load/discharge case and during operation. Experience from car carriers and container vessels and high value cargo in general, shows that there can be enormous material damages to both vessel and cargo during sailing in rough weather, if the cargo comes loose by other reasons. This is occurring from time to time and will have a certain degree of risk. The possible solution with loadable added fuel could be realized through pre designed sections on the lower deck, with protection/cofferdam between the cargo holds and the load and dischargeable LNG tanks, with piping and necessary equipment nearby and easily reachable. If the vessel would have to carry added amount of fuel in order to reach the desired route, this section will be protected in case of detachment of the cargo during sailing. If the vessel however would be operating within the radius between bunkering options, this space would in such a case be accessible and used for cargo. This solution will make the vessels very dynamic in choosing between range and exploitation of cargo space. The ramps used for loading and unloading has a limit of 150 tons, so issues regarding strength on existing designs and ships should not be considerable as long as the LNG tanks are within this weight. It is difficult to estimate the investment in implementing piping arrangements, reinforced and removable doors within the cargo hold, and strong certified anchorage points for the removable fuel tanks.

Figure 56. Tank loading onboard Höegh St. Petersburg. Courtesy:Höegh Autoliners.

Such an idea can, for probable better cost efficiency, be implemented within a new design. It is assumed that it could be a costly pioneer project that would have to include close cooperation with classification societies, insurance, design offices and other players. In operation it would require special certification from crew and harbor masters and management to reduce the risk found from the PHA. From e-mail from Martin Wold at DNV, he claimed that in general, if the division between a tank and cargo room is satisfactory designed, there should not be a problem of using the room as a tank room, and would be evaluated on a case to case situation.

Dual fuel 2-stroke solution

As found engine makers are working on delivering various 2-stroke DF engines, and this is expected to be at the market in various sizes and variant soon, within the first years to come. Norwegian offshore vessels and the coast guard are as seen currently operating with dual fuel engines, though medium speed types. As far as I have seen, there are few problems or issues regarding this technology. The most debated is however the slip of methane in a dual fuel engine. This is however most likely to be an old problem as the technology develops. When it comes to the benefits of a dual fuel design, this can be listed as follows:

- Reduces risk in terms of future price variation between the two types.
- Redundancy in fuel systems.
- Greener than HFO and better range than LNG-options.
- Operate at HFO at low loads and LNG at higher load to increase efficiency.
- Can change lossless and immediately between the two at sailing.
- Gives a green image to the company, seen by offshore ship owners.
- Tested technology

Dual fuel is in many ways a good alternative as seen in the listings above, and could be easily implemented in todays RoRo design without having to remove cargo space or change significantly of the layout of the hull.

Studies from the fuel prices earlier predicts that LNG is likely to be a cost efficient fuel in the future, so when coming to optimization of this solution, the feasible region is still the region where the vessels has a capacity of 9500 [nm] or a bunker limit of 1.100 [tons] Since LNG has a higher heat value than HFO, it will have a ratio of 1.2 when it comes to needed tons to reach ports, compared to HFO. The least amount of LNG tanks is however a selection made by the designer. As seen from future ECAs, the vessel could be dependent on LNG when sailing of the cost of US, Europe and South East Asia and Far East. Of these Areas, the longest voyage between bunkering ports looks to be in the Mediterranean, with also likely convoy and waiting to cross the Suez. The vessels are likely to in addition have sailed in the ECA area in the channel or coming for the US east coast ECA, making the range for LNG being about 3600 nm (The distance from Hamburg to Suez). Using the consumption figures found earlier in Figure 51. Tank capacity., we see that the ships will use about 0.1 tons LNG per nm, dependant on speed. It will most likely sail slower than 18 knots where 0, 1 [tons/h] applies, so this will also give us some safety. The least amount of LNG will then be 360 tons in a dual fuel option. We also know that the maximum volume available for fuel in the traditional design is 4500 [m^3]. Using linear programming, the limits and relations can be seen as:

$$x_1 = LNG,$$
$$x_2 = HFO$$

x_1 and x_2 notates the different fuels in dual fuel option.

$$x_1 + 1,2x_2 = 1100$$

This is the demand in amount of bunker fuel in tons. LNG is modeled to have a 20% higher heat value. By setting this equal to 1.100 tons, we will find the max amount of LNG possible on the dual fuel setting.

$$9x_1 + x_2 = 4500$$

As we have seen in the current design, the approximate volume available for fuel is 4500 m^3. Without HFO in the voids under the LNG tanks, LNG will use about 9 times the volume due to clearance of 2 meters down to the keel, and due to the volume of the tanks with isolation and the density of LNG being only half of HFO.

$$x_1 \geq 360$$

Is the least amount of LNG stated in this setup, to be able to operate in the future ECA regions without refueling. This could be smaller as the vessels visit several ports on route. However, by having a margin, the value of being able to switch between the cheapest type of fuel is better implemented in this border limit.

$$\max z = 2x_1 + x_2$$

The ratio between LNG and HFO in the maximum expression will have no impact to the result when we use this method to find the maximum capacity of LNG onboard, as long as LNG is of higher value i.e. cheaper than HFO. If LNG is lower, the method will logically find x_1 to be the stated minimum value of LNG, in this case 360 [tons]. As we see from the solution below, to be able to fulfill the trade routes, the dual fuel solution will have a maximum of about 440 [tons] of LNG capacity, and 551 [tons] of HFO. This means that 88% of the volume under deck 1 is occupied by LNG tanks, with the remaining 12% of the 4500 [m^3] consisting of HFO. This will fulfill the desired routes and sailing in ECA, as well as maximizing the LNG capacity. If it would be possible to have bunker oil in the void space underneath the LNG tanks, the capacity of LNG can be increased to 500 tons without stealing space from cargo decks. It will then take up the entire acceptable volume of about 1500m^3, based on data from fuel oil capacity in the stability table. This volume is known to be between 2[m] from the keel up to underneath deck 1, and from in front of engine room all the way to the ballast tank in the bow section. The capacity under the LNG tanks available for fuel oil in tons, adding a safety of 20% for space for piping and bulkheads, and 0.8 factor for HFO density, is

$$V = 4500m^3 - 1500m^3$$
$$V = 3000m^3$$
$$V_{HFO} = V \bullet 0,8$$
$$V_{HFO} = 2400m^3$$
$$Capacity_{HFO} = 1900tons$$

Table 19. LNG capacity in DF design

Dual fuel capacity					
	x1	x2	Total fuel capacity		
Decision result with void under LNG tanks:	425	675	1.100		
Result with HFO between keel and LNG tanks	500	1900	2.400		
	LNG	HFO			
Fuel price relation					
	2	1	1429		
Limitations					
Neccecary amount of fuel	1	1,2	1100	=	1100
Space available	9	1	4500	=	4500
Least amount of LNG for ECA sailing + Aux	1	0	439	>=	360

The current PCTC design is capable of carrying enough LNG to operate within ECA limitations and regions without reducing the cargo capacity. However, the height of the volume is only about 1 [m], so it is debatable if this volume is actually accessible for LNG tanks.

Discussion

Predictions in natural gas price in relation to low sulfur crude oil, from Figure 13. Ratio of low-sulfur crude oil vs. HH natural gas price. Source: [21], predicts that the natural gas price will stay lower than 1/3 of the fuel oil price in the US. As the Far East-market is heavily influenced by long term contracts and shipments from Qatar mainly, the LNG price imported to Japan and Korea is about three times the price of natural gas in US. I find it questionable that the natural gas price will stay significantly lower than other sources of energy, as politicians are pushing for greener energy in the industries. The main consumers will be able to use natural gas, and the dynamic between oil and gas could become even clearer. I find it to be likely that LNG will become both more influenced by the oil price, and due to this relationship it will also more accessible at a global scale. I also find it likely that additional ECAs will come as many countries will experience higher standards of living, and better air quality and health will be important drivers, as the EURO limits also have become global.

From experience by vessels operating in North European waters, fueled by LNG, we see little problems connected to LNG being a fuel. The major challenges are to further develop the technology, as LNG has different qualities in combustion. As the demand for specific LNG designed engines it is highly likely that there will be significantly less methane slip since this is as stated only a question of physics and technology.

The results of installing either lean burn natural gas or dual fuel will also likely have added investments for the two systems to when it will become profitable. The added costs of LNG installations has been put to10- 15% of the total newbuilding cost, though probably will be reduced. Depending on the price differential between LNG installation and the traditional bunker oil solution, an additional capital cost will be included on the extra investment. This has been in the order of 8.5% in the Triality concept. This percentage is very hard to argue because of the huge uncertainties in the 4-5 years LNG as it is per. today, so I chose not to include it as it would make a small difference.

Conclusion

The shale gas development together with increased environmental developments and constructions of natural gas terminals looks very promising in terms of a global LNG supply. From studying the various technological evolutions, the Northern Parts of Europe looks for me to be a area that might be a pioneer in implementing LNG to deep sea ships. I also find LNG capable of being significantly cheaper than similar oil products due to the developments seen. This would require further development in both technology and the push for cleaner fuel in the industry and energy market.

There are also solutions that can be used in order to overcome the downside of LNG being less energy dense than fuel oil, such as having removable tank installations. A further development in membrane tanks will increase the energy density. The industries and classification societies are developing new solutions within this area, which is of high importance to be able to compete with the standard oil solution.

In my work, I found that the bunker tank volume included in current PCTC-ships is sufficient for the vessel to operate on dual fuel with more than 400 tons LNG onboard. The problem regarding a pure gas design is that the majority of the bunker volume is too close to the keel, making it unsuited for LNG tanks as of todays regulations. From the PHA it is also clear that LNG tanks will create a larger hazard if moved to the very bottom of the ship. From a system based ship design point of view, a rearrangement of the fuel tank volume and deck 1 would reduce the need of taking volume from the cargo space. If this volume is split in two in longitudinal direction, the 1st deck could stretch down to the very lowest parts of the vessel, and occupy the front half of the ship. The bunker volume could consist of the volume from the keel up to underneath deck 2, and half of the ships length from the engine room and forward to the cargo room in the rearranged deck 1. If acceptable, this solution would need no loss of cargo space. If the first deck would have to be reduced by 1500 [m^3] from LNG tanks, the total cost of lost opportunity would depend on freight rates and the degree of utilization of deck 1. From the overview, we would reach a break-even point as long as the two types have approximately the same price per ton. This is due to MDO having to be part fuel consumption if not using LNG, increasing the fuel cost.

LNG has a lesser efficiency at lower loads compared to HFO engines from early sketches. This can be solved by installing shaft generators, and reducing the installed main engine power, making it running on a higher load at the optimum amount of time. The size of the main engine will be dependent on actual efficiency of the engine and operational profile. This solution looks to be highly feasible, and it also would reduce the cost of electricity onboard and would add a redundancy of parts of the propulsion system. It would also make the vessel more maneuverable since it can operate with the auxiliary engines at lower speeds.

The dual fuel solution would have a capacity of about 425 tons LNG and 675 tons HFO to be able of serving the various routes used by Höegh. If it is possible to ha bunker tanks underneath the void between the keel and the 2 [m] up to the LNG tank, the fuel capacity would be approximately 500 tons LNG and 1900 tons HFO. The dual fuel solution will also add redundancy to parts of the propulsion system in terms of the fuel system, and it is not necessary to install shaft generators as HFO has better efficiency at lower loads. It could however be feasible if LNG is sufficiently cheaper than HFO from the same reasons as in the pure gas part.

The dual fuel engines are said to be 4% less efficient when operation on HFO compared to a pure diesel engine, and one would also likely have a higher methane slip. The dual fuel setup will be economical if the LNG price is between the sulfur free MDO price and the HFO price. If the LNG price is lower than HFO, a purely LNG solution is found to be most likely economical (dependant on freight rates and utilization) If HFO and MDO is to be cheaper than LNG, LNG would not be economically feasible.

Höegh Fleet Services and Höegh Autoliners having experience from the Vinashin project could together with Höegh LNG set a new standard for LNG fueled merchant vessel. And from this work, that is likely to be a future large market.

Further work

The goal of this work was to study if LNG is possible for a Höegh operated PCTC. From the solutions presented, there are different designs that will be possible and profitable in the different market and operational situations. In future work, a study regarding 4-stroke LNG engines in a diesel-electric setup would be of interest to be able to select the optimal solution. From Appendix XI we see the lower cost per [kW], but also lower efficiency compared to the 2-stroke option. However, as the lean burn engine is most effective at higher loads, a diesel-electric setup will make the separate engine operate at higher loads when in use thus making it interesting.

I found that a lean gas engine is efficient at the higher loads, compared to diesel engines loosing efficiency at loads over NCR. This could make several interesting simulation problems on modeling how much lower the installed power from the main engine can be without having too large expenses in terms of arriving too late at ports. The same applies with the possible shaft generator case, being dependant on various loads.

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Appendix

Appendix I

Common properties of natural cas		
Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	0-20%
Butane	C_4H_{10}	0-20%
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulphide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	trace

From http://www.naturalgas.org/overview/background.asp

Appendix II

Properties of Fuels (a)									
Property	**Gasoline**	**No.2 Diesel Fuel**	**Methanol**	**Ethanol**	**MTBE**	**Propane**	**Compressed Natural Gas**	**Hydrogen**	**Biodiesel**
Chemical Formula	C4 to C12	C8 to C25	CH3OH	C2H5OH	(CH3)3COCH3	C3H8	CH4 (83-99%), C2H6 (1-13%)	H2	C12-C22 FAME
Molecular Weight	100–105	~200	32.04	46.07	88.15	44.1	16.04	2.02	~292(q)
Composition, Weight %									
>Carbon	85–88(b)	87(g)	37.5	52.2	68.1	82	75	0	77(g)
>Hydrogen	12–15(b)	13(g)	12.6	13.1	13.7	18	25	100	12(g)
>Oxygen	0	0(g)	49.9	34.7	18.2	–	–	0	11(g)
Specific gravity, 60° F/60° F	0.72–0.78(b)	0.85(g)	0.796(h)	0.794(h)	0.744(k)	0.508(m)	0.424	0.07(o)	0.88(g)
Density, lb/gal @ 60° F	6.0–6.5(b)	7.079(g)	6.63(b)	6.61(b)	6.19(k)	4.22	1.07(n)	–	7.328(g)
Boiling temperature, °F	80–437(b)	356-644(g)	149(h)	172(h)	131(h)	-44(m)	-263.2 to -126.4(m)	-423(m)	599-662(g)
Reid vapor pressure (100° F), psi	8–15(c)	<0.2	4.6(i)	2.3(i)	7.8(l)	208	2400	–	<0.04(r)
Heating value (2)									
>Lower (Btu/gal) (d)	116,090	128,450	57,250	76,330	93,540	84,250	–	–	119,550
>Lower (Btu/lb) (d)	18,676	18,394	8,637	11,585	15,091	19,900	20,263	52,217	16,131
>Higher (Btu/gal) (d)	124,340	137,380	65,200	84,530	101,130	91,420	–	–	127,960
>Higher (Btu/lb) (d)	20,004	19,673	9,837	12,830	16,316	21,594	22,449	59,806	17,266
Octane no.(1)									
>Research octane no.	88–98(c)	–	–	–	–	112	–	130+	–
>Motor octane no.	80–88(c)	–	–	–	–	97	–	–	–
Cetane no.(1)	–	40-55(g)	–	0-54(f)	–	–	–	–	48-65(g)
Freezing point, °F	-40(e)	-40–30(4)	-143.5	-173.2	-164(h)	-305.8(m)	-296	-435(p)	26-66(g)(7)
Viscosity, mm^2/s									
>@104 °F	–	1.3-4.1(g)	–	–	–	–	–	–	4.0-6.0(g)
>@68 °F	0.5-0.6(f)	2.8-5.0(f)	0.74(f)	1.50(f)	0.47(f)	–	–	–	–
>@-4 °F	0.8-1.0(f)	9.0-24.0(f)	1.345(f)	3.435(f)	0.77(f)	–	–	–	–
Flash point, closed cup, °F	-45(b)	140-176(g)	52(i)	55(i)	-14(c)	-156(m)	-300	–	212-338(g)
Autoignition temperature, °F	495(b)	~600	867(b)	793(b)	815	842(m)	900-1170(m)	932(m)	–
Water solubility, @ 70° F									–
>Fuel in water, volume %	Negligible	Negligible	100(h)	100(h)	4.8(f)	–	–	–	–
>Water in fuel, volume %	Negligible	Negligible	100(h)	100(h)	1.5(f)	–	–	–	–
Flammability limits, volume%									
>Lower	1.4(b)	1.0	7.3(i)	4.3(i)	1.6(c,e)	2.2	5.3	4.1(o)	–
>Higher	7.6(b)	6.0	36.0(i)	19.0(i)	8.4(c,e)	9.5	15	74(o)	–
Latent heat of vaporization									
>Btu/gal @ 60° F	~900(b)	~710	3,340(b)	2,378(b)	863(5)	775	–	–	–
>Btu/lb @ 60° F	~150	~100	506(b)	396(b)	138(5)	193.1	219	192.1(p)	–
Specific heat, Btu/lb °F	0.48(e)	0.43	0.60(j)	0.57(j)	0.50(j)	–	–	–	
Stoichiometric air/fuel, weight	14.7	14.7	6.45	9.00	11.7	15.7	17.2	34.3(o)	13.8(g)
Volume % fuel in vaporized stoichiometric mixture	2.0 (b)	–	12.3(b)	6.5(b)	2.7(l)	–	–	–	–

Table found from: http://www.afdc.energy.gov/afdc/pdfs/fueltable.pdf

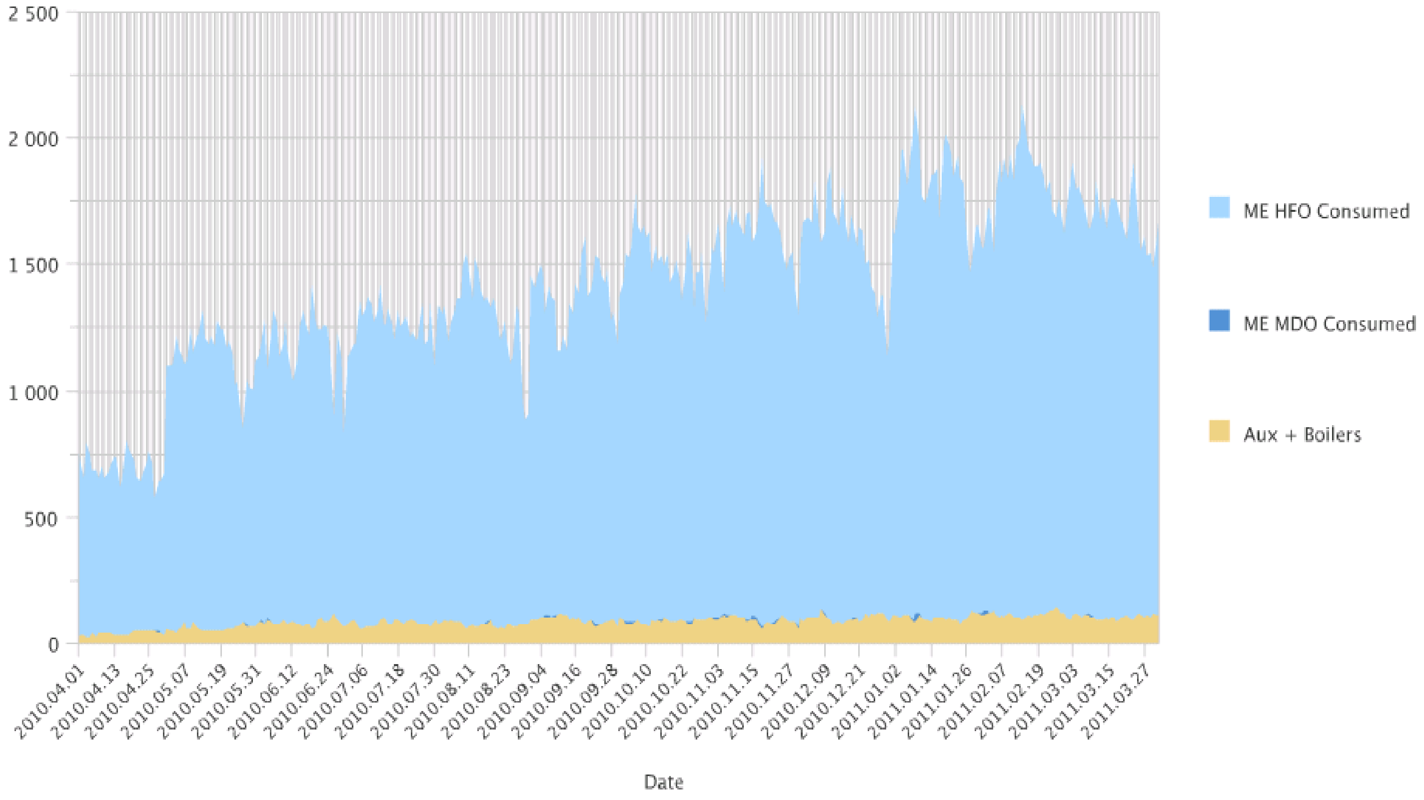
Appendix III

Common Properties of Commercial Fuels

Fuel	MJ/m3	MJ/kg	MJ/L	GJ/Ton	Ltr/Ton
Natural Gas	38.7	53.6		53.6	
LNG		53.6	22.2	53.6	2410
LP Gas Propane	93.3	50.0	25.4	50.0	1960
LP Gas Butane	124.0	49.5	28.7	49.5	1720
Kerosene - Lighting		46.6	36.7	46.6	1280
Kerosene - Power		45.8	37.2	45.8	1230
Motor Spirit - Petrol		46.5	34.4	46.5	1360
Heating Oil		46.0	37.4	46.0	1220
Automotive Diesel Fuel		45.7	38.4	45.7	1190
Industrial Diesel Fuel		45.5	38.0	45.5	1170
Heavy Fuel Oil - Low Sulphur		44.5	40.1	44.5	1110
Heavy Fuel Oil - High Sulphur		42.9	42.0	42.9	1020
Lubricating Oil		27.9	40.0	27.9	1120
Crude Oil - Indigenous		46.3	37.0	46.3	1250
Crude Oil - Imported		44.9	38.7	44.9	1160
Naphtha		47.1	32.0	47.1	1470
Coal - Brown Briquettes		22.3		22.3	
Coal - Brown (Vic)		9.8		9.8	
Coal - Black (NSW)		27.9		27.9	
Coal - Leigh Creek (SA)		13.5		13.5	
Electricity	1kWh = 3.6 MJ				

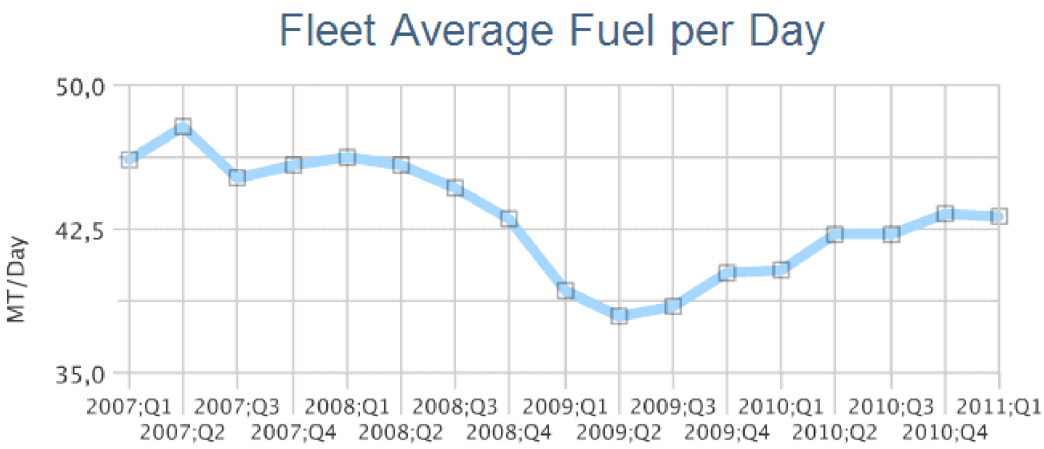
Figures from http://www.natural-gas.com.au/about/references.html

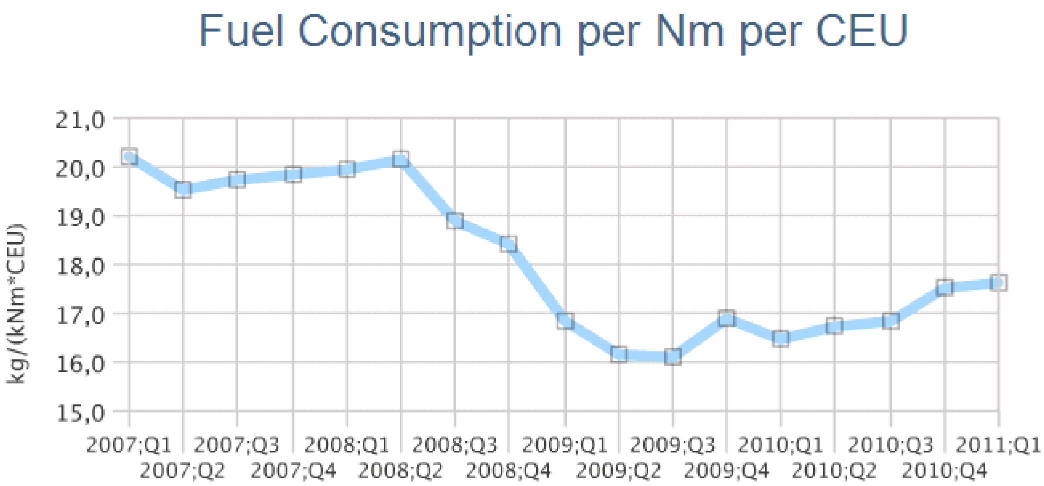
Appendix IV



Data from the totalt consumtion of fuel oil [tons/day] for a Höegh operated vessel from April 2010 to April 2011. Based on noon reports found in Oracle BI at Oslo head office.

Appendix V





Fuel consumtion over a period of 4 years. Illustration the effect of market changes. Based on noon reports found in Oracle BI at Oslo head office.

Appendix VI

WATER BALLAST TANKS (S.G=1.025)

COMPARTMENT	LOCATION (FR.NO.)	CAPACITIES VOLUME 100% (M^3)	CAPACITIES WEIGHT 100% (TONS)	CEN.OF GRAVITY L.C.G (M)	CEN.OF GRAVITY V.C.G (M)	MAX F.S.MOM. (M^4)
F.P.TK	261 - 281	878.3	900.3	214.532	10.903	3490
NO.1 DEEP TK (C)	249 - 261	477.7	489.6	201.727	8.464	1584
NO.2 DEEP TK (P)	234 - 249	368.7	377.9	192.623	4.736	239
NO.2 DEEP TK (S)	234 - 249	368.7	377.9	192.623	4.736	239
NO.3 DB.W.B.TK (P)	198 - 234	475.9	487.8	170.510	1.668	1635
NO.3 DB.W.B.TK (S)	198 - 234	480.7	492.7	170.671	1.677	1647
NO.4 DB.W.B.TK (P)	162 - 198	711.1	728.9	143.990	4.219	626
NO.4 DB.W.B.TK (S)	162 - 198	711.1	728.9	143.990	4.219	626
NO.5 DB.W.B.TK (P)	126 - 162	823.6	844.2	115.145	3.516	1183
NO.5 DB.W.B.TK (S)	126 - 162	806.5	826.6	115.008	3.461	1183
NO.6 DB.W.B.TK (P)	90 - 126	790.3	810.1	86.591	3.486	1137
NO.6 DB.W.B.TK (S)	90 - 126	807.5	827.7	86.655	3.544	1138
NO.7 DB.W.B.TK (P)	52 - 90	794.2	814.1	54.418	4.100	980
NO.7 DB.W.B.TK (S)	52 - 90	716.5	736.4	54.356	3.738	996
A.P.TK (P)	-5 - 13	116.9	119.8	4.636	10.007	366
A.T.TK (S)	-1 - 13	59.4	60.9	5.348	9.853	39
A.P.TK (C)	-5 - 13	244.6	250.7	2.966	9.365	954
SUB TOTAL		9633.7	9874.5	125.047	4.775	18060

FRESH WATER TANKS (S.G=1.000)

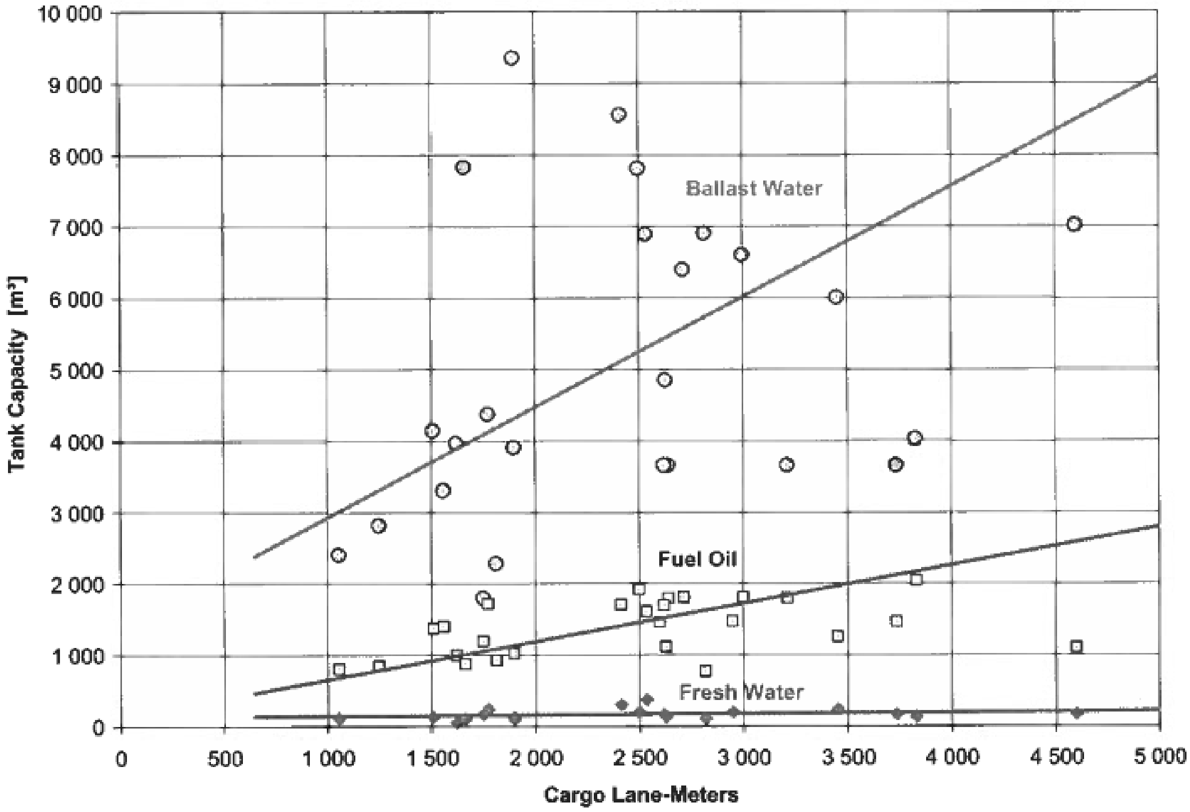
COMPARTMENT	LOCATION (FR.NO.)	CAPACITIES VOLUME 100% (M^3)	CAPACITIES WEIGHT 100% (TONS)	CEN.OF GRAVITY L.C.G (M)	CEN.OF GRAVITY V.C.G (M)	MAX F.S.MOM. (M^4)
F.W.TK (P)	7 - 13	155.0	155.0	8.003	12.387	447
F.W.TK (S)	9 - 13	107.4	107.4	8.762	11.888	239
SUB TOTAL		262.4	262.4	8.314	12.203	686

HEAVY FUEL OIL TANKS (S.G=0.980)

COMPARTMENT	LOCATION (FR.NO.)	CAPACITIES VOLUME 100% (M^3)	CAPACITIES WEIGHT 98% (TONS)	CEN.OF GRAVITY L.C.G (M)	CEN.OF GRAVITY V.C.G (M)	MAX F.S.MOM. (M^4)
NO.4 DB.F.O.TK (P)	162 - 198	602.8	578.9	143.970	1.546	1154
NO.4 DB.F.O.TK (S)	162 - 198	602.8	578.9	143.970	1.546	1154
NO.5 DB.F.O.TK (P)	126 - 162	601.2	577.4	115.275	1.540	1155
NO.5 DB.F.O.TK (S)	126 - 162	601.2	577.4	115.275	1.540	1155
NO.6 DB.F.O.TK (P)	90 - 126	604.5	580.6	86.400	1.543	1155
NO.6 DB.F.O.TK (S)	90 - 126	604.5	580.6	86.400	1.543	1155
NO.7 DB.F.O.TK (P)	52 - 90	428.5	411.5	58.160	1.490	423
NO.7 DB.F.O.TK (S)	52 - 90	428.5	411.5	58.160	1.490	423
HFO SETT.TK (S)	7 - 15	65.7	63.1	9.005	11.332	12
HFO SERV.TK (S)	7 - 15	66.6	64.0	8.958	11.302	13
LS.HFO SETT.TK (P)	7 - 13	34.5	33.1	8.062	11.481	4
LS.HFO SERV.TK (P)	7 - 13	35.3	33.9	8.062	11.481	4
SUB TOTAL		4676.1	4490.9	100.139	1.958	7805

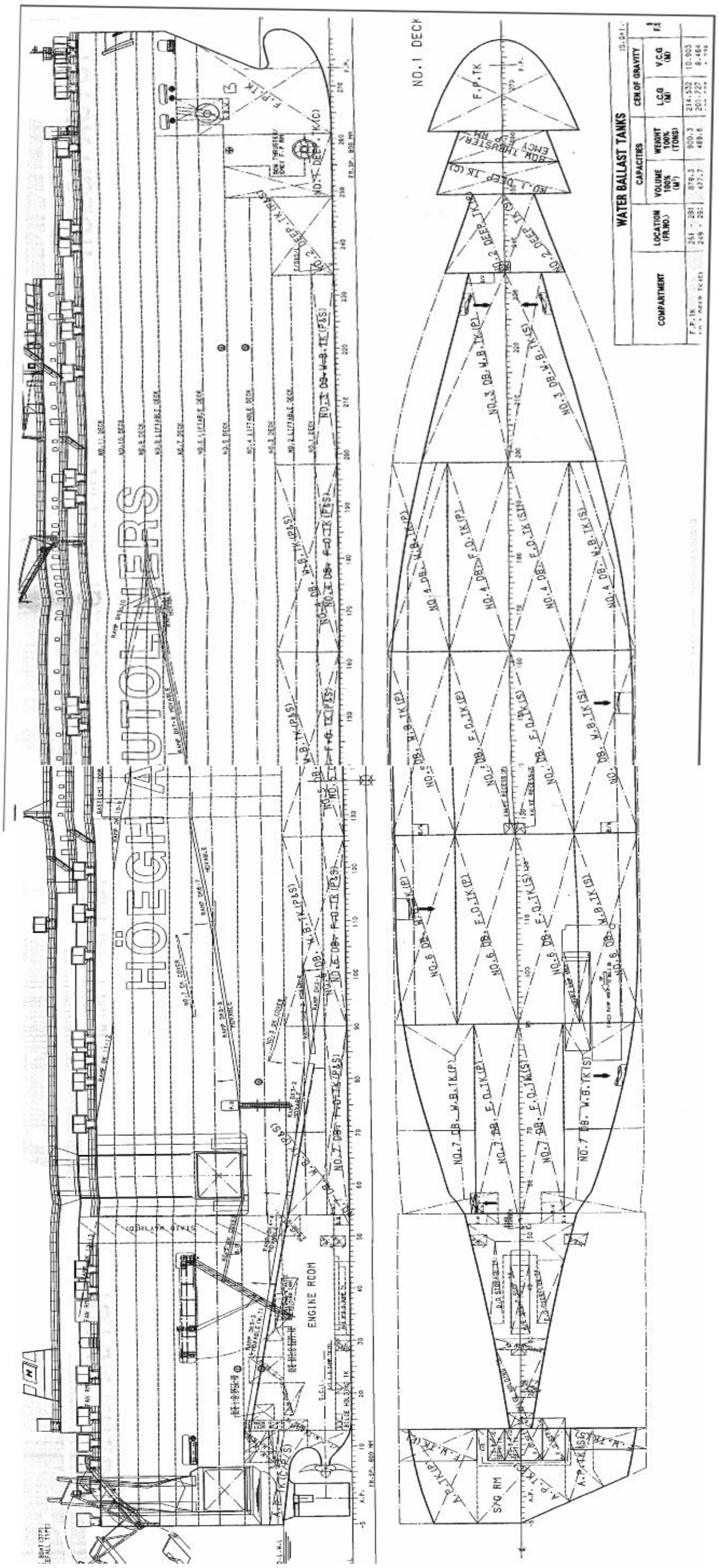
Tank capacities from general arrangements of the lengthened sister class by DSME ship yard.

Appendix VII



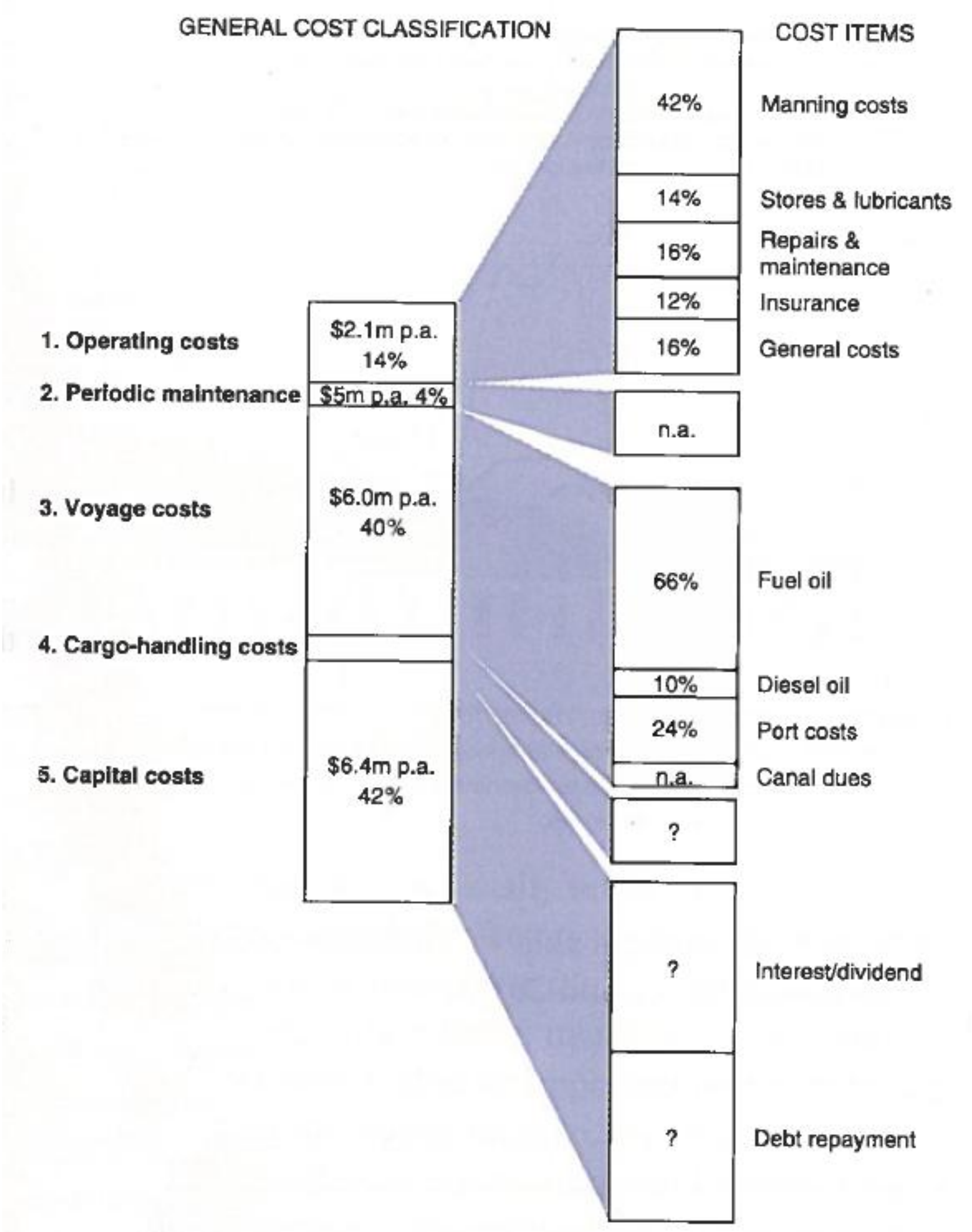
Tank capacity for RoRo-ships. From Kai Levander, System Based Ship Design.

Appendix VIII



General arrangement of a RoRo-vessel. From DMSE ship yard.

Appendix IX



Ship

General costs for running a bulk carrier. From Maritime Economics, Martin Stopford. [5]

Appendix X

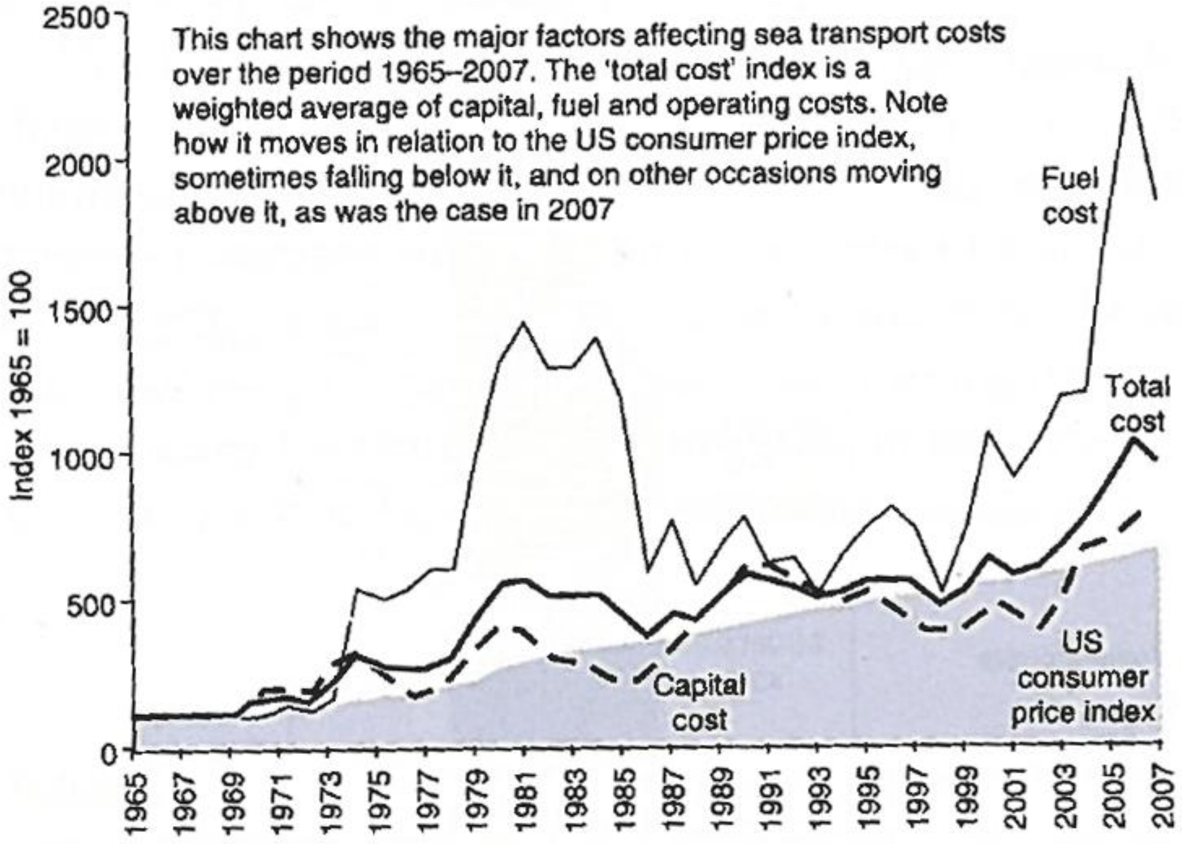


Chart from Maritime Economics by Martin Stopford. Ilustrates the development in fuel costs compared to total costs. [5]

Appendix XI

Name	Type	Power range MW	Spec power kW/ton (W/kg)	Spec Vol kW/m^3 (W/ltr)	Efficiency %	Spec Cost Euro/kW
Petrol Engine (SI)		0.001 - 0.01 (10 – 100 kW)			30 - 35	
Diesel Engine	High speed Traction	(40 – 400 kW)			38 - 42	
Diesel Engine	High speed Marine (Vee)	0.5 – 9	160 – 430	125 – 350	38 – 42	200 – 400
Diesel Engine	Medium speed (Vee)	0.5 – 35	50 – 200	36 – 250	40 – 50	140 – 240
Diesel Engine	Medium speed (Line)	0.5 – 35	50 – 200	36 – 250	40 – 50	180 – 280
Diesel Engine	Low speed (Line)	8 – 90	17 – 60	18 – 80	47 – 52	350 – 450
Gas Turbine	Aero derived Simple Cycle	1 – 40	700 – 1000	220 – 400	20 - 35	320 – 500
Gas Turbine	Aero derived ICR	24	550	240	42	500
Gas Turbine	Industrial	25 – 200			30 - 35	250 - 400
Steam plant	Marine Conventional fuel	20 – 45			28 - 33	550 - 620
Steam plant	Marine Nuclear fuel	10 – 55			20 – 25 ?	
Steam plant	Industrial Conventional fuel	100 – 800 MW			42 – 43	
Steam Plant	Industrial Nuclear fuelled	100 – 800 MW			35?	
Free Piston Engine	Hydraulic power pack	1 – 100 kW				
Stirling Engine	Regenerated	1 – 500 kW			40 – 50	
Fuel Cell	Alkaline (AFC)	0.001 – 0.010 (0.1 – 10 kW)	150	135	55 – 65	
Fuel Cell	Phoshoric Acid (PAFC)	0.010 – 1.0 (10 – 1000 kW)	75	100	38 – 42	3000 - 4000
Fuel Cell	Solid Polymer SPFC	0 – 0.3 (1 W – 300 kW)	100	70	39 - 42	target: 1000
Fuel Cell	Molten Carbonate (MCFC)	0.1 - 10			40 - 55	
Fuel Cell	Solid Oxide (SOFC)	0.005 - 10	50	50	45 - 60	

Data for various engine types. From Diesel Engines Volume 1. Performance Analysis. p.21

HÖEGH FLEET SERVICES

Appendix XII

Minutes of meeting

From:	Martin Wattum	**Date:**	15 February 2011	**Pages:**	1
To:	Memo	**Subject:**	Bunker operation and capacity management.		

Bunker operation and strategy.

Dialogue with Geir Inge Asskildt from Global Yield and Capacity Management, Höegh Autoliners.

The daily used strategy when it comes to bunkering and refuelling is to bunker in the ports with the lowest bunker prices within the operation area of the different vessel. For the larger part of the fleet, that would be the Amsterdam, Rotterdam and Antwerp (ARA) area, as these ports holds a generally lower price than other main ports. There is also naturally a question of timing, as the oil price fluctuates over time, and also between the different regions. An example will be the difference in price from bunkering in a traditionally costly port when the global fuel price is (almost momentarily) high, as to bunker in a cost effective port with a low market oil price. These are factors that are hard to predict exactly, so be best strategy over time is therefore to always bunker as much as possible in the ARA-area.

The Höegh Autoliners operated RORO-vessels has a fuel capacity of 2500 to 3500 tons in total, including fuel holds for MDO and lighter fuel oils in order to meet the emission demand from various harbour and state authorities.

When bunkering, a test sample from the fuel is being tested and examined by DNV so that the quality of the product is carefully studied. This is of importance due to the mentioned regulations and also engine operation reliability. An issue with the fuel in relation to sulphur content could lead to a de-bunkering or a protest from the ships master. In case of a protest from the ships master, one would have to call in a broker and representatives from HFS in order to come to an agreement.

If we would have a marked with identical fuel price among the various regions, a conduct of bunkering in every port that has on and off-loading would be possible. The challenge would mainly be a question of logistics, and would call for more planning ahead than today's operation, where the ship only need to bunker once every two months.

Due to situations where ports has sold a larger portion of its fuels to harbouring ships, leaving a too small portion left for the domestic market, unforeseen price developments has occurred. This causes a sudden halt or throttle regulation in the port, leaving the available fuel price to rise significantly.

Appendix XIII

HÖEGH FLEET SERVICES

Minutes of meeting

From:	Martin Wattum	**Date:**	16 February 2011	**Pages:**	1
To:	Memo	**Subject:**	Newbuild department		

Issues and practise from a newbuilding point of view

Dialogue with Sam Holvik, newbuild departement, Höegh Autoliners.

The vessels stability is presented from the loading manual, and to be used as documentation and data during operation. Also, the ship operator has his own regulations when it comes to minimum GM-figures. Today being at least 0.8m in any loaded condition, thus normally closest when fully loaded with payload and fuel oil. In order to meet this regulation and still be able to carry cargo as optimal as possible, subjects such as steel plate thickness and even placement of CO_2- tanks are of importance. Strength data is often not given to the ship owner in a very detailed form. Figures such as load per m^2, axial load and transverse load are the most common data, and any additional numbers would have to be found using these data.

When it comes to range of a vessel, this is a subject that is not of essence to the new build department, and seldom a demand from the Autoliner department either. It is unknown what the optimum bunker capacity should be, and only the ship builders' pre fabricated design is the given number to be taken into account. It is then the capacity manager and bunker division that has to handle every vessel on background of what it is capable of and the variable trading pattern. However, the tendency shows a range of about 25.000 to 30.000 nm range on a typical yard design. In general, one can say that the yard is many steps on front of the ship owner, as the ship owners seek an already finished design that is difficult to alter. This limitation would off course be turned upside down if the ship owner together with a design company has a vessel design, searching for a yard to build it. In that case, one could implement many solutions and characteristics that normally would be hard to meet. That was the case for the new build Horizon class, a new type of RoRo designed by Delta Marine and Höegh during the financial strong period before 2008.

The vision behind the different solutions on a new build is often marked based. In tight markets, low cost and proven design and technology is chosen. In such a situation, the willingness to invest more money than what is absolutely needed is very low. An investment in equipment or machinery that doesn't pay back within 5 years is hard to push through. Most of the ships whit its engines and machinery is therefore to be seen as of the shelf, with as low as possible investment costs and thriving factor. When it comes to cost of lost opportunity, this is something that will fluctuate largely. Factors such as the marked situation, trade route, deck and contracts will have to be taken into account. The new build division is continuously interested in new technology when it comes to meeting emission control area restrictions and future limitations.

Appendix XIV

HÖEGH FLEET SERVICES

Minutes of meeting

From:	Martin Wattum	**Date:**	17 February 2011	**Pages:**	1
To:	Memo	**Subject:**	Market development situation, point of views from Kjetil V. Moen, Market analyses		

Market development and situation for global RORO-trade.

Meeting with Kjeil Vee Moen, market analyses, Höegh Autoliners.

The freight rates are highly trade and region specific, and this will also be the future situation as a fundamental function in any market system reflecting supply and demand. As of today the freight rates are as variable as almost double the price for the same distance travelled between the least and most costly trades. This is in relation to the opportunity to carry cargo on the return trip. If we use historical figures for the last periods, we can talk about prices in the area of 60$/m^3$ for Far East – Europe, 35 $/m^3$ for Europe – Far East, and something in between; about 50 $/m^3$ out of Europe and to Australia, with discharge and loading in South Africa, known as EANF.

Today, China as an example is a very large manufacturer of cars with a high growth in annual production. Since the standard of living in China also increases, the market for cars also improves. This demand is not met by only the self produced Chinese cars. As a matter of fact, former poor car manufacturing countries, experiencing improved standard of life, have an increased demand for more luxury cars from foreign countries such as Europe in addition to the domestic production. In that sense, the market will likely maintain or increase its demand for long travelled foreign cars. This also causes a shift in balance as these countries also may reach western standards regarding quality and user impression, and start to export in addition to increased import. Together with a strong yen, making it tougher for Japanese car manufacturers to claim market share, the balance will have to shift at one point in time.

The freight rate is also dependant on where onboard the ship. As of Höegh's fleet, deck 5 is the most valuable, designed to be suitable for "high and heavy" load, such as industrial machinery and excavators. Also deck 2 is costly as it is also flexible with moveable decks. The higher decks, as well as deck 1 are commonly the least costly decks as these have either more restrictions due to vessel stability and deck height, or are harder to exploit.

Appendix XV

World's LNG Liquefaction Plants and Regasification Terminals

As of June 2011

World's LNG Liquefaction Plants: Source: www.globallnginfo.com

On-Stream	*Under Construction*	*Planned*
Adgas LNG Plant (UAE)	Angola LNG Plant (Angola)	Abadi LNG Plant (Indonesia)
Algeria LNG Plants (Algeria)	Gladstone LNG Plant (Australia)	Arrow LNG Plant (Australia)
Arun LNG Plant (Indonesia)	Gorgon LNG Plant (Australia)	Australia Pacific LNG Plant (Australia)
Atlantic LNG Plant (Trinidad & Tobago)	Iran (NIOC) LNG Plant (Iran) de facto Suspended!	Baltic LNG Plant (Russia)
Bontang LNG Plants (Indonesia)	Pluto LNG Plant (Australia)	Bonaparte LNG Plant (Australia)
Brunei LNG Plant (Brunei)	PNG LNG Plant (Papua New Guinea)	Brass LNG Plant (Nigeria)
Damietta LNG Plant (Egypt)	Queensland Curtis LNG Plant (Australia)	Browse LNG Plant (Australia)
Darwin LNG Plant (Australia)		Delta Caribe LNG Plant (Venezuela)
EG LNG Plant (Equatorial Guinea)		Donggi-Senoro LNG Plant (Indonesia)
Egyptian LNG Plant (Egypt)		Fisherman's Landing LNG Plant (Australia)
Kenai LNG Plant (Alaska, USA)		Ichthys LNG Plant (Australia)
Marsa El Brega LNG plant (Libya)		Kitimat LNG Plant (Canada)
MLNG Satu Plant (Malaysia)		Liquid Niugini Plant (Papua New Guinea)
MLNG Dua Plant (Malaysia)		Olokola LNG Plant (Nigeria)
MLNG Tiga Plant (Malaysia)		Pars LNG Plant (Iran) Suspended!
Nigerian LNG Plant (Nigeria)		Persian LNG Plant (Iran) Suspended!
Nordic (Skangass) LNG Plant (Norway)		Prelude LNG Plant (Australia)
North West Shelf LNG Plant (Australia)		Scarborough (Pilbara) LNG Plant (Australia)
Oman & Qalhat LNG Plant (Oman)		Shtokman LNG Plant (Russia)
Peru LNG Plant (Peru)		Sunrise LNG Plant (Australia)
Qatargas I LNG Plant (Qatar)		Wheatstone LNG Plant (Australia)
Qatargas II LNG Plant (Qatar)		
Qatargas III,IV LNG Plant (Qatar)		
RasGas I LNG Plant (Qatar)		
RasGas II LNG Plant (Qatar)		
Rasgas III LNG Plant (Qatar)		
Sakhalin LNG Plant (Russia)		

Snohvit LNG Plant (Norway)		
Tangguh LNG Plant (Indonesia)		
Yemen LNG Plant (Yemen)		

World's LNG Regasification Terminals: Source: www.globallnginfo.com

On-Stream:	*Under Construction:*	*Planned:*
Adriatic (Rovigo) LNG Terminal (Italy)	Bear Head LNG Terminal (Canada) Cancelled!	Adria LNG Terminal (Croatia)
Altamira LNG Terminal (Mexico)	Brindisi LNG Terminal (Italy)	Bahia LNG FSRU (TRBA) (Brazil)
Andres LNG Terminal (Dominican Rep.)	Dabhol LNG Terminal (India)	Bradwood Landing LNG Terminal (USA) Cancelled!
Bahia Blanca GasPort (Argentina)	Dalian LNG Terminal (China)	Boryeong LNG Terminal (S. Korea)
Barcelona LNG Terminal (Spain)	El Musel LNG Terminal (Spain)	Cacouna LNG Terminal (Canada) Suspended!
Bilbao LNG Terminal (Spain)	Gate LNG Terminal (Netherlands)	Calhoun LNG Terminal (USA) Suspended!
Brunnsviksholme LNG Terminal (Sweden)	Gulf LNG (Clean Energy) Terminal (USA)	Canvey LNG Terminal (UK) Suspended!
Cameron LNG Terminal (USA)	Hachinohe LNG terminal (Japan)	Casotte Landing LNG Terminal (USA) Cancelled!
Canaport LNG Terminal (Canada)	Ishikari LNG terminal (Japan)	Corpus Christi LNG Terminal (USA) Suspended!
Cartagena LNG Terminal (Spain)	Joetsu LNG terminal (Japan)	Creole Trail LNG Terminal (USA) Suspended!
Chita I,II,III LNG Terminals (Japan)	Kita Kyushu LNG terminal (Japan)	Crown Landing LNG Terminal (USA)
Cove Point LNG Terminal (USA)	Kochi LNG Terminal (India)	Dunkirk LNG Terminal (France)
Dahej LNG Terminal (India)	Livorno LNG Terminal (Italy)	Gioia Tauro (Medgas) LNG Terminal (Italy)
Dragon LNG Terminal (UK)	Manzanillo LNG Terminal (Mexico)	Goldboro LNG Terminal (Canada) Cancelled!
Elba Island LNG Terminal (USA)	Naoetsu LNG terminal (Japan)	Hitachi LNG terminal (Japan)
Energia Costa Azul LNG Terminal (Mexico)	Nusantara LNG FSRU (Indonesia)	Ingleside Energy LNG Terminal (USA) Suspended!
Escobar GasPort (Argentina)	Rayong LNG Terminal (Thailand)	Jieyang (Yuedong) LNG Terminal (China)
Everett LNG Terminal (USA)	Shandong LNG Terminal (China)	Jordan Cove LNG Terminal (USA)
Fos Cavaou LNG Terminal (France)	Singapore LNG Terminal (Singapore)	Kitimat LNG Terminal (Canada) Cancelled!
Fos Tonkin (Fos-Sur-Mer) LNG Terminal (France)	Swinoujscie LNG Terminal (Poland)	Le Havre LNG Terminal (France) Suspended!
Freeport LNG Terminal (USA)	Tianjin (Hebei) LNG Terminal (China)	Levan (Falcione) LNG Terminal (Albania)
Fujian LNG Terminal (China)	Zhejiang Ningbo LNG Terminal (China)	LionGas LNG Terminal (Netherlands) Cancelled!
Fukuoka LNG Terminal (Japan)	Zhuhai LNG Terminal (China)	Mangalore LNG Terminal (India)
Futtsu LNG Terminal (Japan)		Mashal LNG Terminal (Pakistan)
Golden Pass LNG Terminal (USA)		Medan LNG FSRU (Indonesia)

Guanabara LNG FSRU (Brazil)
Guangdong LNG Terminal (China)
Gulf Gateway GasPort (USA) decommissioned!
Gwangyang LNG Terminal (S. Korea)
Hatsukaichi LNG Terminal (Japan)
Hazira LNG Terminal (India)
Higashi-ohgishima LNG Terminal (Japan)
Himeji I LNG Terminal (Japan)
Himeji II LNG Terminal (Japan)
Huelva LNG Terminal (Spain)
Incheon LNG Terminal (S. Korea)
Isle of Grain LNG Terminal (UK)
Izmir (Aliaga) LNG Terminal (Turkey)
Jebel Ali (Dubai) LNG FSRU (UAE)
Jiangsu Rudong LNG Terminal (China)
Kagoshima LNG Terminal (Japan)
Kawago LNG Terminal (Japan)
Lake Charles LNG Terminal (USA)
Marmara LNG Terminal (Turkey)
Mejillones LNG Terminal (Chile)
Mina Al-Ahmadi GasPort (Kuwait)
Mizushima LNG Terminal (Japan)
Montoir-d-Bretagne LNG Terminal (France)
Nagasaki Work LNG Terminal (Japan)
Negishi LNG Terminal (Japan)
Neptune Deepwater LNG Port (USA)
Niigata LNG Terminal (Japan)
Northeast Gateway GasPort (USA)
Ohgishima LNG Terminal (Japan)
Oita LNG Terminal (Japan)
Panigaglia LNG Terminal (Italy)
Pecem LNG FSRU (Brazil)

Oregon LNG Terminal (USA)
Port Arthur LNG Terminal (USA) Suspended!
Port Dolphin Deepwater LNG Port (USA)
Porto Empedocle LNG Terminal (Italy)
Priolo (Augusta) LNG Terminal (Italy)
Rabaska LNG Terminal (Canada)
Rosignano LNG Terminal (Italy)
Samcheok LNG Terminal (S. Korea)
SemanGas (ASG) LNG Terminal (Albania)
Shannon LNG Terminal (S. Ireland)
Sonora LNG Terminal (Mexico)
Sparrows Point LNG Terminal (USA)
Tenerife LNG Terminal (Canary Isl.- Spain)
Texada LNG Terminal (Canada) Suspended!
Trieste LNG Terminal (Italy)
Vasiliko LNG Terminal (Cyprus) Suspended!
Vista del Sol LNG Terminal (USA) Cancelled!
Weaver's Cove LNG Terminal (USA)
Wilhelmshaven LNG Terminal (Germany) Suspended!

Penuelas LNG Terminal (Puerto Rico)
Pyeong Taek LNG Terminal (S. Korea)
Quintero LNG Terminal (Chile)
Reganosa (EL Ferrol) LNG Terminal (Spain)
Revithoussa LNG Terminal (Greece)
Sabine Pass LNG Terminal (USA)
Sagunto LNG Terminal (Spain)
Sakai LNG Terminal (Japan)
Sakaide LNG Terminal (Japan)
Senbokui I,II LNG Terminal (Japan)
Shanghai LNG Terminal (China)
Shin Minato Works LNG Terminal (Japan)
Sines LNG Terminal (Portugal)
Sodeshi LNG Terminal (Japan)
South Hook LNG Terminal (UK)
Sudegaura LNG Terminal (Japan)
Taichung LNG Terminal (Taiwan)
Teesside GasPort (England)
Tobata LNG Terminal (Japan)
Tong yeong LNG Terminal (S. Korea)
Yanai LNG Terminal (Japan)
Yokkaichi LNG Terminal (Japan)
Yokkaichi Works LNG Terminal (Japan)
Yung An LNG Terminal (Taiwan)
Zeebrugge LNG Terminal (Belgium)

From www.GlobalLNGinfo.com