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# Life Cycle Cost Comparison Study

An analysis of a LNG ferry's performance and
potential for improvement

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# I. PREFACE

The Norwegian car ferry fleet is estimated to have an average age of 21 years, and the renewal process seems to be somewhat slow. Generally, procurement of new vessels is only done in cases where the tender specifications demand it. The reason is that costs have a strong focus in such tender competitions. Older vessels tend to be depreciated and thus have very low capital costs. However, in several tender competitions in the recent years, it has been demanded that the vessels are to be equipped with LNG propulsion.

LNG engines have several environmental advantages compared to conventional diesel fuelled engines. The emissions of CO2 are reduced, while NOx and SOx are nearly eliminated. In addition, a significant price difference between LNG and marine gas oil has evolved during the last ten years. Therefore, it has been claimed by many that the extra cost related to the investment of an LNG propulsion system has a payback time in the order of 5-10 years, dependent on the vessel type.

In the turn of the year 2012-2013, the shipping company Torghatten Nord received four new LNG ferries, which were built at Gdanska Stoczina Remontowa. This study emphasises one of these vessels and seeks to elucidate whether this vessel is cost efficient compared to a 21 year old ferry equipped with a conventional propulsion system.

This thesis contains a life cycle cost comparison study between the mentioned vessels, and an analysis of a potential measure to reduce the LNG vessel’s life cycle cost.

I would like to thank Torghatten Nord for their cooperation and especially those who supervised me: Jan-Egil Sletteng, Tom Hartviksen and Tore Heidegård.

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# II. SAMMENDRAG

I denne studien er det utført en sammenlignende levetidskostnadsanalyse mellom en nybygd LNG-ferge og en 21 år gammel konvensjonell ferge. Målet med studien har vært å studere LNG-fartøyets kostnadseffektivitet i forhold til et sammenlignbart eksisterende fartøy i «moden» alder. I denne studien er det antatt at begge fartøyene skal følge LNG-fartøyets eksisterende produksjonsmønster ved et spesifikt fergesamband. Det er tatt utgangspunkt i en tidshorisont på 30 år. En annen antagelse er at fartøyene antas anskaffet fra henholdsvis nybyggingsmarkedet og andrehåndsmarkedet.

Studien omhandler hovedsakelig kostnader generert av fartøyet. Med dette menes kostnadselementer som blant annet: kapitalkostnader, drivstoffkostnader, smøroljekostnader, vedlikeholdskostnader, nedetidskostnader, kostnader knyttet til utslipp av NOx og fortjeneste fra skraping av fartøyene. Kostnader som for eksempel havneavgifter og utgifter knyttet til rederiets ledelse av fartøyene er ikke inkludert. En sensitivitetsanalyse er også utført på grunn av den høye graden av usikkerhet som er knyttet til flere av kostnadselementene.

Det er etablert en struktur som har til hensikt å identifisere de kostnadselementene som er hensiktsmessig for denne studien. Data til beregningene av disse kostnadselementene er innhentet fra rederiet som eier fartøyene ved hjelp av deres databaser og arkiver. Dokumentasjon og spesifikasjoner er også framskaffet ved hjelp av rederiets leverandører. I tilfeller hvor en tilstrekkelig mengde data ikke har vært tilgjengelig er beregningene delvis basert på ekspertuttalelser.

Et av funnene i denne studien er at levetidskostnadene til det konvensjonelle fartøyet er estimert til å være 12 % lavere enn for LNG fartøyet. De viktigste kostnadselementene er identifisert til å være kapitalkostnadene, drivstoffkostnadene, vedlikeholdskostnadene, kostnadene fra NOx-utslipp og nedetidskostnadene. Hvis en anvender et avkastningskrav med hensyn til levetidskostnadene vil LNG-fartøyets ufordelaktighet i forhold til de totale levetidskostnadene forsterkes. Dette er på grunn av de høye startkostnadene som er knyttet til LNG-fartøyet.

Resultatene viser at realverdien av kapitalkostnaden knyttet til anskaffelsen av det konvensjonelle fartøyet er bare 8 % av LNG-fartøyets. Et annet funn er at det konvensjonelle fartøyet har 19 % lavere energiforbruk en LNG-fartøyet. Til tross for dette er det beregnet at det konvensjonelle fartøyet vil ha 9 % høyere totale drivstoffkostnader over tidsperioden. Dette er hovedsakelig fordi prognosene for de framtidige MGO- og LNG-prisene viser at det eksisterende gapet mellom de to prisene ser ut til å øke fremover.

Det har blitt beregnet at LNG-fartøyet har 9 % lavere vedlikeholdskostnad over tidsperioden. Dette skyldes blant annet at det er forventet lavere slitasje av komponenter og systemer som fødesystemet for drivstoff, motordyser og eksosventiler.

LNG-fartøyets total utgifter i forbindelse med utslipp av NOx er beregnet til å være bare 15 % av det konvensjonelle fartøyets tilsvarende kostnad. Dette er en av de mest signifikante forskjellene mellom fartøyene. Årsaken til dette er at LNG-motoren har et veldig lavt NOx-utslipp.

Det er også utført en analyse av et tiltak som har til hensikt å redusere levetidskostnadene til LNG-fartøyet. LNG-fartøyet er utstyrt med et hybrid akselgeneratorsystem som gjør det mulig å drive fartøyet ved hjelp av dieselelektrisk framdrift, og omvendt benytte hovedmotoren til å produsere strøm til fartøyets strømnett. Dette gir fleksibilitet i forhold til kraftproduksjon og energiforbruk. Tiltaket går i korte trekk ut på å erstatte den eksisterende akselgeneratoren med en ny enhet som har tilstrekkelig kapasitet til å forsyne fartøyets strømforbrukere uten hjelp fra fartøyets standby generator. Da vil hovedmotoren, som er mekanisk tilkoblet propellakslingen, alene kunne forsyne strømnettet ombord. Det gjør det mulig å spare drivstoff, NOx-utgifter og vedlikeholdskostnader på grunn av blant annet økt virkningsgrad av fartøyets strømproduksjon.

Data til denne analysen angående den eksisterende driften av fartøyets hovedmaskineri er samlet inn fra fartøyets kraftstyringssystem. Informasjon angående de forskjellige komponentene i systemet er framskaffet av leverandørene.

Analysen viser at de årlige besparelsene grunnet redusert drivstoff-, NOx og vedlikeholdskostnader er i underkant av 1 million NOK. Tiltaket vil redusere fartøyets NOx-utslipp betydelig. Derfor kvalifiserer tiltaket til støtte fra NHOs NOx-fond. Iberegnet denne støtten er kostnadene knyttet til investeringen estimert til å være cirka 1 million NOK. Følgelig gir dette en nedbetalingstid på cirka ett år, noe som er en relativt kort nedbetalingstid. Det er imidlertid viktig å understreke at det er usikkerhet knyttet til disse beregningene og de iboende begrensningene knyttet til tiltaket.

# III. SUMMARY

A life cycle cost comparison study between a newly built LNG ferry and a 21 year old conventional ferry was carried out in this study. The objective was to study the LNG vessel's cost effectiveness compared to an equivalent existing vessel of "mature" age. It has been assumed that both vessels are to be operating according to the LNG vessel's current production pattern at a specific ferry service. The study has a time span of 30 years. Another assumption is that both vessels are assumed to be procured from respectively the newbuilding market and the second-hand market.

This study emphasises primarily vessel generated costs. The cost elements that are investigated are among other: capital costs, fuel costs, lube oil costs, maintenance costs, downtime costs, NOx emission costs and income due to scrapping. Costs such as port fees and management costs are not included. Due to the high level of uncertainty related to many of the cost elements, a sensitivity analysis is performed.

A cost breakdown structure has been derived to identify the relevant cost elements which are to be studied. Data are gathered from the shipping company that owns the vessels. This is done by use of their databases and records. Documentations and specifications are also provided by the shipping company's suppliers. Estimations which lacked sufficient input data have been partly founded on expert opinions.

It has been found that the total life cycle costs of the conventional vessel are 12 % lower than the LNG vessel's. The most significant cost elements are identified to be the capital costs, fuel costs, maintenance costs, NOx emission costs and downtime costs. If an internal rate of return is applied, the LNG vessel's disadvantage when it comes to total life cycle costs will increase. This is due to the LNG vessel's high initial costs.

The results show that the capital costs related to the procurement of the conventional vessel in real term value are only 8 % of the LNG vessel's capital cost. It has been found that the conventional vessel has 19 % lower energy consumption than the LNG vessel. Despite of this, it is estimated that the conventional vessel will have 9 % higher total fuel cost over the time period. The main reason for this is that the existing gap between the two energy prices is forecasted to increase over the time period.

It is estimated that the LNG vessel has 9 % lower maintenance cost over the time period. One of the reasons for this is the expectation of reduced deterioration of the fuel supply system and other components such as engine nozzles and exhaust valves.

The LNG vessel's total NOx emission costs are estimated to be only 15 % of the conventional vessel's, which is one of the most significant differences between the ferries. This is due to the LNG engine's ability to operate at very low NOx emission rates.

An analysis regarding a measure that may reduce the LNG vessel’s life cycle cost is also conducted. The vessel has installed a hybrid shaft generator system. The main engine is able to deliver power to the vessel’s electricity grid by use of the shaft generator. Vice versa, the shaft generator is able to function as a motor and thus use electric power for propulsion. In other words, the shaft generator gives the vessel flexibility with respect to power consumption and power production. The measure is to replace the LNG vessel’s shaft generator with a new unit which has sufficient capacity to supply all the main switchboard’s consumers without having to run the vessel’s standby generator. Then the main engine will alone be able to provide sufficient electricity power to the vessel’s grid. This is assessed to enable savings of fuel, NOx tax and maintenance cost due to among other increased efficiency of electricity production.

Data for this analysis regarding the current operation of the propulsions system is gathered from the LNG vessel’s power management system. Information regarding the system’s components is provided by the suppliers.

It has been found that the yearly savings due to the reduced fuel, maintenance and NOx expenditures are in lower edge of 1 million NOK. This measure will reduce the vessel’s NOx emission significantly. The measure therefore qualifies to a significant support from the Norwegian NOx fund, which may reduce the financial cost of the replacement to about 1 million NOK. Consequently, the payback time is about one year, which is a relatively short time period. However, it is important to underline that there is uncertainty related to these calculations and the inherent limitations which are associated with the measure.

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# 1. INTRODUCTION

## 1.1 Background

### 1.1.1 Renewal of the Norwegian ferry fleet

A study performed by an independent consultancy bureau found that the Norwegian car ferry fleet is about 21 years old. They concluded that renewal of the ferry fleet only occurred if the tender specification demanded a new vessel. This is because costs have a strong focus in this type of tender competitions. The tender price tends to be the most important factor in such competitions as long as the bidder (shipping company) offers a sufficient capacity and quality level. Since the average age of the ferry fleet is high, most of the shipping companies have already depreciated the older vessels. The capital costs related to a new vessel is therefore a significant cost element, which in many cases makes them too expensive. This is even though modern vessels tend to have lower fuel consumptions and requires less maintenance. However, in several tender competitions in the recent years it has been required that the ferries are to be fitted with LNG propulsion due to among other environmental concerns (Oslo Economics, 2012).

### 1.1.2 Fuels

Marine gas oil (MGO) and liquefied natural gas (LNG) are both fuels that are applied in Norwegian car ferries today. MGO has traditionally been preferred. The fuel is easily accessible even at remotely located ferry services. MGO sold in Norway contains less than 0.1 % sulphur. This is within the IMO requirements, which are effective from 2015. MGO fuelled engines release approximately 3.2 tons of CO2 per ton fuel. The NOx emissions from MGO fuelled ferries depends heavily on the engine installed, but are nevertheless significant compared to LNG engines. Older engines tend to have a higher NOx emission than modern MGO fuelled engines, which has to be in accordance with the IMO Tier 2 (3 from 2015) requirements (Det Norske Veritas, 2011).

The usage of liquefied natural gas as fuel for ships, and car ferries in particular, has increased rapidly the last years. There are several reasons for this. Natural gas contains less carbon per energy unit than for example MGO. Hence, an engine releases only around 2.75 tons CO2 per ton fuel, which is a significant reduction compared to MGO. NOx emissions are also reduced by 80 %. SOx emissions are practically speaking zero. However, there is a lack of infrastructure with respect to distribution of LNG in Norway. Some of the benefits with the fuel are therefore cancelled by cumbersome distribution networks (Det Norske Veritas, 2011, Sören Karlsson, 2010).

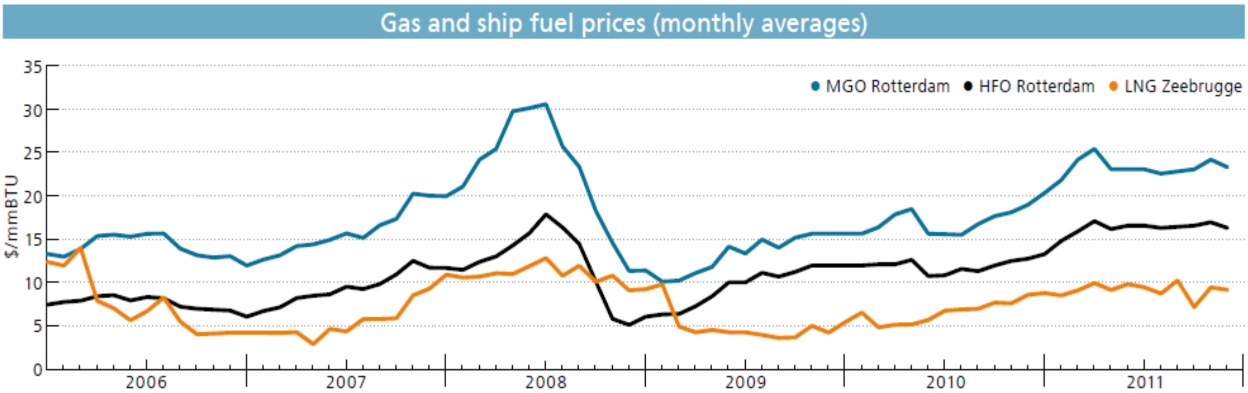

**Figure 1-1 History of gas and fuel prices (Germanischer Lloyd, 2011)**

Figure 1-1 shows the development of MGO, HFO and LNG prices. The prices are based on the fuels specific energy content. At the beginning of the last decade, the price difference between MGO and LNG was small. As the figure illustrates, a significant price difference developed after 2005. One of the reasons for this is the increased shale gas production in the US. Due to stricter regulations from IMO regarding the sulphur content in fuel, several ships have to change from HFO to MGO to comply with the new regulations. Forecasts of the future gas and MGO price therefore predicts a decoupling of two prices, as the shale gas production increases faster than the demand for LNG. The demand of MGO is assessed to rise without a rapid increase of the production. It should be added that there is a great amount of uncertainty related to these forecasts (Det Norske Veritas, 2012). Based on the differences in fuel prices, a study has concluded that an investment in a LNG propulsion system will have a payback time of 5-10 years for several vessel types (Ruud Verbeek, 2011).

### 1.1.3 The gas ferries in the Vestfjord

Statens Vegvesen, which is responsible for the Norwegian national road network and its ferry services, issued in 2009 a tender specification regarding three ferry services in the Vestfjord, North Norway. For the reasons which are already discussed, Statens Vegvesen demanded that the four vessels which operated the ferry service on a regular basis were to be fitted with LNG propulsion (Statens Vegvesen, 2009).

In august 2010, the shipping company Torghatten Nord won Statens Vegvesen's tender competition and was therefore contracted to operate these ferry services. The contract had a total value of 1.4 billion NOK (Torghatten Nord, 2010).

As a result, Torghatten Nord procured four state of the art car ferries fitted with LNG propulsion. The last of the four vessels, M/F Lødingen, was delivered to the shipping company in the turn of the year 2012-2013 (Halvorsen, 2013). However, the vessel and its sister ships experienced technical problems almost from day one and suffered from a large amount of initial downtime. As a result, they have frequently been discussed in local and regional media because of this. A fundamental question, which this study tries to elucidate, is whether these vessels are cost efficient compared to other ferries of more mature age fitted with conventional propulsion systems.

## 1.2 Objective

The fundamental question which motivated this study is: How do these modern LNG ferries perform compared to an equivalent ferry, of a more mature age, with respect to life cycle costs? One way of answering this question is to carry out a life cycle cost comparison study between one of the four LNG vessels and a comparable conventional ferry of a previous generation. It is important that the conventional vessel has similar operational abilities. Such a study may give valuable information about the benefits and potential pitfalls related to the acquisition and the operation of an LNG ferry with respect to LCC. It may also provide knowledge about older vessels' competitiveness in form of life cycle costs.

As already mentioned, there are several obvious differences between a conventional vessel of mature age and a newly built LNG vessel when it comes to capital costs, NOx emissions etc. But how is the big picture with respect to life cycle costs if we include cost elements such as: Maintenance costs, downtime cost, scrapping income, lube oil, insurances and especially fuel costs? And are there any potential measures that may be implemented and reduce the life cycle cost of the newly built LNG vessel?

The objective of this study is to determine, discuss and compare the total life cycle cost of the LNG vessel and a comparable conventional vessel. This involves:

- Derivation of a cost breakdown structure
- Study of the significant cost elements
- Sensitivity analysis

In addition, the study also includes an analysis of a potential measure that may reduce the LNG vessel's life cycle costs. This analysis shall determine:

- The measure's potential when it comes to reductions of life cycle costs
- The approximate investment cost

Any limitations associated with the measure are to be identified.

## 1.3 Scope of thesis

This study emphasises two specific vessels, respectively M/F Lødingen and M/F Tysfjord. M/F Lødingen is, as already mentioned, a newly built LNG vessel which operates the ferry service Lødingen – Bognes. The ferry M/F Tysfjord is selected as a reference vessel for this study. M/F Tysfjord is a 21 year old conventional ferry. The vessels are also referred to as “the LNG vessel” and “the conventional vessel”.

The ferry service Lødingen-Bognes, which the LNG vessel currently is operating, is applied as basis for the vessels’ operation in this study.

## 1.4 The vessels

### 1.4.1 M/F Lødingen

M/F Lødingen is a Norwegian registered ro-ro vessel operated and owned by Torghatten Nord. The vessel was built at Gdanska Stoczina Remontowa S.A. in Poland and delivered to the ship owners in January 2013. It was the last of four ships of the same series. Ship design and engineering were carried out by the Bergen located ship consultant agency LMG Marin (Halvorsen, 2013).

**Figure 1-2 M/F Lødingen Photo: Rita M Pedersen**

***Main dimensions:***

**Table 1-1 Overview of M/F Lødingen's main dimensions. Based on data from Halvorsen (2013), Torghatten Nord (2013a)**

| | |
|---|---|
| Length overall | 93,00 m |
| Length between perpendiculars | 91,39 m |
| Maximal breadth | 16,80 m |
| Draft | 5,70 m |
| Passenger car units | 120 |
| Trailers | 12 |
| Passenger capacity | 390 |
| Gross tonnage | 5695 t |
| Service area | EU-B |
| Max speed | 16 knots |

***Design***

The vessel is of what's often spoken of as a traditional Norwegian fjord ferry design. It basically means that the wheelhouse is placed in the forward region and that the vessel has a defined sailing direction. M/F Lødingen has only one mechanically connected propeller for main propulsion located in the aft region. There are also additional thrusters mounted in the bow and in the aft region to increase the vessels manoeuvring capabilities. Vehicles are transported on two separate car decks, while the passengers are accommodated at a separate passenger deck. The crew accommodation is located at a separate deck above the passenger deck. See references for a more detailed description of the ferry design (Nikolaisen, 2013).

***Machinery***

The vessel is equipped with one LNG fuelled Rolls-Royce C26:33 L9 lean burn main engine. The engine has a maximal power of 2430 kW, while the MTU auxiliary engine (standby generator) delivers a maximum of 920 kW to the vessel's electricity grid. The vessel has installed a shaft generator/motor which enables diesel electric propulsion. It gives the vessel flexibility with respect to power consumption and power production. However, the shaft generator has only a capacity of 800 kW, while the thrusters requires in total 1000 kW at maximum load. This means that the standby generator has to supply the grid with additional power when both thrusters are made use of to avoid the possibility of overload (Global Maritime, 2013). This issue is also discussed in section 2.1.6.

### 1.4.2 M/F Tysfjord

The vessel was built at Myklebust Mekaniske Verksted in Møre og Romsdal in 1993 on behalf of the shipping company Ofoten og Vesterålens Dampskipselskap (OVDS). M/F Tysfjord was tailored for the ferry service Lødignen – Bognes, and was put into service as the main ferry. In 1993, it was one of the three biggest car ferries in North Norway. The vessel operated the ferry service until the end of 2012, only interrupted by maintenance operations (Wikipedia, 2014, SP Database, 2014). Torghatten Nord has included the vessel in their future plans and recently won the tender competition for a ferry service between Lofoten and Vesterålen with this vessel. The vessel is therefore contracted until the turn of the year 2022-2023 (Sørensen, 2014, Sletteng, 2014)

**Figure 1-3 M/F Tysfjord Photo: Uwe Jacob**

***Main dimensions:***

**Table 1-2 Overview of M/F Tysfjord's main dimensions. Based on data from SP Database (2014), Torghatten Nord (2013a)**

| | |
|---|---|
| Length overall | 84,00 m |
| Length between perpendiculars | 70,8 m |
| Maximal breadth | 16,80 m |
| Draught | 4,5 m |
| Passenger car units | ca. 100 |
| Trailers | 9 |
| Passenger capacity | 399 |
| Gross tonnage | 3695 tons |
| Service area | EU-C |
| Max speed | 16 knots |

### ***Design***

The ferry is of what's often referred to as a "double ended" design. It basically means that the vessel has approximately the same shape in both ends and is fitted with at least one propeller in each end. Hence, M/F Tysfjord is able to operate in both directions with the same manoeuvring capabilities. This eliminates the need of turning the vessel around before/after it enters the quay. This reduction of turning operations brings down the crossing time and eases the manoeuvring operations. Double ended designs are often applied to vessels that operate ferry services with relatively short crossing distances.

Vehicles are loaded at two separate car decks. One main deck and one deck which is hanging above the main car deck (supported in the deck above). This deck can be folded when it's not needed or if extra trailer capacity is required. The vessel's car deck arrangement reduces the total height of the vessel, since the secondary car deck is located in the same space as the main car deck.

### ***Machinery***

Propulsion power is obtained by one Bergen BRM-6 engine, which produces a maximum of 2650 kW, while one Scania auxiliary engine of 253 kW produces the vessel's electrical power (SP Database, 2014). The main engine is a conventional six cylinder medium speed engine. The vessel's two propellers are directly connected to the main engine by mechanical gear connections. One benefit with this design is that it has proven to be reliable and require little maintenance (Hartviksen, 2014). M/F Tysfjord is therefore known to be a reliable and cost efficient vessel.

## 1.5 The ferry service

The shipping company Torghatten Nord is contracted to operate the ferry service Lødingen – Bognes from the beginning of 2013 to the end of 2022. As earlier mentioned, M/F Lødingen is designed and intended to operate this ferry service for the contracts entire duration. The ferry service therefore constitutes the basis for this analysis.

**Figure 1-4 Map of the ferry service Lødingen-Bognes (Statens Vegvesen, 2009)**

The distance between the ferry quays in Lødingen and Bognes is measured to be 23 300 m and the trip takes about 60-70 minutes. The crossing is according to the Norwegian Maritime Authority's regulation defined as category C service area (Statens Vegvesen, 2009). The service area dictates among other the vessel's stability requirements, which are important for the vessel's design (Lovdata, 1992).

The ferry service is one of the busiest ferry services in Northern Norway and transports nearly 200 000 vehicles a year. During the normal seasonal, M/F Lødingen and the sister ship M/F Barøy operates the ferry service. An additional ferry with a capacity of approximately 100 cars is added during the summer months. The vessels carry out in total 12 trips a day in the normal seasonal. The trips are not equally spread between the vessels (Statens Vegvesen, 2009).

There are numerous requirements for the vessels in the tender specification regarding for example: environmental friendliness, universal design etc. It is also specified that if a trip is cancelled due to reasons which the shipping company are accountable for, a fee equal to the price of an additional trip is issued the shipping company.

It is specified in the tender specification that a reserve vessel has to be in place in maximum 12 hours (Statens Vegvesen, 2009). M/F Hamarøy serves today as a reserve vessel for this ferry service and is located in Lødingen where it is laid up as long as no trouble with the two other vessels occur.

## 1.6 Requirements for a comparison study between two car ferries

To be able to compare the LCC performance of two car ferries in accordance with the objective of this study, some key parameters of the vessels have to be shared. For this study, one important aspect is that the vessels must be able to roughly carry out the same job in the same service area as the chosen ferry service. This means that the following key parameters have to be shared:

- *Car carrying capacity*
  The vessels' main dimensions are to a large degree dependent on the needed car carrying capacity. The main car deck's length and width is a major constrain in this respect. This is important due to the fact that the main dimensions impact major cost drivers as among other fuel consumption, propulsion system design and manning levels. The reference vessel must therefore have approximately the same capacity.

- *Service area*
  The service area a vessel is supposed to operate in affects many factors such as: stability requirements, manning levels, manning certificates and diverse arrangement details. Stability requirements affect among other the vessels' main dimensions, and therefore the hull design. This means that the service area indirectly impacts the fuel consumption of the vessel.

- *Service speed*
  A hull is as a general rule optimized for at least one design speed, which basically means that a vessel is designed for a specific speed to obtain an optimal fuel consumption. It is therefore important that the vessel has approximately the same service speed, which for M/F Lødingen is about 14 knots.

## 1.7 LCC study boundaries

### 1.7.1. Scope of analysis

The term scope is in this context equal to “aspects” (Kawauchi and Rausand, 1999).

***Procurement***

The study takes basis in that both vessels have to be procured from respectively the newbuilding market and the second-hand market, and to be operated by the shipping company. However, the shipping company’s existing experience with the vessels is not neglected.

***Cost elements***

This study emphasises primarily vessel generated costs such as fuel, maintenance, downtime etc. Capital costs along with insurance costs and income from disposal are also included. However, cost elements as for example port fees, cost of waste handling, management costs etc. are not included. The reason for this is that they are assessed to be nearly independent of the vessel. Hence they are of little interest for this study. Manning costs are only briefly discussed to be able to obtain the bigger picture of operational costs.

***Time span***

The LNG vessel was designed for a minimum service life of 30 years (Sletteng, 2014). It is therefore natural to choose 30 years as the time span for this study. The same assumptions are applied to the analysis of the conventional vessel, which then will be 51 years old at the end of the time period. However, a source claims that there is no reason for removing a vessel only due to its age, as long as the vessel carries out its function satisfyingly (Oslo Economics, 2012).

### 1.7.2. Limits and constraints

As mentioned in the background, M/F Lødingen was built as a result of Torghatten Nord winning the tender competition for the three ferry services across the Vestfjord. Based on section 1.5, the tender specification introduces several issues regarding the LCC study. The conventional ferry is not able to operate the ferry service due to among other: MGO driven main engine, age, universal design etc. Hence, it is important to emphasise that this study doesn’t focus on finding the optimal vessel for this ferry service, but rather elucidate the LNG vessel’s cost effectiveness.

***Reserve capacity and downtime***

The two vessels that are operating the ferry service is, as already described, backed up by one reserve vessel which is standby in Lødingen. Occasional downtime on the vessels will therefore be compensated by the reserve vessel to avoid cancellations. This is an issue in relationship to the estimation of the vessel’s downtime costs. The purpose of this study is, as stated in the objective section, to evaluate the performance of M/F Lødingen in a life cycle cost perspective and compare it with the conventional vessel. Hence, to assess the cost of operating the reserve vessel is beyond the scope of this study. Therefore, this study takes basis in the charges issued for cancelled trips, which is specified in the tender specifications, and thereby eliminates the reserve vessel from the study. By this simplification, it is also avoided that the vessels performance with respect to downtime is camouflaged by the reserve capacity.

# 2. LIFE CYCLE COST COMPARISON STUDY

## 2.1 Discussion of vessel design differences

### 2.1.1 Selection of reference vessel

As already mentioned, M/F Tysfjord is selected as a reference vessel. The vessel is assessed to be the closest match to M/F Lødingen of all ferries within the company. Since the vessel operated the same ferry service for twenty years, a large amount of data is available. This eases the calculation of cost elements. Another handy factor is that the vessel produced about the same amount of operational hours a year at the ferry service as M/F Lødingen is intended to carry out today. This enables utilization of the shipping company's financial statements for the conventional vessel to among other determine maintenance costs. The ferry also meets the derived requirements for service speed and service area (Hartviksen, 2014).

### 2.1.2 Propulsion power and load differences

As already described, the vessels are of two different designs. A single ended ferry design tends to give a more full-bodied vessel in the aft region and thereby a larger deadweight (loading capacity) than a double ended ferry. This means that the block coefficient given in equation ( 2.1 ) is larger for a single ended ferry (Kubarev, 2014). The block coefficient describes how full-bodied a vessel is based on the given parameters.

$$C_b = \frac{\nabla}{(L * B * T)} \tag{2.1}$$

$\nabla = displacement$
$L = length\ of\ vessel$
$B = breadth$
$T = draught$

Increased $C_b$ tends to increase the power demand as shown in figure 2-1. Each series are representing a $C_b$ where $VS_1$ is smallest. The diagram is based on the Harvald power prediction method (Molland, 2008). Therefore, a single ended ferry design may in general demand more power for propulsion than a double ended ferry with the same main dimensions, but benefits on a higher deadweight tonnage (Kubarev, 2014).

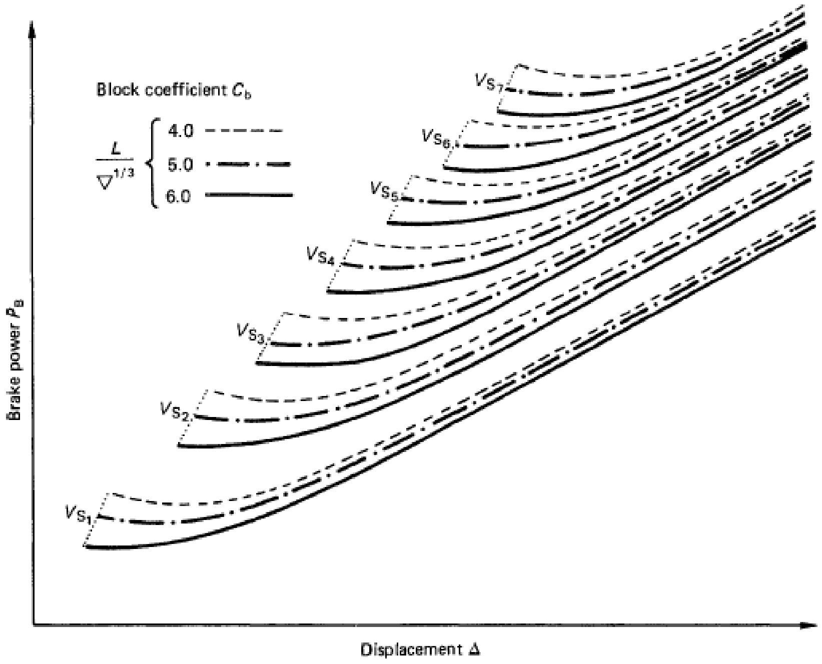

**Figure 2-1 Illustration of the effect of increasing Cb (Molland, 2008)**

### 2.1.3 Correction of vessel length

The major drawback with M/F Tysfjord as a reference vessel is that the vessel doesn't have the same car carrying capacity as M/F Lødingen. The difference is about 20 cars, which means that M/F Tysfjord has only 83 % of the capacity. As already described, the car carrying capacity is important with respect to the vessels main dimensions, which further on is decisive with respect to among other fuel consumption. To improve the quality of the reference cost, a simplified imaginary lengthening of the vessel is carried out. Issues such as stability and safety are not considered. It is important to emphasise that the only purpose of this correction is to obtain more realistic reference costs, and not to carry out a feasibility study of a vessel reconstruction.

M/F Tysfjord has to be lengthened about 18.5 meters to be able to carry 120 cars. The liftable car deck is not considered in the lengthening. Such car decks are standard modules. Further investigations, which are beyond the scope of this study, are therefore needed to reveal whether it is possible to install a lengthened version of the car deck (Bergvoll, 2014).

Generally, a vessel's demand for power to be propelled in a certain speed is decided by the hulls wave-making component $R_w$ and $R_f$, which accounts for the hull and superstructure's frictional resistance (Molland, 2008). The vessel is in this case intended to be lengthened with an 18.5 m section in the mid ship region. This means that the hull shape will remain the same after the lengthening. A source explains that such a lengthening may, based on experience, increase the vessels hull resistance by 5-7 % at a service speed of 14 knots. This is based on the expected increase of the vessel's submerged area, which contributes to an increased frictional resistance. The other component, $R_w$, is very difficult to estimate and is normally found by use of model testing. However, a lengthening will in many cases improve the vessel's performance with respect to wave resistance due to changes in the wave patterns. The wave patterns created by a hull which is moving forward are illustrated in figure 2-2. Accordingly, an improvement means that the wave patterns are cancelling each other and thereby reduces the hull's wave resistance. In some cases, this effect actually causes the vessel's total resistance to be reduced after a lengthening. An increase of resistance by 5-7 % is therefore considered to be conservative. It is nevertheless important to emphasise that this is an estimate based on experience and not detailed calculations or modelling. Hence, there is significant uncertainty related to the estimate (Kubarev, 2014).

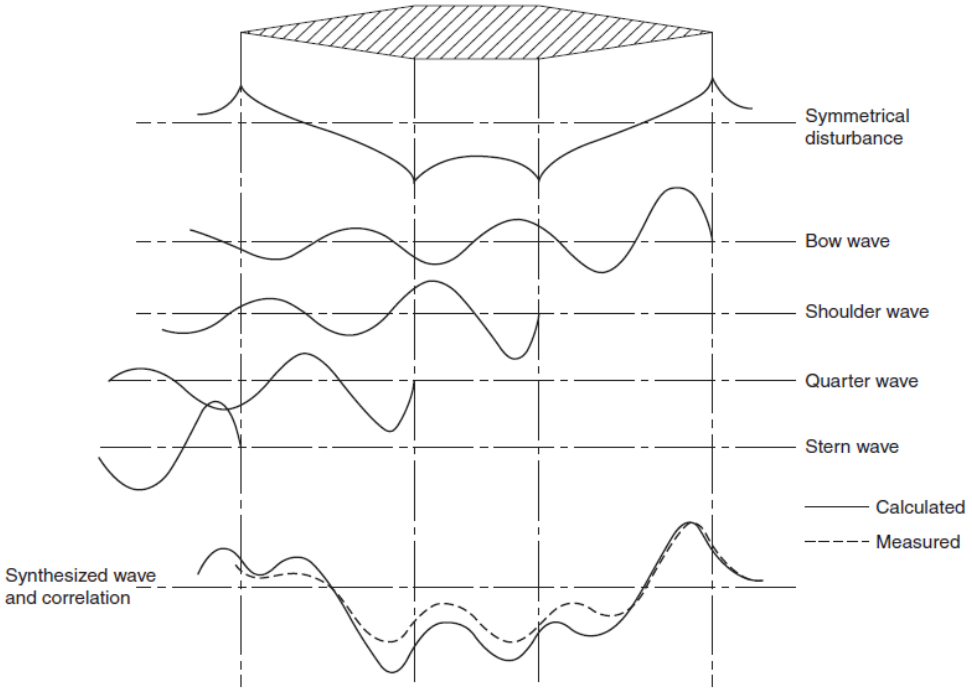

**Figure 2-2 Typical wave patterns (Molland, 2008)**

### 2.1.4 Port manoeuvring

The main principle behind a double ended ferry is that it is able to on- and off-load vehicles in both ends and doesn't have a defined sailing direction. As already explained, the demand for turning operations in port is eliminated. A double ended car ferry can therefore sail at a lower cruising speed and still be within the timetable compared to a single ended ferry as the LNG vessel.

### 2.1.5 Stability requirements

After the tragic capsizing of M/S Estonia in 1994, the IMO had to take action to avoid similar catastrophes to occur in the future. They gathered a panel of experts to make suitable recommendations. The result was the Stockholm Agreement, which is available as IMO Circular letter

No.1891 (29 April 1996) (Vassalos and Papanikolaou, 2002, Johnsen, 2014). The Stockholm Agreement has subsequently been extended to all ro-ro passenger ships operating to or from a port of a member state of the European Union on a regular service. This is regardless of their flag engaged in international voyages in accordance to the Directive 2003/25/EC of the European Parliament (Bureau Veritas, 2007). The convention requires that all ro-ro car ferries are to be able to handle a certain amount of water on the car deck at specific damage stability scenarios. One design measure, which is a direct result of the agreement, is to design car decks with increased elevation from sea level to limit the probability of water on deck (Schreiber, 2006). However, the modern damage stability regulations are complex. It is therefore difficult to assess the effect of these new regulations with the respect to the vessel's main dimensions and design. It depends highly on the ship designers trade-offs and priorities during the design phase. M/F Tysfjord is nevertheless built before the Estonia accident and is therefore not in accordance with today's damage stability regime. If the vessel shall comply with the new regulations within the same main dimensions and design draught, altering the internal watertight subdivision as well as increasing the reserve buoyancy on car deck will likely be required. This will increase the vessel's damage stability capabilities. Installation of additional watertight subdivisions will in general increase the vessel's lightweight at the cost of its deadweight. The design has therefore a higher load (weight) capacity than it would have had if it was built today, but the extent of this is hard to quantify without extensive damage stability and weight calculations (Johnsen, 2014).

### 2.1.6 Propulsion system

There are significant differences between the vessels' propulsion systems. A discussion of the differences is given in the following sections.

#### Gas vessel

***Loading and storage of LNG***

A vessel which is fuelled by LNG needs a bunkering station and a dedicated LNG tank(s). The bunkering station provides a connection to the onshore terminal during bunkering operations. It typically consists of three different lines. These are one bunkering line (LNG line), one return line and one nitrogen purging line. The nitrogen purging line is designed as a safety measure in case of a pressure build up in the system, while the return line transports any evaporated gas, due to for example heat leakages, back to the onshore facility (Sören Karlsson, 2010).

A LNG storage tank is usually cylindrically shaped with dished ends, and it serves as a pressure vessel. This type of tank is installed in M/F Lødingen. The benefit of this type of tank (pressure vessels) is that it can allow pressure increase, a simple fuel system, requires little maintenance and is easy to install. On the other hand, this type of tank has a higher space demand than other tank types (Sören Karlsson, 2010). There are also requirements which specify where the tank can be located in the vessel to reduce the risk of structural damage in case of an accident (Det Norske Veritas, 2013).

It is also necessary to have a facility that keeps the tank pressure at a level which prevents unintended evaporation of LNG and ensures a sufficient gas supply to the consumers. This facility is often referred to as “the cold box” and consists basically of a set of heat exchangers, lines and valves, which provides the mentioned functions (Sören Karlsson, 2010). The tank pressure is then kept constant at 6.5 bars regardless of the fuel level (Global Maritime, 2013).

### *Flow control*

The gas ramp is a module that ensures that gas is delivered at a correct pressure to the consumers (Global Maritime, 2013). It consists of valves, filters, manometers and a pressure safety device. The module is to be located in an allocated space separated from the rest of the machinery room (Det Norske Veritas, 2013).

### *Machinery arrangement*

To achieve the DNV class notation GAS FULLED, it’s required that the gas system shall be arranged in such a way that there is sufficient power to maintain propulsion and other main functions after the loss of one engine room. This means that if a failure with the gas system occurs, the engine room which the fail is detected in is to be shut down. It’s then required that it is sufficient power left to maintain propulsion and other main functions  in case of a shutdown of the gas system (Det Norske Veritas, 2013).

There are many ways of solving this issue. On M/F Lødingen, this is done by having a genset in backup. Hence, the vessel has a so-called hybrid system, which enables both conventional mechanical operations, diesel electric operations and a combination (hybrid). Torque may be transferred to the propeller shaft by use of a shaft generator/motor, which basically transfers electrical energy to mechanical energy.

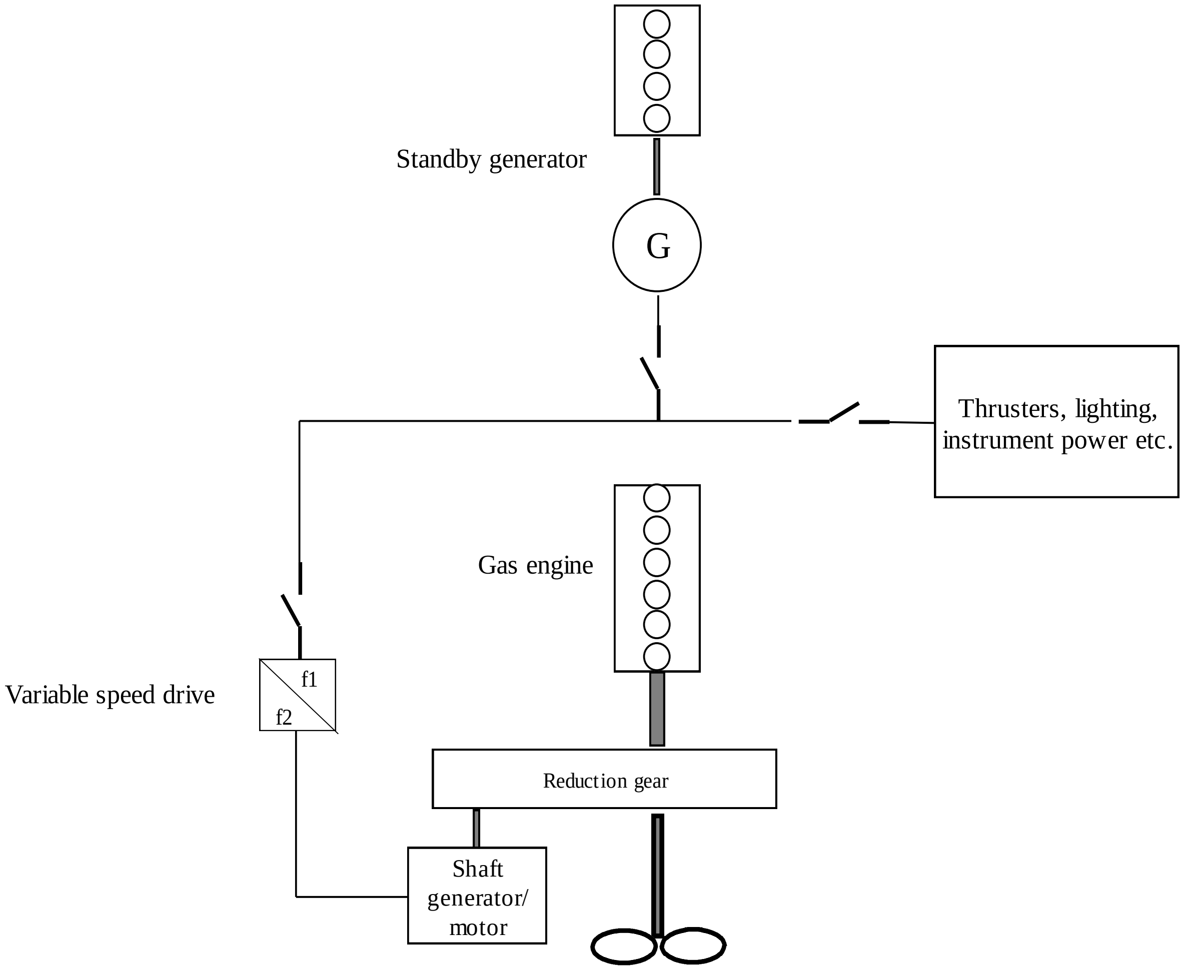

**Figure 2-3 Illustration of the hybrid system**

A hybrid system is quite different from a directly connected mechanical system, with additional components that increases the complexity of the system. In a diesel electric system, mechanical energy from the prime mover (diesel engine) is transformed to an AC 60 Hz current (electrical energy) in the generator. To control the speed of the propeller, a variable speed drive is transferring the 60 Hz current to a frequency that gives the desired propeller speed. The shaft generator is then functioning as a motor that provides power to the reduction gear at the specified speed. Vice versa, the shaft generator may be used to produce electricity to the vessel's electricity grid. To incorporate all these components increases the losses in the system (Ådnanes, 2003). However, the system's total efficiency is heavily dependent on the main engine's and the standby generator's loading conditions. This type of system is therefore often claimed to have an improved overall efficiency compared to a conventional system due to its flexibility (Rolls Royce, 2014a). This issue is discussed further in chapter 6.

The standby generator has a maximum output of 920 kW, which is sufficient to maintain propulsion and other main functions in case of a shutdown of the main engine. It is also used to provide additional power to the system in manoeuvring situations. As mentioned in section 1.4.1, this is because the shaft generator isn't able to carry the full load from the thrusters. It is important to notice that the vessel is not able to be in service by use of the genset alone. It is designed to function only as an auxiliary engine due to its limited power output (Sletteng, 2014, Global Maritime, 2013).

### Conventional vessel

As already mentioned, M/F Tysfjord is fitted with a conventional BRM-6 medium speed engine. It is connected to each of the propeller shafts by use of two clutch gears. The vessel is equipped with reversible propellers. The main engine is therefore constantly running at 750 rpms while the torque is adjusted by the propeller blades. M/F Tysfjord's propulsion system is therefore significantly simpler and involves only a fraction of the components compared to the gas vessel's hybrid system. Electricity is provided by a small auxiliary engine (Hartviksen, 2014, Ulstein Bergen Diesel, 1991).

## 2.2. Methodology

### 2.2.1 History of LCC

The term life cycle costs, or LCC, can simply be explained as the sum of costs during an item's life span. It was first used in a report in 1965, which was made by the Logistics Management Institute, Washington D.C, for the U.S Department of Defence. The development of life cycle cost analyses was encouraged by experience which indicated that the major portion of an item's ownership cost was related to the operational costs, and not the acquisition costs. Studies revealed that these costs could be 10 to 100 times the original acquisition cost. LCC calculations have been widely used since the 1970's (Dhillon, 2010).

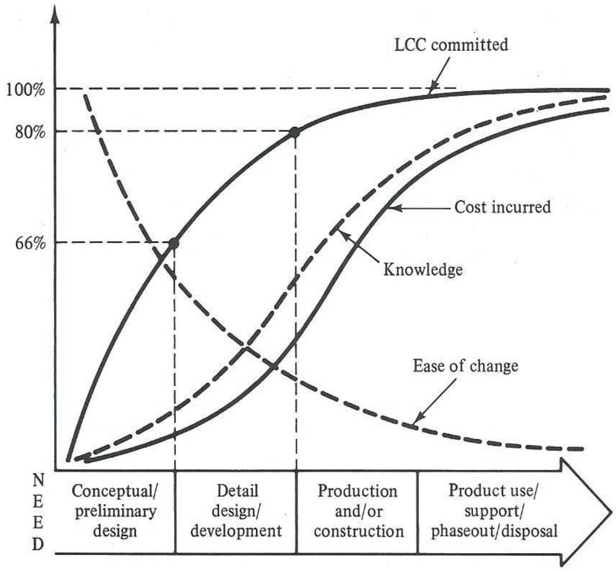

**Figure 2-4 Illustration of the LCC's degree of commitment through the life cycle (Fabrycky and Blanchard, 1991)**

### 2.2.2 Area of application

Large portions of a systems life cycle costs are constrained during the design phase, while the dominating part of costs are generated during the operational phase. Figure 2-4 and figure 2-5 indicates the importance of considering life cycle costs at an early stage in a project. LCC analyses provide the design team with cost estimates for all aspects of the life span, and not only the acquisition costs (Fabrycky and Blanchard, 1991).

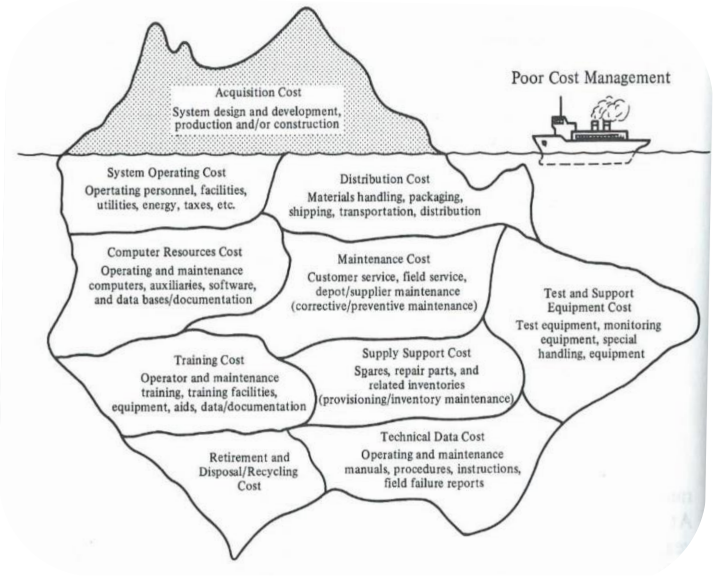

**Figure 2-5 Illustration of the relationship between capital- and operational expenditures (Fabrycky and Blanchard, 1991)**

Other applications for life cycle cost analysis are (Dhillon, 2010):

1. Long-range planning and budgeting
2. Controlling an ongoing project
3. Comparing competing projects
4. Deciding the replacement of aging equipment
5. Comparing logistics concepts.

The method is in this study applied as a tool for evaluation of two already existing vessels' performance. However, most of the life cycle costs for these vessels are already constrained in their design and equipment, as shown in figure 2-4.

### 2.2.3 The LCC process

Since 1965, several procedures have been proposed for LCC analyses. The differences between the procedures are to some degree a result of the large variation of systems which are analysed. However, studies have revealed that there is a common process that seems to be essential in the proposed procedures. This process is illustrated in figure 2-6.

The LCC process consists of six basic processes (Kawauchi and Rausand, 1999):

1. Problem definition
2. Cost elements
3. System modelling
4. Data collection
5. Cost profile development
6. Evaluation

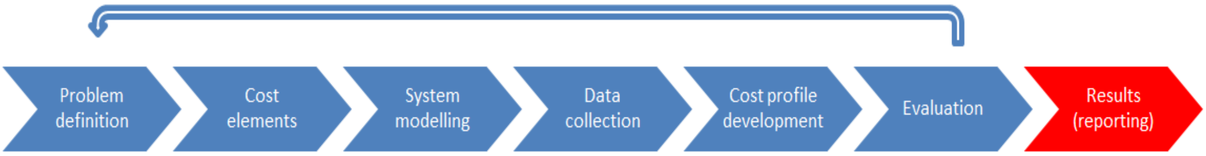

**Figure 2-6 The LCC process (Kawauchi and Rausand, 1999)**

For a more thorough study of the LCC process and the different estimation approaches, see references (Nikolaisen, 2013).

### 2.2.4 Net present value

An important principal in most life cycle cost calculations is the net present value. Net present value (NPV) is the today value of a single or an annual payment done today or someday in the future.

The value of money is often claimed to be time dependent. The background for this is that a company can earn interest on their money. Cash paid sometime in the future are therefore worth less than if the same amount had been paid today (Stopford, 2009).

Discounting of cashflows convert future payments or expenditures into a “present value”. An important step of this calculation is to determine the discounting rate. There are mainly two factors influencing the discount rate, the companies’ interest rate and the inflation rate (Stopford, 2009, Brealey et al., 2014).

The interest rate expresses the expected rate of return in a comparable investment. It may also be risk adjusted (Sending, 2009). There are many ways to determine an interest rate, but a common way is to use the average return rate on capital returned from investments in other parts of the company’s business (Stopford, 2009).

Inflation is an expression for the increase in prices over time. The main reason for this is that the total amount of money increases more than the society’s total increase of productivity. The inflation is on national basis measured by the consumer price index, which is a percentage measure of the yearly increase of consumable commodities’ prices (Store Norske Leksikon, 2011). The Norwegian central bank, Norges Bank, states that Norway has a long term inflation target of yearly inflation of 2.5 % (Norges Bank, 2013).

Shipping companies like Torghatten Nord makes use of the cost index for domestic shipping, and not the central banks inflation goal. This cost index measures the advance in prices for domestic shipping, and is therefore used to regulate the shipping company's income in contracts such as for this ferry service. The index takes into account cost elements such as crew costs, maintenance costs, management costs and fuel costs (Statistisk sentralbyrå, 2013, Sletteng, 2014). It therefore forms the basis for the rate of inflation in this study. It is important to emphasise that there is extreme uncertainty related to forecasting of inflation. Another drawback is that fuel costs are incorporated in the estimation of the cost index. Fuel prices are in this study treated as a cost element which requires individual forecasting due to its large variation over time. It's therefore not optimal that the fuel price variations are incorporated in the cost index. The effect on the cost index is nevertheless difficult to assess.

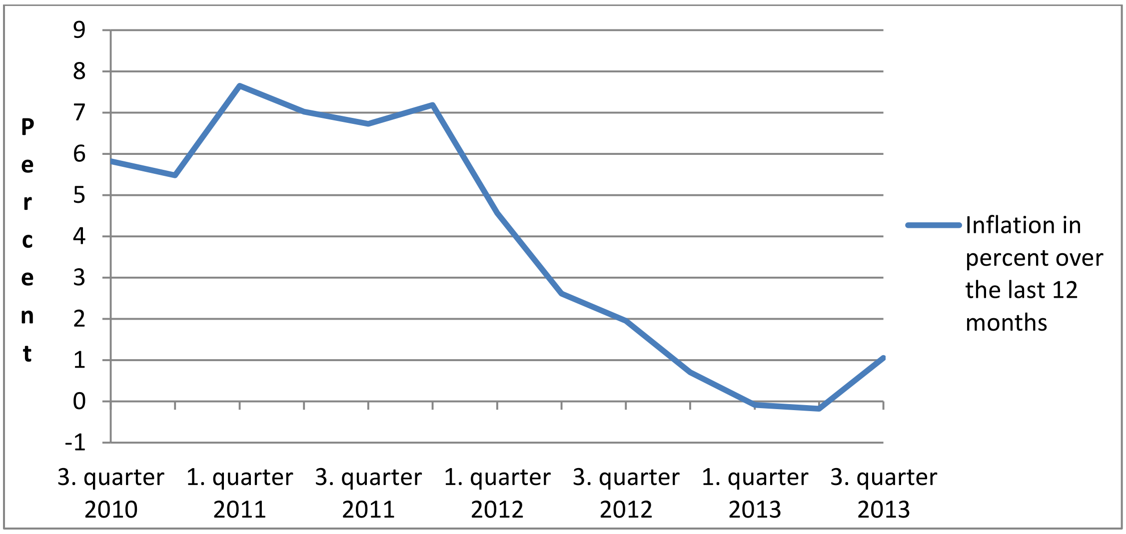

**Figure 2-7 Inflation in percent over the last 12 months. Based on data from Statistisk sentralbyrå (2013)**

Based on figure 2-7, 3 percent average yearly inflation is used as a basis for the study.

It's important to separate between the nominal interest rate and the real interest rate. This study is based on cashflows of 2013 value. A real interest rate is therefore applied. The rate expresses the actual profit on an investment when the numbers are corrected with respect to inflation. Nominal interest rates are not corrected with respect to inflation. The discount rate can then be expressed as given below (Brealey et al., 2014):

$$r_d = \frac{r_{nom\_interest}}{r_{inflation}} \qquad (2.2)$$

Then the net presented value may be calculated according to formula ( 2.3 ). In this study, as a general rule all expenditures are calculated to fall due at the end of the year. This is done to simplify the calculations and is accepted as good enough, even though the cashflow is acquired through the whole period (Sending, 2009).

$$NPV \quad = \quad C * \frac{1}{(1+r_d)^n} \tag{2.3}$$

$$C = future\ cost$$
$$r_d = discount\ rate$$
$$n = number\ of\ years$$

Formula ( 2.3 ) is applied to calculate the NPV of a single cost *C* which occur once at time *n* in the future.

### 2.2.5 Uncertainty

Life cycle cost analysis isn't an exact science. People tend to get different results from their analysis even though they are analysing the same object. Thus, there are no right or wrong answers of a LCC analysis, but rather reasonable or unreasonable. The results can therefore never be more accurate than the inputs (Barringer and Weber, 1996).

To measure the inaccuracy of an analysis is often difficult since the variances obtained by statistical methods are in general large. A model tends to require volumes of data which is often difficult to get hands on in a reasonably timely manner (Barringer and Weber, 1996).

Uncertainty should be analysed in relationship to the input data, the results itself and when the results are compared against each other (International Standard Organization, 2001).

Factors that in general typically contribute to uncertainty are (International Electrotechnical Commission, 2005):

- Political circumstances with respect to among other legislative changes.
- Organizational and economic circumstances.
- Technological factors such as safety and environmental impact.
- Natural events, human behaviour etc.
- Lack of data traceability.

The level of uncertainty which is related to each part of the study is addressed continuously through the report. A sensitivity analysis is also conducted to investigate this uncertainty.

### 2.2.6 Modes of analyses

Life cycle cost analyses can be carried out in several different modes. Examples of such modes are net savings analyses, savings to investment ratio analyses and payback analyses. This study is conducted in a total life cycle cost mode. This means that all the significant costs regarding the vessels are summed up. Salvage values, or residual prices of the vessels at the end of the time span are treated as negative costs (Ruegg, 1987).

### 2.2.7 Exchange rates

It is natural to carry out this LCC study in Norwegian kroner (NOK) since both vessels and the shipping company are Norwegian. However, several expenditures are given in dollars or euros, and must therefore be transferred to NOK. The relationship between the values of the different currencies is continuously changing. It is beyond the scope of this study to thoroughly investigate the mechanisms which influence the different currencies. Therefore, 1 dollar is valued as 6.5 NOK, while 1 euro is valued 8.4 NOK as a simplification. However, it is important to emphasise that this is an assumption which implements extreme uncertainty.

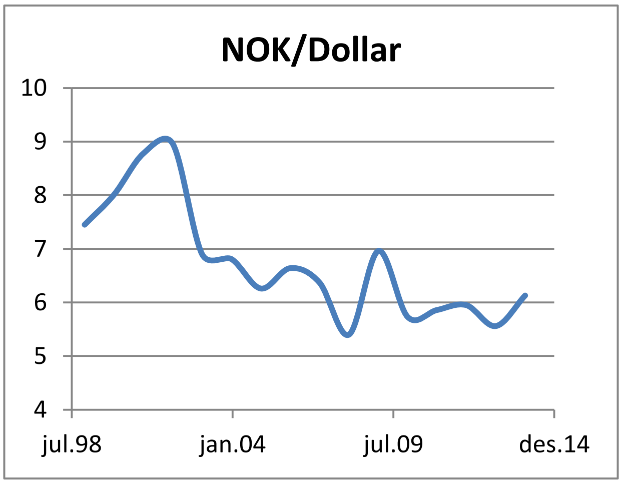

**Figure 2-8 Historical NOK/Dollar exchange rates. Based on data from Norges Bank (2014a)**

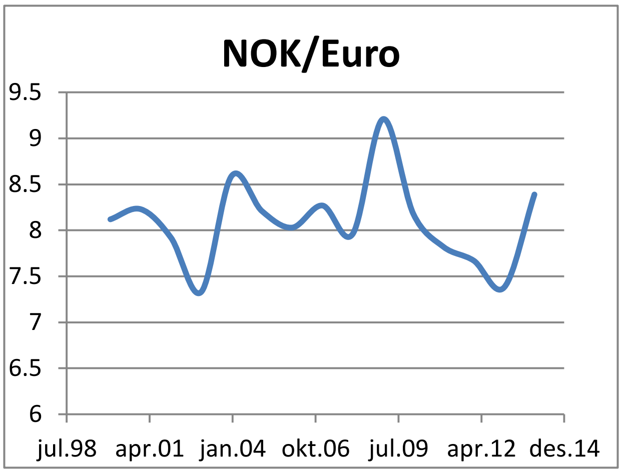

**Figure 2-9 Historical NOK/Euro exchange rates. Based on data from Norges Bank (2014b)**

# 3. SYSTEM MODELLING

In an LCC analysis, it is necessary to establish a model to quantify the net present value of all the cost elements combined. “To make a model means to find the appropriate relations among input parameters and cost elements“ (Kawauchi and Rausand, 1999).

LCC models, like all other models, are simplified descriptions of the real world. A model is intended to capture the most important features and aspects of a product and translate them into cost estimating relationships. A realistic model should capture the following bullet points (International Electrotechnical Commission, 2005, Fabrycky and Blanchard, 1991):

- Represent the characteristics of the product which is studied. This includes environment, maintenance concept, operating and maintenance support scenarios as well as any constraints or limitations.
- Be sufficiently extensive in order to include and pinpoint all the factors that are relevant to the LCC.
- The model should be simple in such a way that it can be easily understood and communicated.
- The design should enable evaluation of specific elements of the life cycle cost model independent from each other.
- Allow easy incorporation of additional elements.
- Describe the system dynamics and be sensitive relative to the relationship between key input parameters.

There is still no general cost model available today, even though LCC analyses have been conducted for decades. Some of the reasons for this are: Varying requirements to system performance and specifications, special system characteristics such as maintainability, availability etc. (Fabrycky and Blanchard, 1991).

## 3.1 Yearly production

It is assumed that the vessels are to be producing 52 weeks a year according to M/F Lødingens timetable. The time needed to carry out preventive maintenance and corrective maintenance is not taken into account. The production is significantly increased during the three summer months and therefore taken into account. Adjustments of the timetable due to holidays are not considered in the calculation, but are nevertheless marginal (Torghatten Nord, 2014f). The vessel produces the majority of trips in the ferry service despite of the fact that the second vessel in the ferry service is the sister ship M/F Barøy. From a technical point of view, it is desirable that the vessels have approximately the same amount of operational hours each year. This would ease among other maintenance assessments. However, the crew are employed at one specific vessel. A transfer of crew between the vessels is considered to create more problem, than the achieved benefits (Sletteng, 2014). It is therefore assumed that M/F Lødingen will continue to produce the same proportion of trips as it is currently doing. This is an important assumption.

**Table 3-1 Assumed yearly production. Based on data from Torghatten Nord (2014f)**

| | Mon-Fri | Saturday | Sunday |
|---|---|---|---|
| **Trips pr. day (one way)** | 14.50 | 11.50 | 13.00 |
| **Trips pr. week (one way)** | 72.50 | 11.50 | 13.00 |
| **Total trips per day (one way)** | 3 770.00 | 598.00 | 676.00 |
| **Sum trips per year (one way)** | **5 044.00** | | |

**Table 3-2 Applied modelling data. Based on data from Torghatten Nord (2014f), Statens Vegvesen (2009)**

| | Value | Denomination |
|---|---|---|
| **Distance per trip (one way)** | 23.30 | km |
| **Distance per year** | 117 525.20 | km |

# 4. COST BREAKDOWN STRUCTURE AND ESTIMATION OF COST ELEMENTS

It is necessary to break down the total LCC into cost elements in order to estimate the total LCC. These cost elements should be identified individually. The detail level and scope of the estimation have to be in accordance with the study's purpose and scope (International Electrotechnical Commission, 2005).

To identify all the cost elements that have significant influence on the total LCC costs is an important task in the analysis. A cost breakdown structure is often used as a basis for the definition of cost elements. There are several ways to design a CBS. Some structures are two dimensional, while others are three dimensional. Since there is no such thing as a universal LCC analysis, the CBS has to be tailored for each application (Kawauchi and Rausand, 1999). See references for a more thorough discussion of different CBS designs (Nikolaisen, 2013).

The cost breakdown structure regarding this thesis is based on a two dimensional concept. This indicates that the cost categories are located at the top level, while the most significant cost elements with respect to LCC are derived below in a structured manner. Each cost element will in many cases also have a substructure. A substructure in this context constitutes all the considerable costs which form a cost element. In the following sections, all the cost elements that significantly influences the total life cycle cost are addressed and the estimation methods are shown.

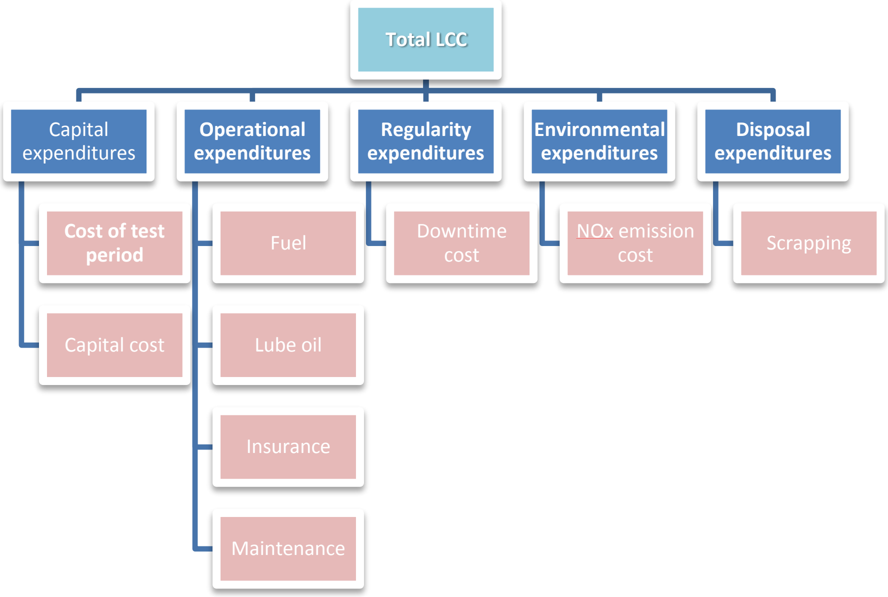

**Figure 4-1 The derived cost breakdown structure for this study.**

## 4.1 Capital expenditures (CAPEX)

CAPEX is defined by a source as “money used to purchase, install and commission a capital asset” (International Standard Organization, 2006). In this context, CAPEX denotes all the significant costs related to the acquisition of a vessel. Both vessels are in this study treated as if they were procured at the turn of the year 2012/2013.

### 4.1.1 Procurement cost: LNG vessel

The acquisition cost of a new complex system as a LNG vessel consists of several sub elements. These costs are on a general basis often divided into sub cost elements as for example product management, product planning, product research, engineering design, design documentation, software and testing, construction and quality control (Fabrycky and Blanchard, 1991). However, the most significant cost elements in this case are identified as costs related to shipbuilding, design and hiring of classification society.

The total building cost of M/F Lødingen are estimated by the shipping company to be 219 263 411 NOK. Design costs and costs related to the classification society are included in this number. They are not specified in detail due to their high level of sensitivity (Torghatten Nord, 2014c). However, the cost elements are discussed qualitatively.

***Shipbuilding costs***

This is the most significant cost element under the CAPEX category. The construction cost includes all the costs which are related to the actual building and outfitting of the vessel as for example: man hours, machinery, steel, sea trials etc. The construction cost is often decided 2-3 years in advance of the delivery. To do this, a detailed specification of the design is needed. A construction cost can then be estimated by the yard based on the specification. Usually fixed price contracts are applied (Stopford, 2009). To have a clear and precise specification is therefore of the utmost importance. In cases where the specification is equivocal, the shipyard tends to find the cheapest solution to gain more profit out of the project. This may result in components and solutions of poor quality, which may reduce the vessel’s capability and increase the operational costs (Heidegård, 2014).

A vessel’s construction cost is, like second-hand prices, dependent on the current supply and demand situation in the market. The demand side is affected by factors related to the shipping company’s income, while key factors for the supply side are production costs and the size of the yard’s order book. A yard with a three year long order book may be reluctant to enter into a new contract due to among other the uncertainty related to inflation, and thereby try to avoid the risk of losing money on a project. On the other hand, if the order book is thin, the yard will significantly reduce its prices to survive. Shipbuilding prices therefore fluctuate similar to second-hand prices (Stopford, 2009).

The shipping company’s shipbuilding cost is therefore highly dependent on the state which the market was in at the time the contract was negotiated. Polish shipbuilders have traditionally taken advantage of their relatively low labour cost and therefore produced hulls and other ship sections for western European builders. However, in recent years Gdansk Stoczina Remontowa shipyard has moved on to concentrate on building fully outfitted vessels (Drewry, 2009).

A source explains that shipbuilding prices rose constantly from the start of the millennium and until 2008, where they peaked and started to decline due to the global financial crisis (Drewry, 2009). The shipbuilding prices had been declining for almost two years at the time when the contract between the shipping company and the yard was settled. Therefore, the shipbuilding cost may be lower in real terms than what it probably would have been if the contract had been negotiated in 2008 when the shipbuilding prices peaked (Drewry, 2010).

### *Design costs*

Often when a shipping company plans to build a new vessel, a ship consultancy agency is hired. The agency’s main objective is to design a vessel tailored after the shipping company’s requirements and in accordance with the prevailing regulation.

When the ship consultancy agency and the shipping company agree on a design, the necessary documentation is handed over to the yards. Information such as technical drawings, hydrodynamic analysis, stability analysis, fuel consumption etc. is at this point provided by the ship consultancy agency and is available for the shipping company.

The cost of hiring a consultancy agency depends of several factors. The market situation is, as in most other industries, important since increasing competition tends to push prices when the demand is low. In the recent years, it has been more common that ship consultancy agencies establish departments in low cost countries. There are two main reasons for this. The increasing demand for Norwegian engineers in the offshore industry has made it harder to get qualified personnel to carry out advanced analyses such as for example finite element analyses. The other reason is of course that the cost of man hours is lower in low cost countries. Time consuming tasks may therefore be carried out to a much lower cost in low cost countries. Ship consultancy agencies which have such departments may therefore be able to offer more competitive prices on their designs. The design cost may typically account for 7 – 15 % of the total shipbuilding costs (Karlsen, 2014). However, it is beyond the scope of this study to thoroughly investigate the prices of ship designs.

### *Classification society costs*

The classifications societies verifies that the technical documentation (technical drawings, analyses etc.) are in accordance with the class notation’s requirements. They also physically inspect both during and after production and verify that the ship is built in accordance with the class approved documentation. The class society is formally working on behalf of the yard. However, they are in reality in a position in between the yard and the shipping company. It is the shipping company which formally selects the classification society (Hagen, 2014). The classification society costs are relatively small compared to the shipbuilding cost.

***Cost of test period***

Before the vessel can be put into service, the crew has to familiarise themselves with the vessel and its equipment. The test period therefore generate several costs, which have to be taken into account. These are mainly related to the fuel that is consumed during the test period and the labour costs. Extra costs related to the operation of the vessel during the test period, such as NOx tax and lube oil, are considered to be minimal and are therefore neglected. In addition, the crew has to undergo a course related to the safety aspects of LNG as a fuel and the risks associated with it. The costs are specified in table 4-1:

**Table 4-1 Cost of test period. Based on data from Torghatten Nord (2014c)**

| Cost | Value | Denomination |
|---|---|---|
| LNG fuel | 348 267 | NOK |
| MGO fuel | 32 856 | NOK |
| Labour | 1 345 000 | NOK |
| Coursing | 97 000 | NOK |
| **Total** | **1 823 123** | **NOK** |

### 4.1.2 Second-hand cost: Conventional vessel

As already mentioned, the conventional vessel is to be treated as if the shipping company has to procure the vessel second-hand in the turn of the year 2012-2013. The second-hand market thrives on price volatility. Prices of second-hand vessels therefore tend to go in cycles which are related to the global economy (Stopford, 2009). However, the market for twenty year old vessels like M/F Tysfjord is relatively small. In periods where there are several similar vessels available in the market, prices tend to drop significantly due to the limited demand. It is therefore very difficult to assess the second-hand price of M/F Tysfjord (Sletteng, 2014).

A source explains that it is fair to assume a second-hand value of 25 000 000 NOK after the imaginary lengthening is taken into account. This is close to the estimated value of the vessel in relation to the tender competition (Torghatten Nord, 2009, Sletteng, 2014). It is nevertheless important to emphasise that this is an estimate which implements significant uncertainty. In periods when the demand is high, the price may be significantly higher and vice versa.

### 4.1.3 Capital costs

Most newly built vessels are financed by use of bank loans. This means that the ship owners have to pay back the loan with interest within a certain time span. The same often goes for second-hand vessels (Stopford, 2009). As mentioned in the introduction, capital cost is a significant disadvantage for new buildings compared to older vessels which are already depreciated.

The procurement cost of the LNG vessel (except the cost of the test period) and the conventional vessel is both assumed to be paid by loaned capital. This calculation of interest costs are based on the shipping company's estimation model for financing of the LNG vessels. There may nevertheless be numerous other ways of financing large investments or constructing a repayment plan.

It is assumed that the shipping company has to raise 20 % of the total needed capital by its own funds as an own risk. Repayments are carried out twice a year and is in the order of 4 000 000 million NOK. The bank interest rate are set to be 5 % (Torghatten Nord, 2009).

Since the conventional vessel costs only a fraction of the LNG vessel, it would probably be possible to repay the loan over a longer period and thereby reduce the yearly repayments. However, in this study it is assumed that the same repayments apply independent of the vessels' value. The repayments schemes for each vessel are given in table 4-2.

**Table 4-2 Interest costs. Based on data from Torghatten Nord (2009)**

| Year | Sum interest LNG vessel | Sum interest Con. vessel |
|---|---|---|
| 1 | 8 670 536 | 900 000 |
| 2 | 8 270 536 | 500 000 |
| 3 | 7 870 536 | 100 000 |
| 4 | 7 470 536 | |
| 5 | 7 070 536 | |
| 6 | 6 670 536 | |
| 7 | 6 270 536 | |
| 8 | 5 870 536 | |
| 9 | 5 470 536 | |
| 10 | 5 070 536 | |
| 11 | 4 670 536 | |
| 12 | 4 270 536 | |
| 13 | 3 870 536 | |
| 14 | 3 470 536 | |
| 15 | 3 070 536 | |
| 16 | 2 670 536 | |
| 17 | 2 270 536 | |
| 18 | 1 870 536 | |
| 19 | 1 470 536 | |
| 20 | 1 070 536 | |
| 21 | 670 536 | |
| 22 | 270 536 | |

As shown in table 4-3, there is an extreme difference between the cost of procuring a 20 year old conventional vessel like M/F Tysfjord and a brand new vessel like M/F Lødingen. The table illustrates that the cost related to the banks revenue accounts for almost 100 000 000 million NOK.

**Table 4-3 Nominal capital costs. Based on data from Torghatten Nord (2009)**

| | LNG vessel | Conventional vessel |
|---|---|---|
| **Own risk** | 43 852 682 NOK | 5 000 000 NOK |
| **Instalment and interest cost** | 273 762 530 NOK | 21 500 000 NOK |
| **Total vessel cost** | **317 615 213 NOK** | **26 500 000 NOK** |

It is normal practice to depreciate the vessels over their intended life time. From a financial point of view, the depreciations along with the interest costs constitute the yearly capital costs. Most ships are depreciated linearly over the time span, which in many cases is a good description of how the ships' value is reduced over time (Stopford, 2009). Therefore, it is assumed that the vessels' are depreciated linearly over the time span. This is in accordance with the shipping company's practice (Torghatten Nord, 2009). Hence, the LNG vessel is then written off with 7 308 780 NOK and the conventional vessel with 833 333 NOK on yearly basis.

However, the effect of inflation is not yet taken into consideration. Hence, the values are given in nominal terms. Since the model is based on values in real terms, the values have to be discounted back to real values by use of the equation below:

$$Pr_n\,(2013) = \frac{Pn_n}{(1+i)^n} \tag{4.1}$$

Where $Pr_n$ denotes the real value (2013) of the yearly capital cost (interests and depreciations) in year *n*, $Pn$ the nominal value of the yearly capital cost and *i* the rate of inflation.

There is uncertainty related to the forecasting of future interest rates. This topic is discussed in section 5.4.1.

## 4.2 Operational expenditures (OPEX)

A standard defines OPEX as "money used for operation and maintenance, including associated costs such as logistics and spares" (International Standard Organization, 2006).

### 4.2.1 Fuel costs

Fuel expenditures are an important cost element with respect to the vessels' total life cycle cost. In this section, the estimation of fuel costs is discussed in detail.

***General energy losses in transit***

The demand for energy to push a vessel forward is in general caused by drag and friction, which is mainly gained by the submerged hull in sea water, but also of the superstructure's air resistance (Stopford, 2009).

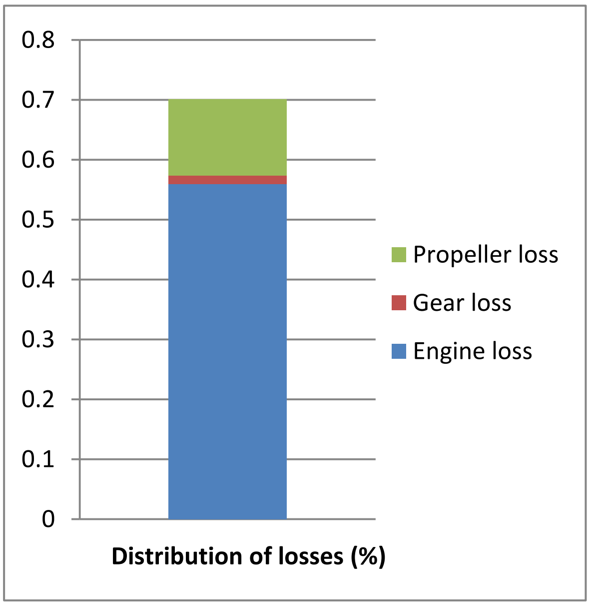

**Figure 4-2 General energy losses. Based on Ulstein Bergen Diesel (1991), Rolls Royce (2014b), Kubarev (2014)**

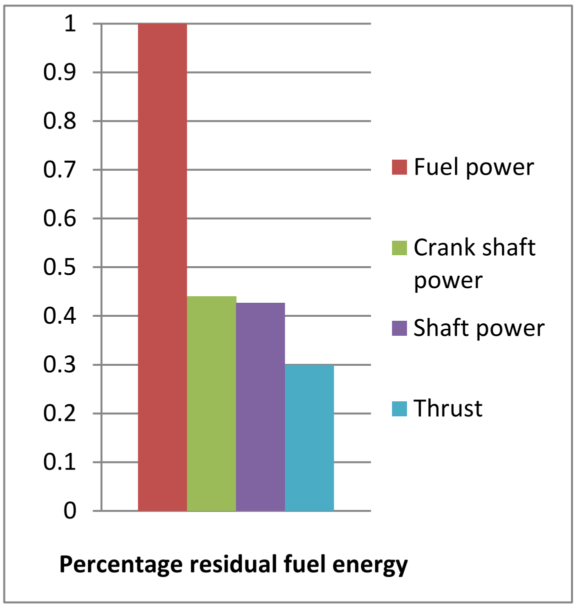

**Figure 4-3 General energy losses. Based on Ulstein Bergen Diesel (1991), Rolls Royce (2014b), Kubarev (2014)**

Figure 4-2 and figure 4-3 illustrate the losses which in general contribute to the fuel consumption of a mechanical connected propeller propulsion system under optimal operational conditions. It is important to add that these are given on a general basis. The efficiencies are to a large degree dependent on the type of components which each design is equipped with. Both vessels are driven by engines that are mechanically connected to the propellers. This means that both vessels have losses in propeller, reduction gear and the engine as such. LNG engines in general are often claimed to have a lower fuel efficiency than modern diesel engines in the order of 1-2 % (Ruud Verbeek, 2011). However, if the two main engines in this study are compared at normal cruising speed load, both engines operate at about 44 % overall efficiency (Ulstein Bergen Diesel, 1991, Rolls Royce, 2012). In addition, the LNG vessel is able to vary propeller speed and pitch automatically. This is to obtain an optimal overall efficiency of both propeller and engine, and not only the engine. Therefore, the main engine operates according to a so-called combination curve, which takes this into account (Haberg, 2014). Hence, the overall efficiency of the LNG vessel's propulsion system may in transit be favourable.

***Losses during manoeuvring***

During manoeuvring the conventional vessel makes use of both propellers. Average engine load during manoeuvring is reduced compared to transit, but the average engine efficiency is still roughly in the order of 39 % (Ulstein Bergen Diesel, 1991, Knutsen, 2014).

On the other hand, the LNG vessel has to utilize both thrusters during port manoeuvring. As mentioned in section 2.1.6, the vessel's shaft generator is not able to carry the full load of both thrusters. Therefore, the standby generator is made use of during port manoeuvring to provide sufficient power to the main switchboard. The standby generator's fuel efficiency is very poor at low load since it is running at constant speed. Its efficiency may be reduced by more than 50 % if the generator load is low compared to optimal efficiency (Torghatten Nord, 2014b). Hence, the LNG vessel has degraded overall fuel efficiency during manoeuvring. This issue is discussed in chapter 6.

***Fuel prices***

As explained in the introduction, MGO and LNG prices have during the last ten years gone from being approximately equal, to today's status where the price difference is significant. To predict the future prices for the time span of this study is a very uncertain exercise. However, during the time period 1970 – 1985, fuel prices increased with 950 %. A source explains that the proportion of operational cost, which fuel cost accounted for, rose from 13 to 34 % (Stopford, 2009). This indicates that fuel prices deviates from the average inflation.

Forecasts of crude oil and natural gas prices are made by among other the International Energy Agency and the UK Department of Energy and Climate Change. DECC states in their forecast from 2013 that it's extremely challenging to forecast fossil fuel prices since it depends on unknown variables such as: Future economic growth across the world, development of new technology, political issues such as global climate changes and strategies of resource holders. The fossil oil price forecasts provided by DECC are based on among other: A supply and demand model, long-run external forecasts and forecasts of oil production margins. The predictions are sense-checked against the forecasts of the International Energy Agency. In this forecast, three scenarios are established (high, low and central) for the future cost of each fuel type. To go further into the details behind each scenario is beyond the scope of this study. See references for a detailed description of each scenario (DECC, 2013).

The price per unit fuel which the shipping company has to pay is not only dependent on the crude oil/LNG price, but also on national taxation, local transportation costs and refinery costs. To predict these elements in addition to the oil/LNG price is extremely difficult. However, a source explains that the variation of fuel oil prices is to a very great extent dependent on the movement of oil prices (Det Norske Veritas, 2012). It is therefore assumed that the price per unit fuel which the shipping company pays today will change relatively to the future variation of the natural gas/crude oil price. This means that if the crude oil price/natural gas price is forecasted to double, it is assumed that the price per unit MGO/LNG delivered to the vessel will double as well.

Since the forecast only stretches to 2030, another simplification is implemented when it is assumed that the forecasts can be extrapolated to 2043. All extrapolations except the high scenario for MGO are linear extrapolations. The curve for the high scenario for MGO after 2030 is based on the equation below.

$$\Delta_n \quad = \quad \Delta_{2030} + (0.1 * n) \tag{4.2}$$

Here denotes $\Delta_n$ the yearly relative increase of the MGO price in year *n* after 2030. $\Delta_{2030}$ represents the yearly relative increase of the MGO price from 2029 to 2030. The purpose of this equation is to maintain the shape of the curve in the extrapolation. It is important to stress that the uncertainty implemented by the extrapolation comes on top of the inherent uncertainty in the fuel forecasting. Therefore, the uncertainty related to the fuel price predictions in this study is no less than extreme.

### *Transportation*

Transportation costs related to today's transport of LNG from Melkøya outside Hammerfest and to the ferry service accounts for about 33 % of the total fuel cost (Sletteng, 2014). It is assumed that the transportation cost of LNG is not directly dependent on the fuel price, and follows the average inflation used in this study. This is based on the assumption that the transportation cost is highly dependent on other cost elements such as the cost of a driver, the cost of tank lorry and maintenance as well as fuel.

The 2013 prices of fuel that constitutes the basis for the future prices are given in table 4-4.

**Table 4-4 Fuel and gas prices. Based on data from Torghatten Nord (2014e)**

| Type of price | Price | Denomination |
|---|---|---|
| **LNG fuel price** | 0.25 | NOK/kwh |
| **LNG transportation cost** | 0.15 | NOK/kwh |
| **MGO fuel cost** | 0.54 | NOK/kwh |
| **MGO transportation cost** | ≈0.00 | NOK/kwh |

Figure 4-4 shows that the central estimate regarding the LNG price suggests that the price will stabilize at approximately 15 % increase from today's level. On the other hand, figure 4-5 illustrates that the central scenario for MGO indicate an increase in the order of 40 % relatively to the 2013 level.

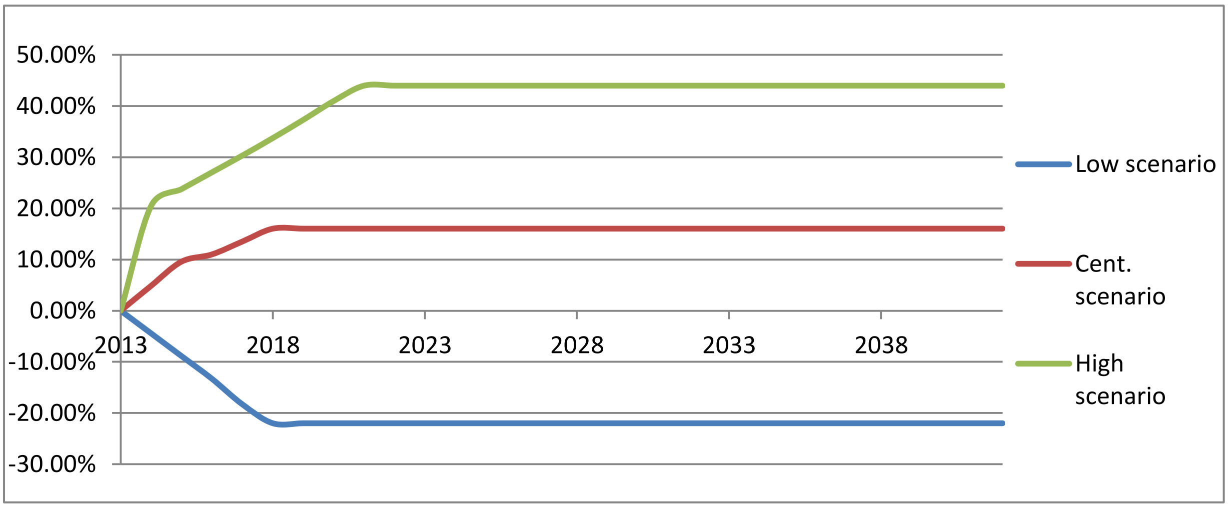

**Figure 4-4 Relative change of LNG prices through the time span of the study. Based on data from DECC (2013)**

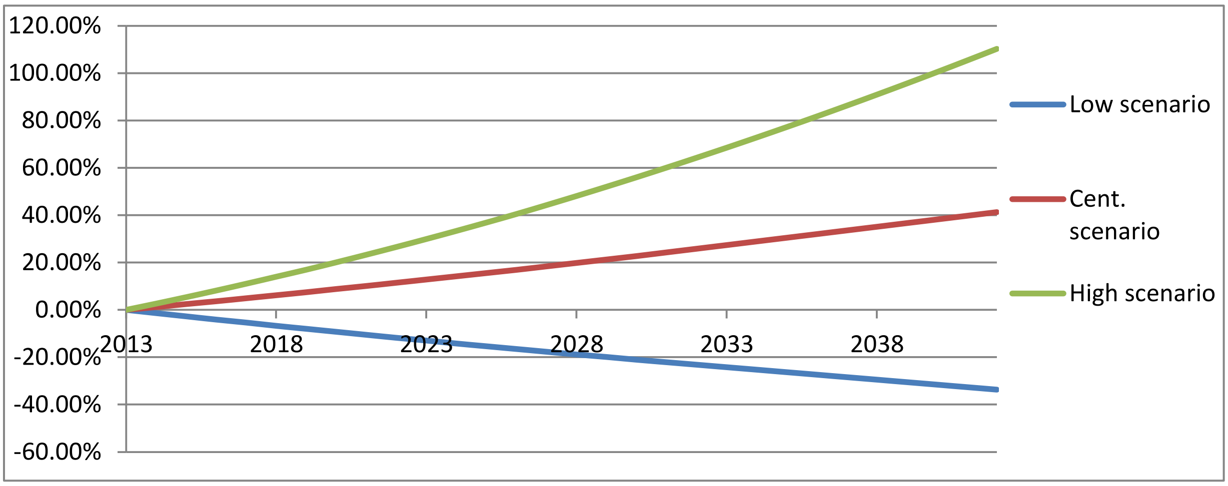

**Figure 4-5 Relative change of MGO prices through the time span of the study. Based on data from DECC (2013)**

***Estimation of fuel costs for the LNG vessel.***

As already discussed, M/F Lødingen has a hybrid solution where diesel electric power production is often made use of in manoeuvring situations. In addition, the standby generator is used to produce electricity to the vessel when it is laid up. Therefore, it is necessary to take into account the consumption of both fuels when calculating fuel costs. Data regarding the specific fuel consumptions are gathered by use of the ship owner's databases. Average values based on data from the first 14 months in service are applied in this calculation. The yearly cost of fuel for M/F Lødingen is calculated by use of the following formula:

$$Cf_i \quad = \quad k * \left( \left( S_{LNG\_i} * P_{LNG\_i} \right) + \left( S_{MGO\_i} * P_{MGO\_i} \right) \right) \qquad \textbf{(4.3)}$$

Where $Cf$ represents the yearly fuel expenditures in year *i* and $k$ the yearly amount of kilometres produced, which is given in section 3.1. $S$ denotes the respective fuel consumptions per produced km in year *i* and $P_i$ is the forecasted price of fuel per unit in year *i*. The fuel consumptions are based on data from the shipping company's internal database and presented in table 4-5. Since the fuel consumption tends to be high in the burn-in phase when the crews experience with the vessel is low, the specific fuel consumption from 2014 and further on is based on the first three months of 2014.

**Table 4-5 The LNG vessel's specific fuel consumption. Based on data from Torghatten Nord (2014d)**

| Engine | Year | Specific fuel consumption | Denomination |
|---|---|---|---|
| **RR C26:33L9PG (LNG)** | 2013 | 14.92 | kg/km |
| **RR C26:33L9PG (LNG)** | 2014- | 14.62 | kg/km |
| **MTU 8V 8000 M235** | 2013 | 5.07 | l/km |
| **MTU 8V 8000 M235** | 2014- | 4.61 | l/km |

***Estimation of fuel cost for the conventional vessel***

As already described, a correction of M/F Tysfjord's length is carried out. The vessel then fulfils the requirement regarding the car carrying capacity, which results in an increased hull resistance of approximately 5-7 % (Kubarev, 2014). To assess the impact of this increase in hydrodynamic resistance with respect to fuel consumption, a simplified study of the vessel's operation at this ferry service is carried out. However, it's important to underline that a detailed study of this effect is considered to be beyond the scope of this study due to among other the limited time and data available. Hence, this calculation is no more than an indication of the lengthening's effect with respect to fuel consumption. This is due to the significant uncertainty related to input data and the low detail level of this analysis.

The calculation takes basis in an increased hull resistance of 6 %. It is assumed to be constant at all speeds, which is a conservative simplification. In reality, the effect of the lengthening will vary with speed. However, the variation with speed has not been investigated due to the limited time and data available. Therefore the approximation is, for the purpose of this study, assessed to be good enough.

It is nevertheless important to underline that the increased hull resistance is only based on expert opinions and not actual analyses. Hence, there is a significant uncertainty related to this calculation.

According to a source, M/F Tysfjord utilizes only 60 % of its main engine capacity in transit (Knutsen, 2014). The vessel's BRM-6 main engine has thus sufficient capacity to handle the estimated increase of power demand. The produced engine power will vary according to which phase of the trip the vessel is in. The vessel's operation is divided into five separate phases: acceleration, transit, retardation, at port and at auxiliary engine (laid up period). For each phase the following parameters are identified: Time duration, average power production in phase before lengthening and specific fuel consumption. Central values for this calculation are given in table 4-6.

**Table 4-6 Central values in relation to the estimation of M/F Tysfjord's new fuel consumption. Based on input data from Kubarev (2014), Knutsen (2014), Ulstein Bergen Diesel (1991)**

| Phase | Duration (min) | Power (kw) | Power increase factor | New Power (after length correction) (kw) | Specific fuel consumption (g/kwh) |
|---|---|---|---|---|---|
| **Acceleration** | 5 | 900 | 1.06 | 954 | 203 |
| **Transit** | 50 | 1600 | 1.06 | 1696 | 191 |
| **Retardation** | 5 | 900 | 1.06 | 954 | 203 |
| **At port** | Timetable dependent | 500 | 1.00 | 500 | 213 |
| **At aux** | Continuously | 125 | 1.00 | 125 | 218 |

It is assumed that the engine's efficiency is unaffected by the load increase. These load increases will in reality result in improved engine efficiency since the engine is running at maximum constant speed in normal operation. However, the changes in engine efficiency due to the relatively low load increase are assessed to be insignificant and are therefore neglected (Hartviksen, 2014, Ulstein Bergen Diesel, 1991).

There are several factors that contribute to uncertainty in this calculation. Increased hull resistance is based on expert rule of thumb calculations, which implements uncertainty. Delivered powers in each phase before lengthening are founded on a chief engineers experience since hydrodynamic analyses are not available. This type of study is normally carried out in the design phase and based on the vessel's estimated hydrodynamic resistance per speed curve. The benefit by gathering power data statistics by use of the crew's experience is that it reflects the actual power consumption and not an estimated value. After all, it all depends on how the vessel is operated. There is nevertheless significant uncertainty related to the power consume during acceleration and retardation. The power demand during manoeuvring as well as the manoeuvring time are highly dependent on the weather conditions and varies consequently significant.

The engine's specific fuel consumption in each phase is determined by use of its technical data. Additional losses generated by engine driven pumps are not taken into account in this data. They are therefore corrected with respect to these losses. This is carried out in accordance with the recommendations in the technical specification (Ulstein Bergen Diesel, 1991). See Appendix K – Electronic attachments for more information. A simplification is made with respect to the fuel consumption of the auxiliary engine. Due to the lack of data regarding the specific fuel consumption, it's been assumed to be 218 g/kWh, which corresponds to an overall efficiency of 38.5 %. This is based on the fact that smaller diesel engines typically have lower efficiency (Heywood, 1988).

The calculation of fuel consumption follows formula ( 4.4 )

$$S_{MGO\_Tys} \quad = \quad \frac{\sum_{i=1}^{5}(t_i * P_i * \dot{m}_i)}{k} \tag{4.4}$$

Here $t_i$ denotes the total accumulated time in phase *i*, $P_i$ average power in each phase, $\dot{m}_f$ the specific fuel consumption in phase *i* and *k* the yearly amount of kilometres produced.

The result of the calculation indicates that the fuel consumption per produced kilometre will increase by approximately 4.9 % due to length correction. This is compared to historical data of the vessel's specific fuel consumption the four last years in regular traffic at the ferry service. It was expected to be lower than 6 % since the vessel is at quay for approximately 10 hours a day where the fuel consumption is unaffected by the lengthening. The result is therefore assessed to be valid for the purpose of this study. This means that the fuel consumption has changed from an average value of 18.59 l/km to 19.5 l/km after the lengthening. However, it is important to take into consideration the extreme uncertainty and therefore treat the result as no more than an indication.

The calculation of yearly fuel costs for the conventional vessel is then calculated according to formula ( 4.5 ).

$$Cf_i \quad = \quad k * \left(S_{MGO\_Tys} * P_{MGO\_i}\right) \tag{4.5}$$

$Cf$ represents the yearly fuel expenditures in year *i* and $k$ the yearly amount of kilometres produced, which is given in section 3.1. $S$ denotes the fuel consumption per produced km in year *i* and $P_i$ is the forecasted price of fuel per unit in year *i*.

### 4.2.2 Lube oil costs

All combustion engines require some sort of lubrication. The lube oil has five main functions in an engine: Reduce frictional resistance, protect against corrosion and wear, assist sealing, contribute to cooling and facilitate the removal of undesirable products (Heywood, 1988). Most medium speed engines, like the engines included in this study, consume between 0.1 g/kwh and 0.5 g/kwh lube oil (Molland, 2008).

Mineral oil, which is the type of lubrication applied in most types of medium speed engines, is a product of crude oil (Store Norske Leksikon, Hartviksen, 2014). The price of lube oil may therefore be assumed to be highly dependent on the fuel price. Torghatten Nord assumes in their estimation of future lube oil costs that they are approximately 3 % of the total MGO cost and 5 % of the total LNG cost. They then utilize the above given price relationships and the fact that the lube oil consumption is roughly proportional to the fuel consumption (Sletteng, 2014). Gas prices are at the moment linked to the oil price due to a so-called gas-to-oil pricing link. This means that gas contracts incorporates the oil price index in the calculation of gas prices. Consequently, a rise of the oil price directly impacts the gas price. Forecasts of the future gas prices cast doubt about whether this arrangement will last (DECC, 2013). To base the future lube oil cost on the LNG price may therefore be misleading. A decoupling of LNG and oil prices will introduce an error in the calculation, which will increase over time.

Lube oil cost are therefore calculated according to the formula ( 4.6 ) for M/F Lødingen and ( 4.7 ) for M/F Tysfjord.

$$C\_lub_i = \left(W_{LNG\_i} * \dot{P}_{LNG\_i}\right) + \left(W_{MGO\_i} * \dot{P}_{MGO\_Lød\_i}\right) \quad (4.6)$$

$$C\_lub_i = \left(W_{MGO\_Tys\_i} * \dot{P}_{MGO\_Tys\_i}\right) \quad (4.7)$$

$C\_lub_i$ denotes the cost of lube oil in year *i*, $W_i$ the vessel's yearly energy consumption per fuel. $\dot{P}$ represents the specific lube oil cost in year *i* per engine, given in NOK/kwh. In others words, the lube oil consumptions and the lube prices are combined in equation ( 4.6 ) and ( 4.7 ). They are based on the prices and consumptions given in table 4-7 and table 4-8. The consumptions tend to vary with engine load, but they are considered to be sufficiently accurate for the purpose of a life cycle cost analysis. Any additional oil changes are not taken into account.

**Table 4-7 Lube oil prices. Based on data from Torghatten Nord (2013b)**

| Vessel | Engine | Price |
|---|---|---|
| **M/F Lødingen** | RR C26:33L9PG (LNG) | 41,75 NOK/l |
| **M/F Lødingen** | MTU 8V 8000 M235 | 56,5 NOK/l |
| **M/F Tysfjord** | BRM-6 | 22,74 NOK/l |

**Table 4-8 Lube oil consumptions. Based on input data from Ulstein Bergen Diesel (1991), Rolls Royce (2012), MTU (2014)**

| Vessel | Engine | Consumption |
|---|---|---|
| **M/F Lødingen** | RR C26:33L9PG (LNG) | 0.4 g/kWh |
| **M/F Lødingen** | MTU 8V 8000 M235 | 0.25 g/kWh |
| **M/F Tysfjord** | BRM-6 | 1.21 g/kWh |

The lube oil prices are based on the shipping company's average prices in 2013. They are modelled to follow the forecasted MGO trends and vary accordingly. The price of lube oil is highly dependent on the quality and the specification that is required by the respective engines. Therefore, the price of lube oil per volume unit varies significantly from engine to engine. For example, the cost of lube oil is three times higher per liter for M/F Lødingen's MTU standby generator compared to M/F Tysfjord's BRM-6 engine (Torghatten Nord, 2013b). These differences are nevertheless cancelled due to the variation in lube oil consumption between the engines (MTU, 2014, Ulstein Bergen Diesel, 1991). This is shown in table 4-9.

**Table 4-9 Specific lube oil cost for each engine.**

| Vessel | Engine | Cost |
|---|---|---|
| **M/F Lødingen** | RR C26:33L9PG (LNG) | 0.0196 NOK/kWh |
| **M/F Lødingen** | MTU 8V 8000 M235 | 0.0167 NOK/kWh |
| **M/F Tysfjord** | BRM-6 | 0.0308 NOK/kWh |

There is extreme uncertainty related to these calculations as with most other long term forecasts. To link the lube oil price directly to the oil price adds additional uncertainty. However, the estimation is assessed to be more accurate than the shipping company's procedure and is therefore applied in this study.

### 4.2.3 Insurance costs

A vessel and its crew require in general two types of insurances. The major proportion of insurance costs is related two insurance of hull, equipment and machinery. This insurance protects the owner against physical loss or damage. The other type provides cover against third part liabilities such as example injury or death of crew members or passengers, as well as damage to cargo, pollution etc. This type of insurance cannot be covered by the regular insurance market and is therefore obtained by so-called protection and indemnity clubs. Where an insurance company is hold accountable for its owner, a P&I club is held accountable for its members. A club investigates claims on behalf of their members, gives advices during negotiations over a claim and hold reserve funds on behalf of its members. These funds are used to settle any claims (Stopford, 2009).

The yearly insurance costs for each vessel are given in table 4-10.

**Table 4-10 Insurance costs. Based on data from Torghatten Nord (2014c)**

| Vessel | Insurance cost |
|---|---|
| **M/F Lødingen** | 414 000 NOK |
| **M/F Tysfjord** | 271 000 NOK |

The cost includes all expenditures related to the vessels' insurance, both with respect to the hull, equipment and machinery insurance and third part liabilities. Any extra insurance costs due to the lengthening of the conventional vessel are not taken into account.

### 4.2.4 Maintenance costs

The cost element "maintenance costs" may be the most complex and difficult to estimate due to its numerous sub elements. It forms a major cost element to the life cycle cost. The company mostly applies a preventive maintenance policy with fixed age and fixed time intervals. For a more detailed description of the companies maintenance policy, see references (Nikolaisen, 2013, Torghatten Nord, 2012). The preventive maintenance costs can be categorised according to figure 4-6. A brief qualitative assessment of the different sub elements are given in the following sections.

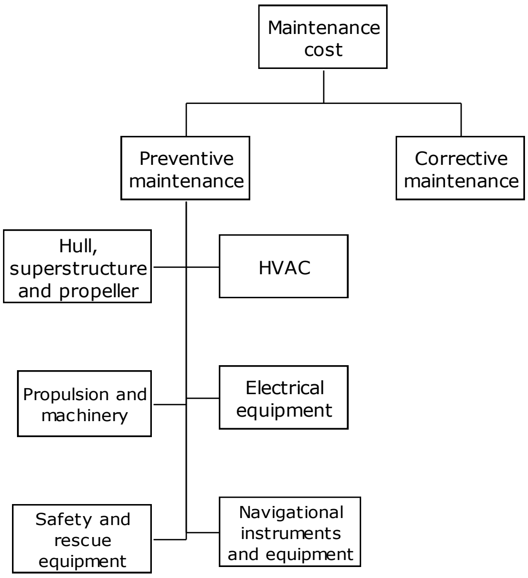

**Figure 4-6 Illustration of the sub elements which make the shipping company's maintenance costs for each vessel. Based on Hartviksen (2014)**

### *Hull, superstructure and propeller*

The propeller has a significant impact on the fuel economy. It is therefore important to maintain the propeller efficiency as optimal as possible. Careful examinations should be carried out each time a vessel is docked. Even the smallest crack may increase local stresses and result in loss of a blade. As for the hull, the propeller absorbs more power when the roughness increases. The increased roughness can be caused by fouling, cavitation erosion and corrosion (Molland, 2008). Maintenance with respect to hull, superstructure and propellers are usually carried out each time the vessel is docked.

### *Engine*

The repair cost related to maintenance of engines is highly dependent on the engine's number of cylinders, which decides the number of cylinder liners, piston rings, valves and bearings. These are all items which require periodic attention. The interval between inspections/replacements is usually decided by the engine's amount of running hours. The demand for spare parts is also dependent on the engines number of cylinders (Molland, 2008, Hartviksen, 2014).

**Table 4-11 Engine data. Based on data from Ulstein Bergen Diesel (1991), Rolls Royce (2012)**

| | **C26:33L9PG** | **BRM-6** |
|---|---|---|
| **Number of cylinders** | 9 | 6 |
| **Mean piston speed** | 11m/s | 9 m/s |

M/F Lødingen's Rolls Royce C26:33L9PG main engine is a nine cylindered liner engine, while M/F Tysfjord currently has a BRM-6 main engine, which is a six cylindered liner engine. Based on the above given statement, the nine cylindered engine will require more maintenance hours per action than Tysfjord's BRM-6. In addition, the gas engine has a higher mean piston speed than the BRM-6. Increased mean piston speed gives higher viscous friction and thereby increased liner and piston ring deterioration. However, modern engines are often claimed to be more sustainable and can therefore handle larger stresses than comparable older engines (Rolls Royce, 2012, Ulstein Bergen Diesel, 1991, Heywood, 1988, Hartviksen, 2014).

### *Hybrid system*

The hybrid system installed in M/F Lødingen consists mainly of switches, a variable speed drive, a shaft generator, cabling and a regular generator. These are all objects which require minimal maintenance compared to for example a diesel engine. It is not unusual that several of the mentioned components last for the entire intended lifetime without failures or maintenance. The hybrid system's contribution to maintenance expenditures is therefore assessed to be minimal (Hartviksen, 2014).

### *Fuel supply system*

The vessels have two completely different fuel supply systems. Conventional systems typically have a set of fuel pumps which pumps MGO to the engine's fuel injection system (Heidegård, 2014). The fuel-injection pump increases the pressure significantly, before the fuel is distributed into the injection nozzles, where the fuel is injected into the cylinder (Heywood, 1988). Over time, the fuel injection system suffers from wear and therefore needs regular maintenance. This wear occurs because of fuel particles, which cause erosion in the nozzles, or of cavitation of the high pressure fuel pump. Eventually this results in poor fuel spray into the cylinder, which may cause additional thermal stresses, incomplete combustion and accelerate the deterioration of several cylinder components (Rasmussen, 2003).

As explained in section 2.1.6, gas flow from the LNG tank and to the engine is provided by a heat exchanger, which evaporates LNG into gas (Sören Karlsson, 2010). This eliminates the need of a fuel pump to push the fuel to the engine. Natural gas is an extremely clean fuel compared to MGO. This reduces the wear of the fuel injection system significantly, since the gas doesn't contain any particles. The combustion process is also cleaner and therefore mitigates soot from accumulating at the exhaust valves, which is a normal problem at several marine diesel engines. It is therefore expected that the LNG system (engine and fuel supply system) may require less maintenance over time than a conventional system (Heidegård, 2014).

The cost of maintenance regarding the LNG tank and the valve system upstream and downstream is very uncertain. Many of the procedures which are necessary to carry out in relationship to the fuel system, as for example emptying of the LNG tank, are not carried out at the local yards before. It is these local yards which typically carry out the maintenance on the vessels at this ferry service. Another factor that should be taken into account is that the shipping company is not familiar with this type of maintenance since this is the company's first LNG vessels. The extent and cost of this maintenance is therefore still somewhat unclear (Sletteng, 2014).

### *Standby generator*

As already mentioned, the MTU standby generator is made use of in situations where both thrusters are needed, as for example when the vessel is entering port. This generates a significant amount of running hours on the MTU generator. According to information from the supplier, the engine accumulates 10-12 euros maintenance cost per running hour (Bertel O. Steen, 2014). This means that 2 000 running hours per year will result in 20 000 – 24000 euros in maintenance cost. The cost of maintenance of for example the fuel pumps, which transport MGO, comes in addition. Therefore, extensive usage of this generator generates a significant amount of extra maintenance costs, which were not intended from the designers. This issue is discussed further in chapter 6.

### *HVAC, electrical equipment and navigational instruments, safety and rescue equipment*

All of these equipment groups contribute to maintenance cost over time. Safety and rescue equipment constitutes in particular a significant contribution to the maintenance budget since renewal and testing of this equipment is relatively expensive (Sletteng, 2014). However, to assess the maintenance aspect of these equipment groups in detail is considered to be beyond the scope of this study. The costs are nevertheless taken into account in the maintenance cost estimation.

### *The shipping company's maintenance cost estimations*

The shipping company doesn't have any standard procedure for estimation of maintenance costs. Budgeting of maintenance costs are mostly based on the company's best practise, experience and suppliers recommendation. The detail level of these budgets depends to a great extent on the time and resources available each fall when these budgets typically are carried out. The preventive maintenance costs are ideally conducted in a detailed data sheet, where the maintenance cost for each component that requires regular overhaul/replacement is estimated. Costs of inspections, painting and cleaning of for example the hull and its superstructure are also included. However, no such calculations are carried out for M/F Lødingen, while M/F Tysfjord's maintenance budgets are based on experiences from earlier years (Sletteng, 2014, Hartviksen, 2014). It is therefore very difficult to quantitatively assess the maintenance costs on a detailed level for the purpose of this study.

### *The conventional vessel's maintenance cost.*

M/F Tysfjord's maintenance cost is exclusively based on the financial statements from the last four years in service at the ferry service Lødingen – Bognes. The expenditures are discounted to 2013 value by use of the inflation rate given in chapter 2.2.4 as shown in table 4-12. The costs include all the maintenance groups given in figure 4-6.

**Table 4-12 The conventional vessel's maintenance costs. Based on data from Torghatten Nord (2014c)**

| Year | Cost | Discount factor | 2013 value |
|---|---|---|---|
| **2009** | 2 007 384 | 1.13 | 2 259 328 |
| **2010** | 4 913 882 | 1.09 | 5 369 531 |
| **2011** | 3 890 680 | 1.06 | 4 127 623 |
| **2012** | 4 019 586 | 1.03 | 4 140 173 |
| **Average** | 3 707 883 | 1.08 | 3 974 164 |

The relatively low maintenance cost in 2009 is due to an extensive overhaul in 2008, which reduced the need of maintenance in the following year (Heidegård, 2014).

This way of calculating maintenance costs has several benefits. In this time period, the vessel had the same environmental conditions and approximately the same amount of operational hours a year. Premises for maintenance were also similar. This means that for example the availability of mechanics and equipment, docks etc. were comparable to what can be expected today. Such factors affect the maintenance cost of a vessel. It may for example be a lot more expensive to get parts and personnel to a location that is far from the suppliers/yards. This again can create more downtime and thereby generate additional overtime for the crew, which is an expensive extra cost (Hartviksen, 2014).

Several factors may contribute to uncertainty in this calculation. The vessel is docked, or at least at a yard, twice every fifth year. Large preventive maintenance actions are carried out at these visits. Only one yard visit (2010) is included in these numbers, which may give too low values. This is because of a significant difference between the maintenance cost in 2010, in which the vessel had a scheduled yard visit, compared to for example 2011 and 2012. Another issue which contributes to uncertainty is that the maintenance costs are modelled to be constant. An older vessel may have increasing maintenance costs over time due to required replacements of large components such as for example the main engine. The steel structure may also gradually demand more maintenance attention as it deteriorates over time. In addition, maintenance costs tend to peak when a vessel is docked. This variation is not captured by the model, which is a weakness.

### ***Maintenance cost estimation for the LNG vessel***

The only maintenance cost estimation available for M/F Lødingen is the maintenance costs that were estimated in relation with the tender competition in 2009. Little information and knowledge about the vessel's maintenance cost was available in 2009. This is a rather rough estimate of the expected maintenance cost, which is still unclear even today. Table 4-13 shows the estimated maintenance cost. The shipping company's calculation is based on a yearly inflation of 2.5 %. Therefore, the values are discounted back to 2013 value by use of this inflation rate (Torghatten Nord, 2009). All maintenance elements given in figure 4-6 are included in this maintenance cost.

When this estimation was carried out, it was intended that the LNG vessels were to be producing an equal amount of trips per year at the ferry service (Torghatten Nord, 2009). However, today M/F Lødingen is producing 58.3 % of the total amount of trips that are carried out by the LNG vessels (Torghatten Nord, 2014f). The shipping company has no current plan of changing this production pattern (Sletteng, 2014). Most of the maintenance costs are generated as a function of the vessel's amount of running hours. An increase of the total amount of running hours per year may therefore result in a roughly proportional increase of the vessel's maintenance cost (Hartviksen, 2014). The maintenance cost is corrected with a factor of 1.17 as a consequence of the relative increase of production from 50 % to 58.3 %. It is nevertheless important to emphasise that these maintenance cost are based on rather rough estimates. When this is combined with the time span from when the estimation was carried out in 2009 to 2013, the data may be assessed to be obsolete. The data are therefore evaluated to serve only as an indication of the maintenance cost level.

**Table 4-13 The LNG vessel's maintenance costs. Based on data from Torghatten Nord (2009)**

| Year | Cost (NOK) | Discount factor | Cost (2013) | Corrected (2013) |
|---|---|---|---|---|
| **2013** | 2 383 132 | 1.03 | 2 325 007 | 2 709 017 |
| **2014** | 2 342 807 | 1.05 | 2 229 917 | 2 598 222 |
| **2015** | 3 329 132 | 1.08 | 3 091 430 | 3 602 027 |
| **2016** | 4 113 685 | 1.10 | 3 726 796 | 4 342 332 |
| **2017** | 4 616 163 | 1.13 | 4 080 015 | 4 753 892 |
| **2018** | 2 569 161 | 1.16 | 2 215 379 | 2 581 283 |
| **2019** | 4 628 402 | 1.19 | 3 893 714 | 4 536 820 |
| **2020** | 3 773 168 | 1.22 | 3 096 815 | 3 608 301 |
| **2021** | 3 757 888 | 1.25 | 3 009 048 | 3 506 037 |
| **2022** | 3 438 972 | 1.28 | 2 686 519 | 3 130 239 |
| **2023** | 3 524 946 | 1.31 | 2 686 519 | 3 130 239 |
| **Average** | **3 497 951** | **1.16** | **3 003 742** | **3 499 855** |

Compared to the maintenance cost of the conventional vessel, M/F Lødingen's maintenance cost is estimated to be, on an average basis, about 10 % lower in the first 11 years in service. According to the shipping company this may be realistic. The reasons are among other the expectation of reduced deterioration of the fuel supply system and other components such as engine nozzles and exhaust valves. In addition, modern engines and components tend to have significantly longer maintenance intervals than equivalent equipment at the conventional vessel. The reduction of maintenance actions may therefore result in reduced maintenance costs (Hartviksen, 2014, Sletteng, 2014, Heidegård, 2014). On top of this, most equipment and components have guarantees that reduce the corrective maintenance costs in the vessel's first years in service. The need of preventive maintenance at this stage is also low. As a consequence, the vessel will not reach its "normal" maintenance cost level before these guarantees have expired (Sletteng, 2014). According to the shipping company's financial statement, the vessel accumulated a maintenance cost of 2 953 936 NOK through 2013, which is close to the preliminary estimation (Torghatten Nord, 2014c, Torghatten Nord, 2009).

Since there is neither a detailed maintenance cost analysis nor maintenance data available, a simplified model based on the preliminary estimation is established. Figure 4-7 illustrates how the maintenance cost for the LNG vessel is modelled. The estimation takes basis in the actual maintenance cost in 2013, while it is increasing linearly the first two years. This is to take into account the expected reduced amount of corrective- and preventive maintenance costs the first years in service. The upper threshold is based on the average maintenance cost after 2015 from the preliminary estimation, which is 3 669 102 NOK. As earlier mentioned, the LNG vessel has several additional critical components and systems, which need preventive maintenance. However, based on the assumption of reduced maintenance cost for most of the components and the system as such, the average value may be realistic.

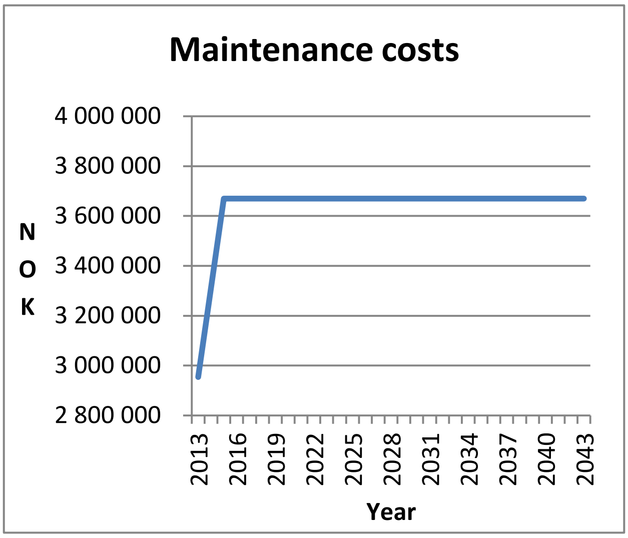

**Figure 4-7 Modelling of maintenance costs**

It is very important to underline that there is extreme uncertainty related to this simplified model. The shipping company's lack of experience with LNG vessels constitutes a major proportion of this uncertainty. Spare parts may turn out to be more expensive, and the maintenance procedures more extensive than expected. Systems and components may deteriorate at another rate than forecasted. Another issue is how the extra amount of running hours on MTU generator will affect the maintenance cost over time. To model the maintenance cost as constant cost contributes also to uncertainty, especially since maintenance costs tends to peak when a vessel is docked. This variation is not captured by the model, which is a weakness. The uncertainty related to the maintenance cost is discussed further in chapter 5.

### 4.2.5 Manning costs

As already mentioned, manning costs are only briefly discussed to be able to obtain a bigger picture of the operational costs. Costs related to the manning of the vessels include all direct and indirect charges incurred by the crewing of the vessel such as salaries, social insurance, pensions, victuals and travelling expenditures. In general, the manning cost of a vessel is determined by the size of the ship's crew and the ship owner's employment policy (Stopford, 2009).

In shipping today, many European shipping companies are flagging out, which means that they are registering the company in a country with a less stringent national statute. This allows them to employ crew members which have a much lower salary compared to for example his/her Norwegian equal (Stopford, 2009). According to the tender specification, Torghatten Nord is allowed to use foreign personnel. The company doesn't even have to be registered in Norway. However, it is required that the crew are paid in accordance with Norwegian tariffs no matter what nationality they may have (Statens Vegvesen, 2009). It can therefore be assumed that the crew costs will follow Norwegian tariffs through the time span of the study.

Since both vessels require the same crew, produces the same amount of kilometres after the same timetable, the crew costs are assessed to be equal for both vessels. They are based on the budget numbers for the ferry service, which was carried out in relation to the tender competition. It includes travelling expenditures, wages, crew courses and work wear. The costs are estimated by the shipping company to be 16 500 000 NOK on a yearly basis (Torghatten Nord, 2009).

There is inherent uncertainty related to the use of budget numbers for this calculation. The benefit is that it is meant to serve as an average value. It is beyond the scope of this study to investigate the details of the crew cost for the ferry service. The crew cost is included to be able to form a bigger picture of the total life cycle costs. This enables studies of the relationships between crew costs and other major cost elements.

## 4.3 Regularity expenditures (REGEX)

### 4.3.1 Downtime cost

Regularity may be defined as a systems ability to meet the demand for deliveries or performance (Kawauchi and Rausand, 1999). This cost category is often included in life cycle cost estimations where the system's regularity, availability etc. are important in the cost estimation (Utne, 2009).

Vessels like M/F Lødingen and M/F Tysfjord consists of systems with numerous components. A source explains that if a component fails in a system with a large number of components, and the component is immediately replaced or repaired, the system's reliability after the repair may be assumed to be the same as before the failure. This is due to the fact that only a small fraction of the system's components are changed. In other words, the system's failure rate is basically the same as before the failure. This pattern may be characterised as a nonhomogeneous Poisson process. See references for a thorough description of NHPP and reliability theory (Rausand and Høyland, 2004).

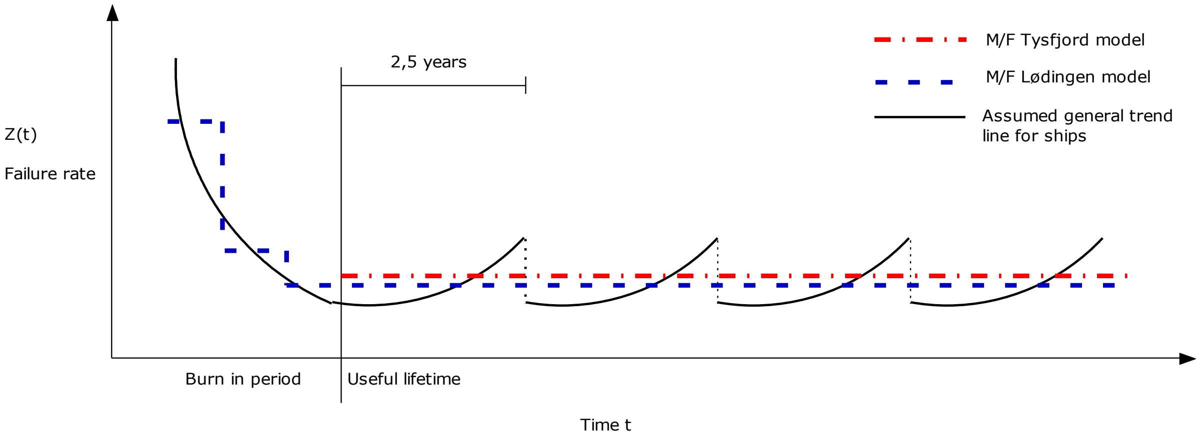

**Figure 4-8 Illustration of the reliability theory which the downtime cost estimations are founded on.**

Figure 4-8 illustrates the basis for the estimation of downtime with respect to reliability theory. Often, newly built vessels suffer from so-called childhood diseases due to the system's immaturity and possible construction defects. As for the LNG vessel, the failure rate is often high in the so-called "burn-in" period, but decreases rapidly before it reaches its "useful life" (Rausand and Høyland, 2004, Hartviksen, 2014). Torghatten Nord has a preventive maintenance policy, which consists of a combination of fixed age and fixed time interval strategies for preventive maintenance actions. The vessels are at the yard with two and half year intervals for inspections and major preventive maintenance actions, as described in section 4.2.4. Any corrective maintenance is carried out continuously within this interval (Hartviksen, 2014). The vessels' actual failure rate in their "useful life" may be described as in figure 4-8, which is based on a NHPP. It may be assumed that the vessels' failure rates are "reset" after a major preventive maintenance action. This is based on the shipping company's maintenance policy. It states that the vessels shall be in adequate technical conditions in accordance with the regulations independent of age (Hartviksen, 2014). In reliability theory, such repairs are often referred to as "perfect repairs/actions". The assumption of perfect repairs is nevertheless uncertain. Equipment may deteriorate over time despite of regular maintenance. In reality, most repairs are so-called "imperfect repairs", which set the system back to a condition better than it was, but not as good as new (Rausand and Høyland, 2004).

However, several preventive maintenance actions are conducted between the scheduled yard visits by the crew or by the supplier's personnel (Hartviksen, 2014). The trend line given in figure 4-8 is therefore an extreme simplification.

***Downtime cost estimation***

As mentioned in section 1.7.2, there are several issues regarding the calculation of downtime costs, since the shipping company has a reserve vessel on standby in case of any downtime with the LNG ferries. However, the purpose of this study is to measure the performance of the LNG vessel with respect to life cycle costs. A major simplification is therefore implemented to the model. The downtime cost is based on the fee that the shipping company is issued when a trip isn't carried out. A simplification of Torghatten Nord's expenditures related to cancelling of trips can be expressed by formula ( 4.8 ) (Sundbakk, 2014).

$$K_{cancelling} \quad = \quad C_{fee} + C_{income} - C_{fuel} \tag{4.8}$$

Here denotes $K_{cancelling}$ the total cancelation cost per trip, $C_{fee}$ the fee issued when a trip is cancelled, $C_{income}$ the lost income from sale of tickets per trip and $C_{fuel}$ the saved fuel. The values are given in table 4-14.

**Table 4-14 Cost of downtime per trip. Based on input data from Sundbakk (2014)**

| Constant | M/F Lødingen | M/F Tysfjord |
|---|---|---|
| $C_{fee}$ | 20 000 NOK | 20 000 NOK |
| $C_{income}$ | 5 000 NOK | 5 000 NOK |
| $C_{fuel}$ | 2 539 (2013) NOK | 2 488 (2013) NOK |
| $K_{cancelling}$ | **22 461** NOK | **22 512** NOK |

$C_{fuel}$ is in this downtime cost estimation simplified to be constant in real terms during the study's time span. This is to simplify the model. After all, $C_{fuel}$ is relatively small compared to the other factors. Consumptions and fuel prices are therefore based on 2013 values.

The yearly cost of downtime per year can then be calculated according to formula ( 4.9 ).

$$C_{down_i} = n_i * d * K_{cancelling} \qquad (4.9)$$

Here, $n$ is the number of days out of service in year $i$, $d$ the average number of trips per day and $K_{cancelling}$ the cost of cancelling one trip. As discussed in section 3.1, the model is based on 52 weeks in service each year and 5 044 trips in total, which is 13.86 trips per day.

The number of trips cancelled each year is based on the shipping company's database, which records the number of days a month the vessel is out of service. Only downtime that exceeds 24 hours is recorded in the database. The frequency and duration of each incident are not captured by the database, which is a significant limitation. This means that cancellations due to minor problems or events are not captured by the data. The numbers are therefore lower than the actual number of cancelled trips a year (Torghatten Nord, 2014d). However, all cancellations are not due to technical problems. It's normal to cancel trips due to for example safety drills and minor preventive maintenance actions. These are as a rule of thumb short downtime periods, and are therefore normally not captured by the database (Hartviksen, 2014). Hence, it may be assumed that the model only takes unexpected downtime into account. The actual cost of these corrective maintenance actions are included in the maintenance cost estimation given in section 4.2.4.

### *Conventional vessel*

For M/F Tysfjord, the expected amount of downtime is based on data from the period 2009-2012, which were the four last years the vessel operated the ferry service. The vessel had scheduled yard visits in the turn of the year 2008-2009 and in 2010, which the data are corrected for. It had approximately the same amount of operational hours during this period (Torghatten Nord, 2014d). The calculated downtime is an average value of the downtime from 2009-2012. This is illustrated in figure 4-9.

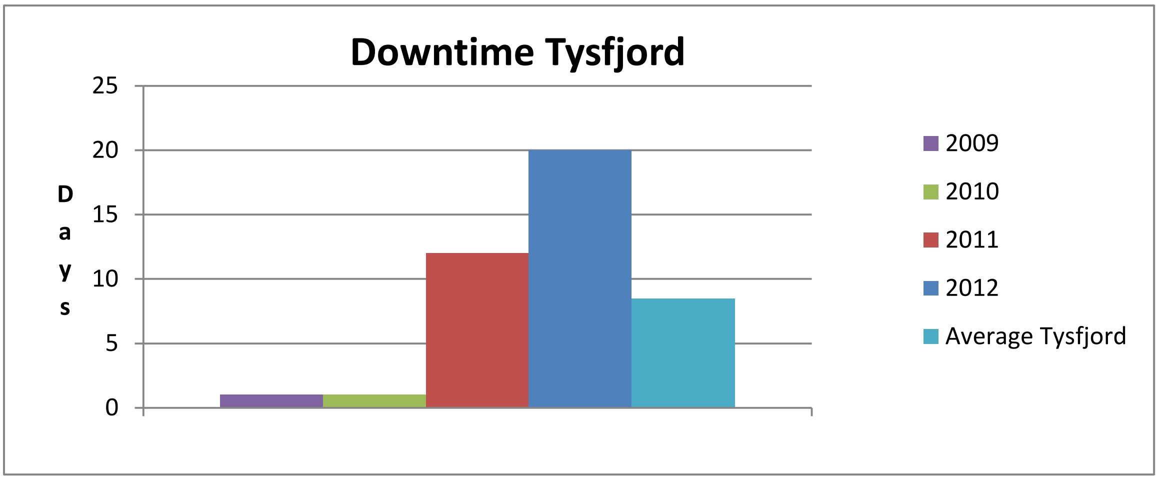

**Figure 4-9 The conventional vessel's downtime statistics. Based on data from Torghatten Nord (2014d)**

However, two simplifications are implemented when expected downtime is calculated by use of this experience data. As the red line for M/F Tysfjord in figure 4-8 illustrates, the failure rate is assumed to remain constant at the average 2009-2012 level and ergo also the mean time to failure. The other assumption is that the downtime caused by each event remains at the same level as the average from 2009 to 2012. Formula ( 4.10 ) is the general expression for operational availability (Rasmussen, 2003).

$$A = \frac{MTTF}{MDT + MTTF} \tag{4.10}$$

In other words, the two simplifications assume MTTF and MDT to be constant over the life span. According to formula ( 4.10 ), the availability will also be constant. This simplification implements uncertainty into the calculations. However, based on the limited data and time available, the simplifications are assessed to adequately represent the reality.

***LNG vessel***

There is obviously limited data available to use as basis for the estimation of the LNG vessel's downtime costs. This is because the vessel has only been in service for about one year. The downtime statistics for this period is given in figure 4-10.

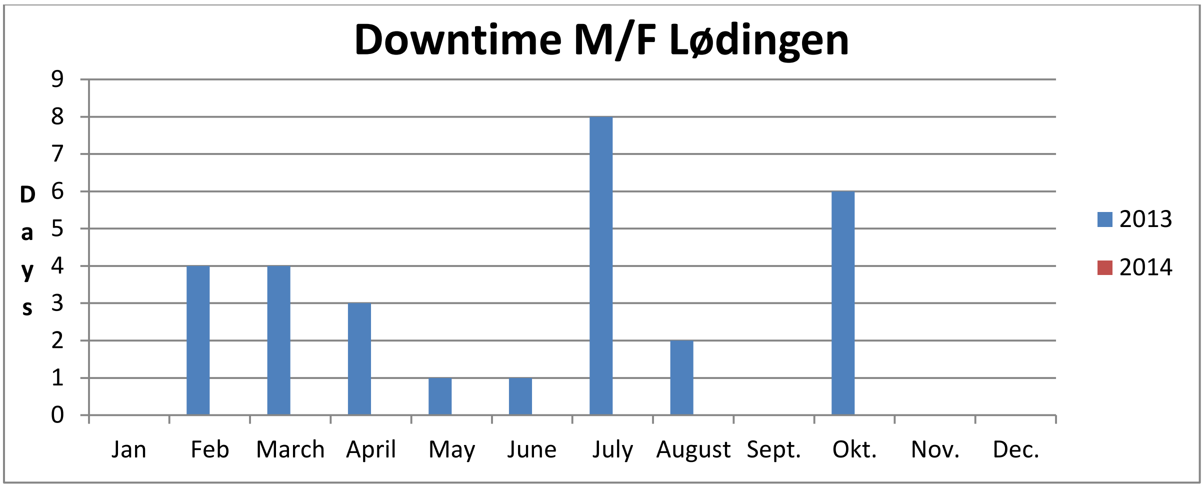

**Figure 4-10 The LNG vessel's downtime statistics. Based on data from Torghatten Nord (2014d)**

The vessel had 29 full days out of service from the day it was set into operation and to the turn of the year 2013-2014, which is a significant amount of downtime. However, it is important to notice that the vessel had no downtime from November 2013 to March 2014 (Torghatten Nord, 2014d). Since there aren't any additional data to use as basis for the estimation of future downtime, the calculation has to be partly based on expert opinions.

The vessel's downtime in its first time in service is to a large degree caused by childhood diseases, which have occurred on a variety of components. The coldbox and the hybrid system, which is described in section 2.1.6, have in particular turned out to be vulnerable. However, the downtime caused by these failures is also generated due to the crew's lack of experience with the machinery. It has therefore taken significantly longer time to restore the vessel's operational ability after a failure, than what can be expected in the future (Heidegård, 2014). These factors will reduce both MTTF and MDT, given in equation ( 4.10 ), and thereby improve the vessel's availability.

The vessel's burn-in period may span over as much as two years. This is due to the unusually large amount of childhood diseases (Heidegård, 2014). Hence, it may be assumed that the vessel will reach its "useful lifetime" availability level from year 3.

To determine the average availability level after the burn-in phase in form of a specific number of days is a rather difficult task, and is therefore associated with a lot of uncertainty. In this case, the only references are the vessel's short production history. However, there are some key factors that are central with respect to availability (Heidegård, 2014).

LNG is evaporated in the cold box and flows downstream to the engine injection system without any pumping. This is in contrast to a conventional system which requires fuel pumps and filtering. Nature gas is a very clean fuel, and doesn't clog and tear the system in the same scale as MGO. The combustion of nature gas is also cleaner, and produces significantly less amounts of soot and particles. This reduces the degradation of for example exhaust valves, cylinder liners and lube oil. Hence, the probability of unexpected failures may be reduced. The effect of improved technology, and thereby also improved reliability of components and systems, comes on top of this (Heidegård, 2014).

However, it is important to emphasise that there are several factors that may contribute to a degraded availability. The low gas temperature in the fuel system may cause problems over time, and therefore weaken the vessel's availability performance. A diesel electric system, like the one installed in M/F Lødingen, incorporates numerous additional failure modes compared to M/F Tysfjord. This is due to among other the increased amount of components and the system's complexity. In addition, the vessel is required to always have the standby generator ready to ensure the "bring-me-home" capability, which is discussed in section 2.1.6. The requirement raises the number of components that has to be functioning at all times. This degrades the vessel's performance with respect to availability (Heidegård, 2014).

To quantify the average amount of downtime a year is as already mentioned a very difficult task. However, a source explains that the average amount of unexpected downtime is assessed to be reduced compared to the conventional vessel. This is based on the experience with the machinery and its design, in addition to the information given by the suppliers. Unexpected failures will nevertheless occur and have to be taken into consideration. An average unexpected downtime in the order of 7.5 days a year may be a reasonable assumption (Heidegård, 2014).

Figure 4-11 illustrates the development of downtime for M/F Lødingen and M/F Tysfjord, which is based on the given data and expert opinions. A linear reduction of downtime during the burn-in phase is assumed. It is crucial to emphasise that there is extreme uncertainty related to the prediction of future downtime for both vessels, and in particular with respect to the LNG vessel. The issue is to be addressed in the sensitivity analyses in chapter 5.

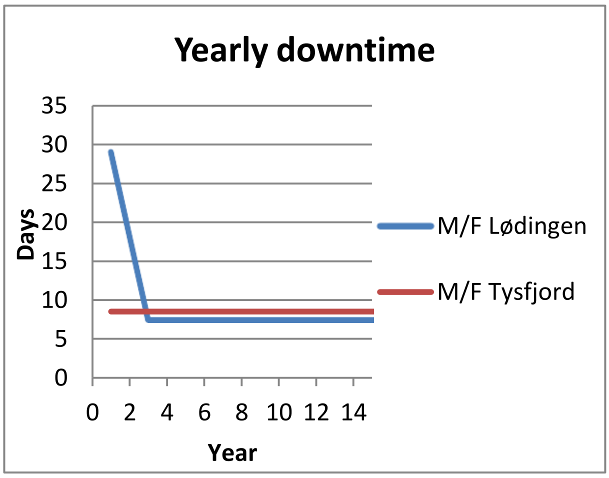

**Figure 4-11 Modelling of downtime**

***Modelling limitations***

The downtime cost model doesn't take into account indirect effects like for example poor media publicity. Frequent cancellations, as for M/F Lødingen in 2013, may cause frustration among the passengers, which is either delayed or in some cases even forced to use other transportation alternatives. This frustration is often captured by local and regional newspapers, which over time may impair the shipping company's reputation. To thoroughly estimate the cost of poor media publicity is a difficult task, which is beyond the scope of this study. However, a parallel may be drawn to the airline company Norwegian. The company experienced significant regularity problems with their brand new Boeing 787 "Dreamliner" aircrafts during 2013. A source claims that these problems caused a major impairment of the company's reputation. It is nevertheless hard to determine whether the impaired reputation had significant impact to on the company's income (Hegnar, 2014).

Another drawback with the model is that it doesn't describe the effects of preventive maintenance with respect to downtime. Modern propulsion systems, like the one installed in M/F Lødingen, are often claimed to have longer maintenance intervals and thereby cause less downtime due to preventive maintenance. Based on this statement, the conventional vessel may require more downtime due to preventive maintenance than the LNG vessel. This is not captured by the model, which is a significant weakness. Ideally, the downtime should have been modelled by a thorough reliability assessment of the vessel's critical systems. Due to the lack of data and the limited time available, the downtime costs have in this case been based on the shipping company's records and expert opinions.

Unexpected failures that results in downtime often occur while the vessel is in transit. If a critical component/system fails while the vessel is in transit, the vessel may experience loss of propulsion power. This has been the case for the LNG vessel at several occasions (Lillebø, 2013, Trellevik, 2013). Such events involves a risk of damage to humans, environment and to the vessel. Modern studies indicate that it may be important to consider the cost of these risks (Nam et al., 2011). To carry out such an assessment of risk expenditures includes in many cases to set a price on a human life, which is controversial from a morally point of view. Another issue is that these costs have to be discounted back to a net present value. To do this, it's necessary to decide a discount rate on asset damage, which is also debatable with respect to the moral aspect (Utne, 2009). There are nevertheless standards which describes how these analyses are carried out such as NORSOK Z-013 (NORSOK, 2001). However, due to the time limitation of this study, such an analysis is not carried out.

## 4.4 Environmental expenditures (ENVEX)

### 4.4.1 Nitrogen oxide (NOx) tax

Combustion engines and diesel engines in particular, are major sources of urban pollution. NOx gas is created in the combustion chamber due to a reaction between oxygen and nitrogen caused by the high temperatures during combustion (Heywood, 1988). NOx is harmful for among other human and animal health, vegetation and causes acidification of water (Store Norske Leksikon, 2009).

The Norwegian Ministry of Taxes has therefore implemented a tax on NOx emissions for vessels with more than 750 kW installed propulsion power. The ship owner is charged 17.01 NOK per kg NOx which is produced by the ship’s machinery. According to the regulation, the NOx emission is calculated by multiplying the vessel’s fuel consumptions with an emission factor as given in formula ( 4.11 ). The emission factor depends on the type of fuel which is used, and the type of engine installed. Each engine has its own emission factor as presented in table 4-15 (Norwegian Ministry of Taxes, 2013).

$$NO_{x\,tax} \quad = \quad m_{fuel} * f_{NOx} * 17.01 \tag{4.11}$$

$NO_{x\ tax}$ denotes the yearly NOx tax, $m_{fuel}$ the yearly amount of fuel burned, $f_{NOx}$ the emission factor multiplied with the NOx emission tax, which here is given in NOK per kg NOx. The emission factor ($f_{NOx}$) can be determined by use of the engines EIAPP certificate, or by measurements carried out by an approved third party (Norwegian Martime Authority, 2011).

Torghatten Nord usually hires a third party, which estimates an emission factor for each engine based on actual measurements. The estimations are then approved by the Norwegian Maritime Authorities (Hartviksen, 2014). The NOx emission factors for the vessels’ main engines are given in the table below.

**Table 4-15 NOx emission factors. Based on data from Norwegian Martime Authority (2011/2013)**

| Vessel | Engine | Nox emission factor |
|---|---|---|
| **M/F Lødingen** | RR C26:33L9PG | 2.94 kg NOx/ton fuel |
| **M/F Lødingen** | MTU 8V 8000 M235 | 30,34 kg NOx/ton fuel |
| **M/F Tysfjord** | BRM-6 | 64,8 kg NOx/ton fuel |

As shown in table 4-15, the NOx emission factor is significantly higher for the 21 year old BRM-6 compared to the modern MTU engine, which produces 50 % less NOx. The LNG engine has, as already explained, a very low NOx emission factor. It is nevertheless important to emphasise that LNG has approximately 10 % higher energy density than MGO (Barents naturgass, 2014). When the NOx emission factors are compared on the basis of NOx emission cost per energy unit, the LNG engine has an even lower emission factor relatively to the diesel engine's. This is shown in table 4-16, which states that the NOx emission cost is over 25 times higher per fuel energy unit for the 21 year old BRM-6 engine.

**Table 4-16 Specific costs of NOx emissions for each engine**

| Vessel | Engine | Specific NOx emission cost |
|---|---|---|
| **M/F Lødingen** | RR C26:33L9PG | 0.0037 NOK/kwh |
| **M/F Lødingen** | MTU 8V 8000 M235 | 0.0434 NOK/kwh |
| **M/F Tysfjord** | BRM-6 | 0.0927 NOK/kwh |

Calculations of NOx emission costs are based on the formulas below where ( 4.12 ) represent the LNG vessel and ( 4.13 ) the conventional vessel.

$$C_{Nox_i} = \left(W_{LNG\_i} * \dot{p}_{Nox\_RR} + W_{MGO\_i} * \dot{p}_{Nox\_MTU}\right) \tag{4.12}$$

$$C_{Nox_i} = \left(W_{MGO_{Tys_i}} * \dot{p}_{Nox\_BRM6}\right) \tag{4.13}$$

Here denotes $C_{Nox_i}$ the yearly NOx emission cost per vessel in year *i*, $W_i$ the vessel's yearly energy consumption and $\dot{p}_{Nox}$ the respective emission cost per energy unit for each engine. $\dot{p}_{Nox}$ is given in table 4-16. All the MGO consumed by the conventional vessel is assumed to be burned by the vessel's main engine.

## 4.5 Disposal expenditures (DIPSEX)

Torghatten Nord's current practice is that all vessels shall at all times, no matter where they are in their life span, be certified and capable of being put into service whenever needed. Their fleet's technical condition is therefore in accordance with the prevailing standards and regulations for such vessels. According to the shipping company's rule of thumb, the vessels are sold before their technical condition has deteriorated to an extent where scrapping is the only alternative (Hartviksen, 2014).

To estimate the value of a ship 30 years from now is a difficult task. In addition, shipping is a small market. There are therefore often situations where there are no "willing buyers". In such situations, prices may be heavily discounted (Stopford, 2009). It is extreme uncertainty related to this issue due to the long time span of the analysis. Stricter regulations and technological development can make the vessels superfluous. A central question is whether it is possible to earn money on these vessels in the future. Several banks and financial institutions that values ships have a rule stating that ships after a certain age are valued according to its scrap value (Stopford, 2009). Therefore, DISPEX costs are in this study based on the vessels' estimated scrap value. The validity of this assumption is difficult to assess. However, calculations of DISPEX based on the vessels' scrap value are intended to serve as a lower limit regarding the expectations of income at the end of the time span.

### 4.5.1 Estimating scrap value

The age limit, from which a vessel's value is assumed to be the same as its scrap value varies between institutions and is dependent on the vessel type. For example may the age limit for very large crude oil tankers be 20 years. Estimating a vessel's scrap value involves two steps. The first step is to find the vessel's lightship weight tonnage (lwt). The second step is to find the scrap prices. Scrap prices are given in dollars per lwt (Stopford, 2009). The lightweight tonnage of a vessel is simply the weight of the hull and the vessel's machinery (Molland, 2008).

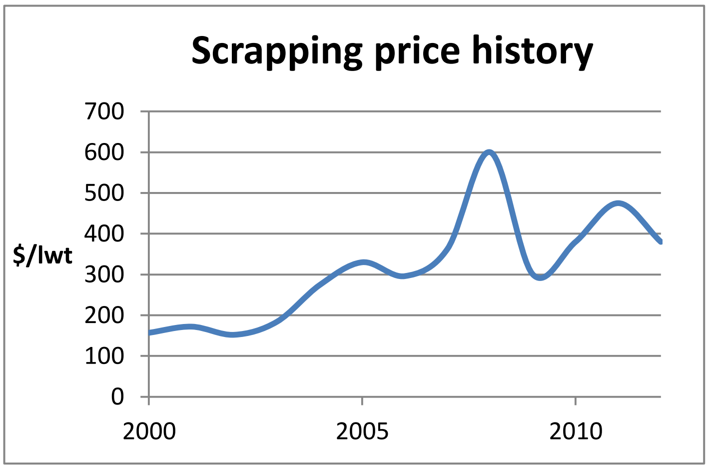

**Figure 4-12 Historical scrapping prices. Based on data from Knapp et al. (2008), Platou (2013)**

The scrap price has during the last years varied between $ 100/lwt and $ 600/lwt (Platou, 2013, Knapp et al., 2008, Stopford, 2009). To predict the scrap prize 30 years in the future is associated with uncertainty. Figure 4-12, which is based on two different sources, illustrates the trend for the average scrap value on a global basis. Based on the current market situation, 400 $/ltw is applied as the scrap price in this estimation. However, it is significant uncertainty related to the scrap prize.

Income due to scrapping is calculated by the following formula (Stopford, 2009):

$$C_{scrap} = -K_{scrap} * \Delta_{ltw} \tag{4.14}$$

$K_{scrap}$ denotes the scrap price ($/lwt) and $\Delta_{ltw}$ the lightweight tonnage (tons). A minus is added in front to take into account the fact that this is an income for the shipping company.

***Effect of length correction***

Due to the length correction of M/F Tysfjord, an increase of the vessel's lightweight has to be calculated. When a vessel is lengthened, it is typically cut in two, and then an additional section is added in the middle. A rule of thumb is to avoid any interference with the machinery room (Bergvoll, 2014).

The weight of a vessel per unit length is equal to the buoyancy per unit length. Consequently the buoyancy of a vessel has to be equal to its weight (Molland, 2008). Since the added section is to be welded as a mid-section, the centre frame forms the basis for the calculation. The added weight due to the length correction are given by the formula ( 4.15 )

$$\nabla_{add} = l * A * \rho \tag{4.15}$$

Here denotes *l* the length of the added section, *A* the area of the centre frame and $\rho$ the seawater density. Uncertainty is implemented by calculating the added weight based only one frame. This is due to the fact that the hull shape is changing over the vessel's length. Therefore, the estimation probably gives a slightly high weight addition. However, for the purpose of this study the value is assessed to be applicable. The added weight due to the length correction is estimated to be 690 tons. The lightweight tonnages applied in this calculation are given in table 4-17.

**Table 4-17 The vessels' lwt. Based on input data from Torghatten Nord (2014a), NSK Ship Design (2014)**

| Vessel | Lwt |
|---|---|
| M/F Lødingen | 2239.2 tons |
| M/F Tysfjord | 2338.2 tons ( included 690 tons weight addition) |

# 5. RESULTS

The results indicate that there are several significant differences between the vessels' life cycle costs. This is with respect to among other capital expenditures, NOx emission costs, fuel costs and maintenance costs. An individual discussion of each vessel's life cycle costs is given in section 5.1 and 5.2, while the most significant cost elements for both vessels are compared in section 5.3.

As already described, the results given in this chapter are based on central scenarios for fuel and lube oil prices. This modelling is based on real term values. The real rate of return is set to be 0 %. However, the rate of inflation is set to 3 %, as given in section 2.2.4, since the capital costs are given in nominal values (see section 4.1.3). Costs related to the manning of the vessels are only discussed in section 5.1.2 and 5.2.2. They are not included in the total life cycle costs or any other results, except from the total operational expenditures discussed in the mentioned sections.

## 5.1. LNG vessel

Figure 5-1 and figure 5-2 illustrate that the capital expenditures and the operational expenditures are very important with respect to the total life cycle costs. While the capital expenditures are decreasing over the time period, the operational expenditures are increasing. It may be noticed that the regularity expenditures are peaking in year 1 and make a significant cost category. All the cost categories are discussed in the following sections.

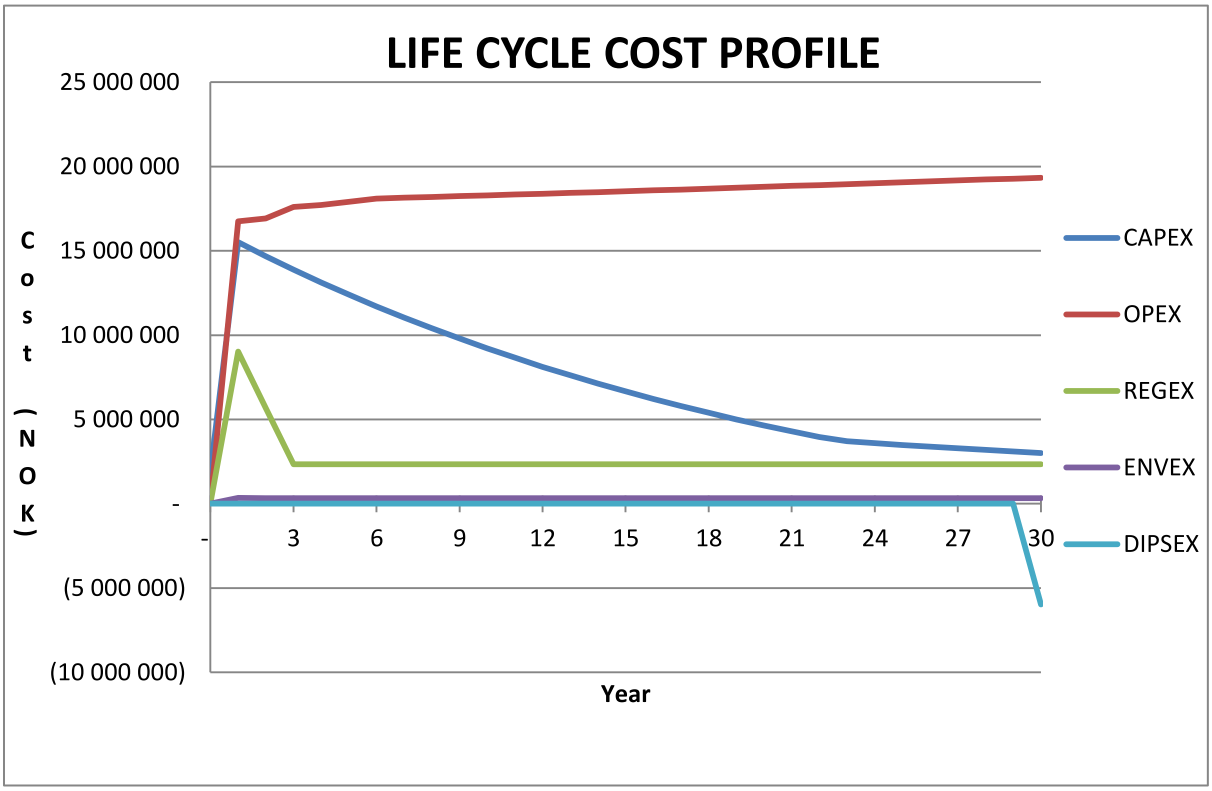

**Figure 5-1 The LNG vessel's life cycle cost profile. Manning costs are not included in OPEX.**

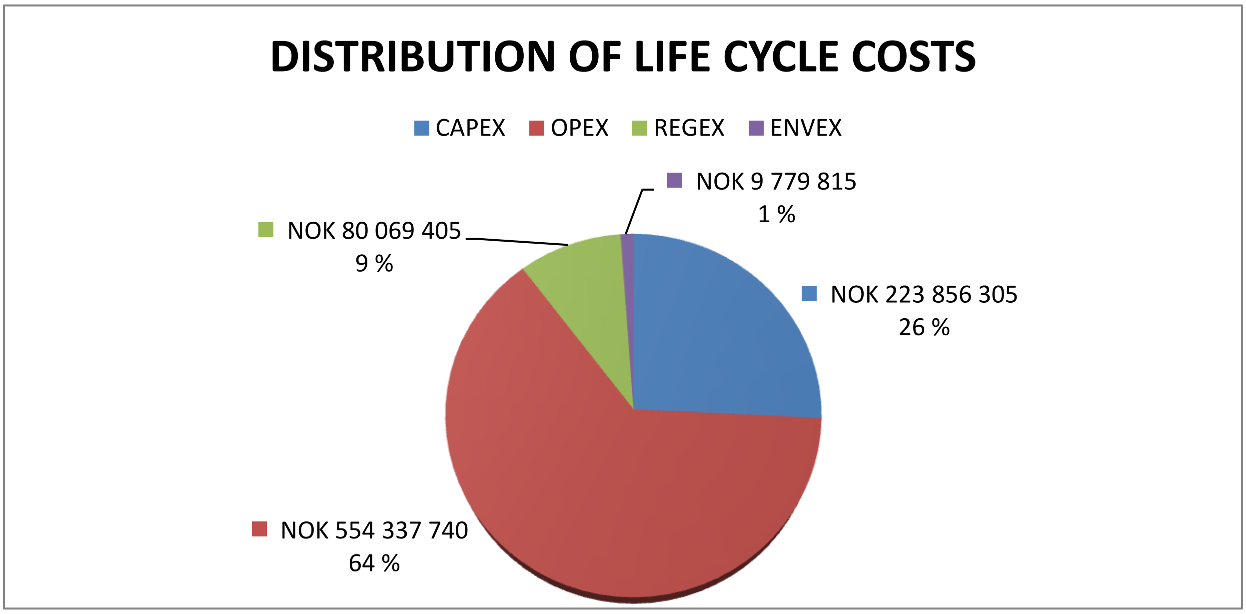

**Figure 5-2 Distribution of the LNG vessel's total life cycle costs. Manning costs are not included in OPEX.**

### 5.1.1 CAPEX

Capital expenditures, which only consist of the capital cost and the cost of the test period, have a steady decrease until the end of year 22 when the last interest costs are paid. At the end of year 1, capital expenditures are generated by the yearly depreciation and the interest costs. As the loan is gradually repaid, the interest costs are reduced until the last instalment in year 22. The effect of the inflation increases the declination of the capital expenditure graph over the time period. The capital costs are, as already mentioned, given in nominal values in section 4.1.3. As the inflation gets to work over time, the yearly capital cost is significantly lower in real terms than in nominal terms. The costs related to the procurement are very high in the beginning relative to the others cost categories, but decreases significantly over the time span. At the end of the life time, the loan is depreciated and the cost category is thereby eliminated. Figure 5-2 illustrates that capital expenditures account for about 26 % of the total life cycle costs, which is a significant portion. According to figure 5-1, most of this portion is generated through the early stages of the vessel's life time.

### 5.1.2 OPEX

As already mentioned, the operational expenditures are increasing over the time period, and they are very important with respect to the total life cycle costs. Figure 5-3 and figure 5-4 shows that it is mainly the fuel costs related to MGO that gives the increase in total operational expenditures after year 5. However, costs related to procurement of LNG constitute the most significant cost element. All the cost elements which form the operational expenditures are addressed in this section.

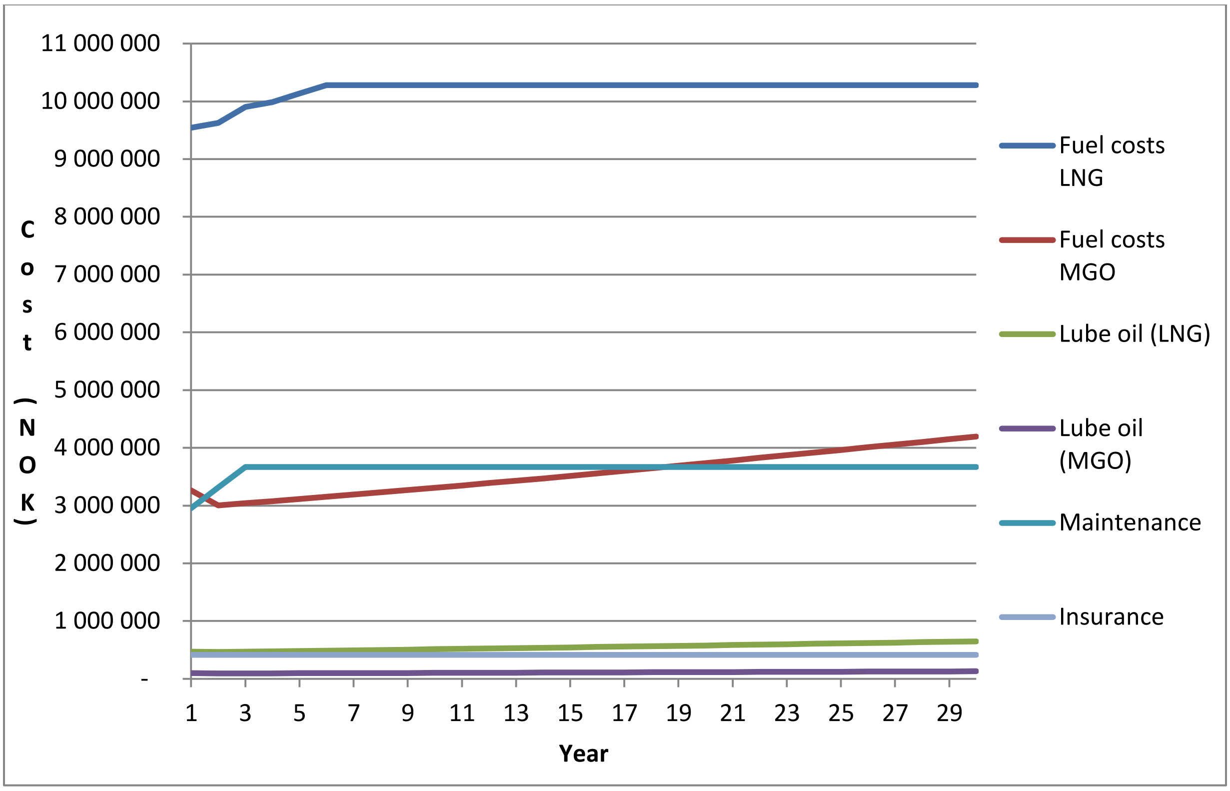

**Figure 5-3 The LNG vessel's operational expenditures**

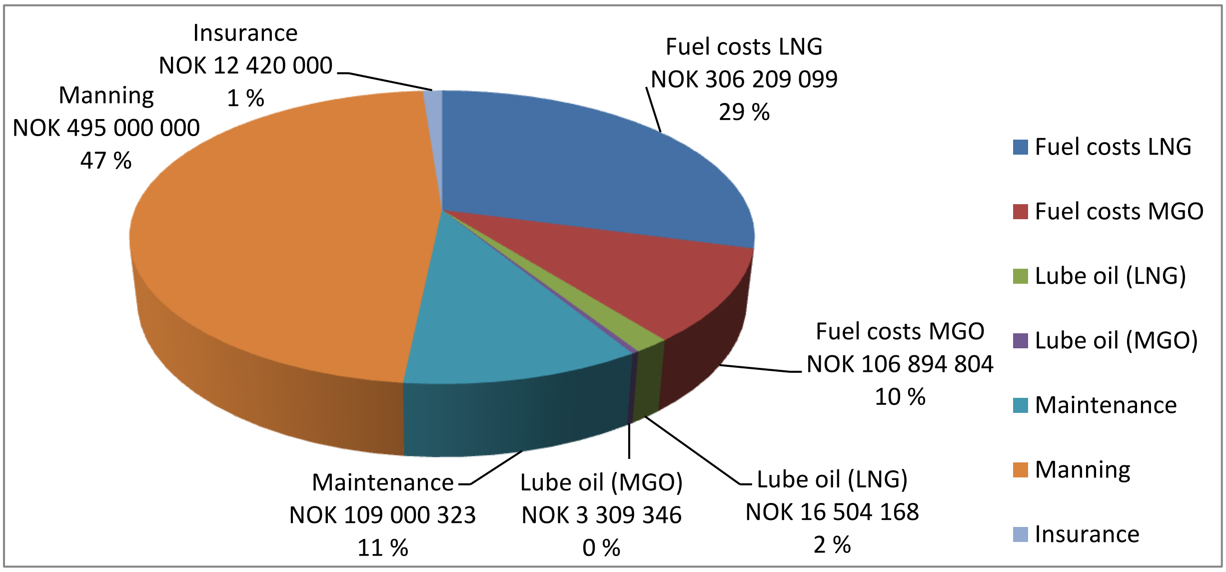

**Figure 5-4 Distribution of the LNG vessel's total operational expenditures**

### *Manning*

Costs related to the manning of the vessel account for 47 % of the total operational expenditures. This is the most significant cost element and illustrates that the operational costs generated by the vessel accounts for only 53 % of the total operational life cycle cost. However, this study emphasises the costs generated by the vessel. Hence further studies are not carried out regarding this cost element, and they are therefore not included in the total life cycle costs.

### *Fuel costs*

Procurement of LNG represents 29 % of the total operational expenditures. It increases rapidly until year 5 before it stabilises. This is due to the forecasted increase of the LNG price in the central scenario given in section 4.2.1.

The cost of acquiring MGO accounts for 10 % of the operational expenditures. According to figure 5-3, the yearly cost of MGO drops significantly from year 1 to 2 before it slowly increases for the rest of the lifetime. The drop is caused by the estimated reduction in fuel consumption after year 1, while the later increase is a result of the projected increase of MGO prices in the central scenario. MGO costs increases relatively more over the time span than LNG. In total, fuel forms 39 % of the total operational expenditures and 48 % of the total life cycle costs. Hence, fuel costs are the most important cost element if manning costs are disregarded. It is nevertheless important to underline that there is extreme uncertainty related to forecasting of fuel prices.

The price difference between the central scenarios, for respectively LNG and MGO, results in a disproportion between the energy supplied relationship and the fuel cost relationship. It is therefore significantly more expensive to run the MGO fuelled engine than the LNG fuelled engine.

**Table 5-1 The LNG vessel's energy consumptions versus energy costs.**

| Engine | Share of total energy consumption | Share of total fuel cost |
|---|---|---|
| **RR C26:33L9PG** | 81 % | 74 % |
| **MTU 8V 8000 M235** | 19 % | 26 % |

### *Maintenance*

Expenditures related to maintenance form 10 % of the total operational expenditures and 13 % of the total life cycle costs, which is a significant share. It is therefore important to consider the effect of uncertainty related to the maintenance cost. However, it may be noticed that the yearly MGO fuel cost passes the yearly maintenance cost in year 19.

### *Lube oil*

Lube oil costs constitutes in total only approximately 2 % of the total operational expenditures. It makes an insignificant share of the total life cycle cost. However, the costs related to lube oil are increasing over the time span. This is because the lube oil prices are modelled to follow the MGO prices. As a result, the significance of lube oil costs in relationship to the total life cycle cost is increasing over time. The total lube oil cost may in reality be higher since lube oil changes are not taken into account. However, it is important to emphasise that there is extreme uncertainty related to the modelling of future lube oil prices.

***Insurance***

Costs related to insurance generate only 1 % of the total operational expenditures and are also of minor importance with respect to the total life cycle cost.

### 5.1.3 REGEX

Regularity expenditures are in this model only generated by downtime costs and vary therefore only according to the downtime level. It peaks in year 1 when the downtime level is assessed to be at its highest, and stabilises when the vessel enters its average downtime level. Regex accounts for 9 % of the total life cycle cost, and is thus a significant cost element. The level of downtime is therefore a sensitive issue with respect to the total life cycle cost. This is discussed in the sensitivity analyses.

### 5.1.4 ENVEX

NOx emissions, which is the only cost element in this cost category, are highly dependent on the amount of fuel burned per engine and the respective engine's NOx emission per energy unit. The fuel consumption, which dictates the variation of the NOx emission cost, is modelled to be stabile after year 1. The cost category represents only 1 % of the total life cycle cost.

Table 5-2 clearly shows the effect of the LNG engine's performance with respect to NOx emissions. Even though it is supplied with 81 % of the total energy supply, the resulting NOx emission accounts only for 26 % of the total NOx emission cost. This is the main reason for ENVEX's relatively low share of the total life cycle costs.

**Table 5-2 The LNG vessel's energy costs versus NOx emission costs.**

| Engine | Share of total energy consumption | Share of total NOx emission cost |
|---|---|---|
| **RR C26:33L9PG** | 81 % | 26 % |
| **MTU 8V 8000 M235** | 19 % | 74 % |

### 5.1.5 DISPEX

As illustrated in figure 5-1, income related to the scrapping of the vessel is estimated to be about 6 million NOK in real value. This gives a reduction of the total life cycle costs less than 1 %. Income due to scrapping is therefore of small significance with respect to the total life cycle cost even though there is extreme uncertainty related to the scrapping price.

## 5.2 Conventional vessel

The operational expenditures are obviously the most important cost category with respect to the conventional vessel's total life cycle cost. This is illustrated in figure 5-5 and figure 5-6. On the other hand, the capital expenditures form only 2 % of the total life cycle costs. All the cost categories are discussed in the following sections.

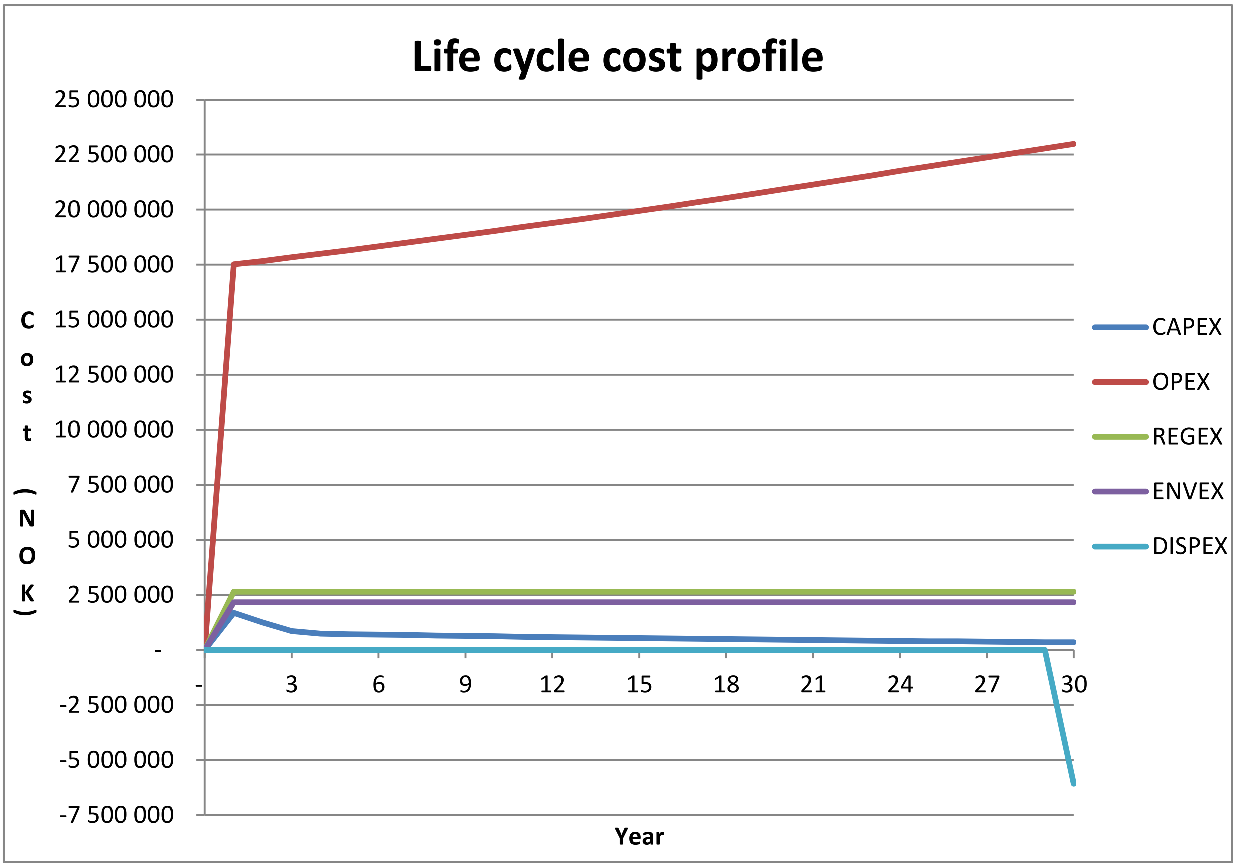

**Figure 5-5 The conventional vessel's life cycle cost profile. Manning costs are not included in OPEX.**

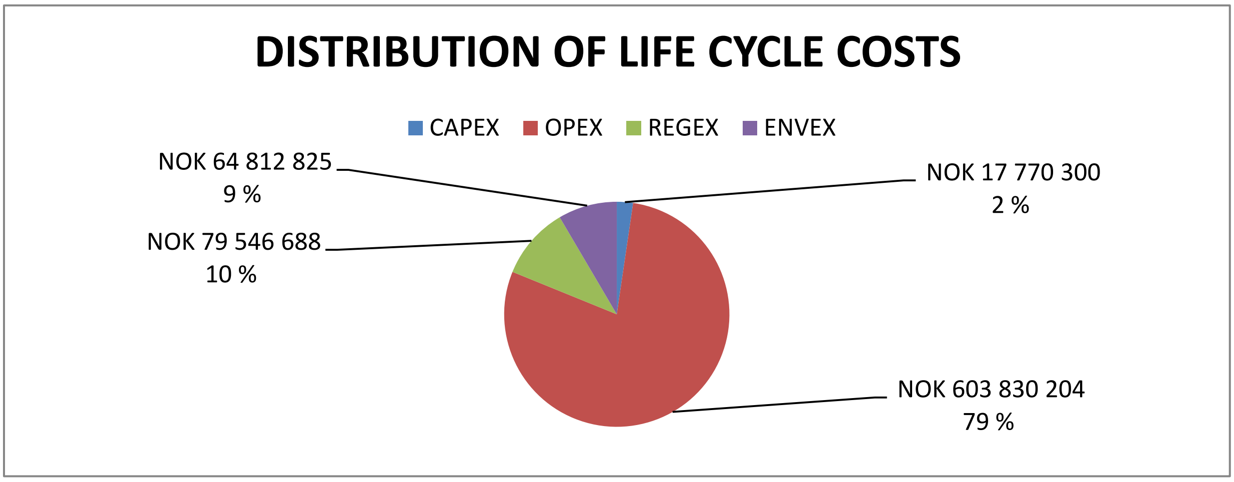

**Figure 5-6 Distribution of the conventional vessel's total life cycle costs. Manning costs are not included in OPEX.**

### 5.2.1 CAPEX

According to figure 5-6, capital expenditures form only 2 % percent of the total life cycle costs. This is since the vessel is modelled to be bought for only 25 000 000 NOK. The instalments are relatively high in relation to the size of the loan. This gives a repayment period of only 3 years. The inflation's influence on the real value of the total capital cost's is relatively low compared to the total life cycle costs.

### 5.2.2 OPEX

Not surprisingly, costs related to procurement of MGO constitute the most significant cost element. The maintenance costs are also significant. This is shown in figure 5-7 and figure 5-8. All the cost elements which make the operational expenditures are addressed in this section.

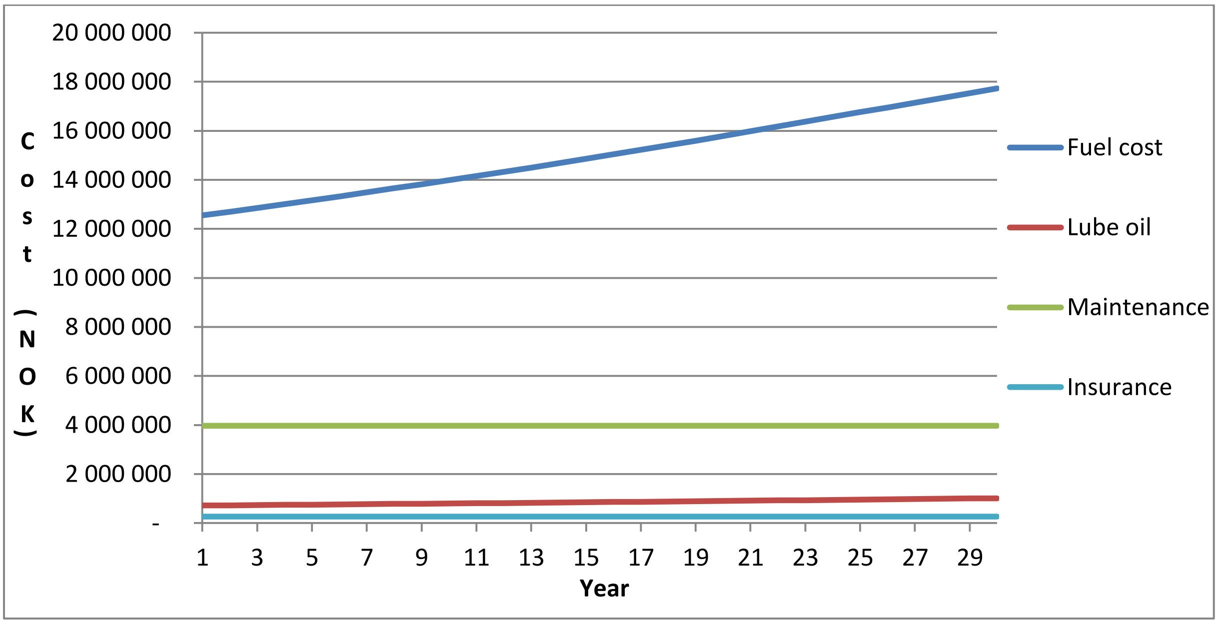

**Figure 5-7 The conventional vessel's operational expenditures**

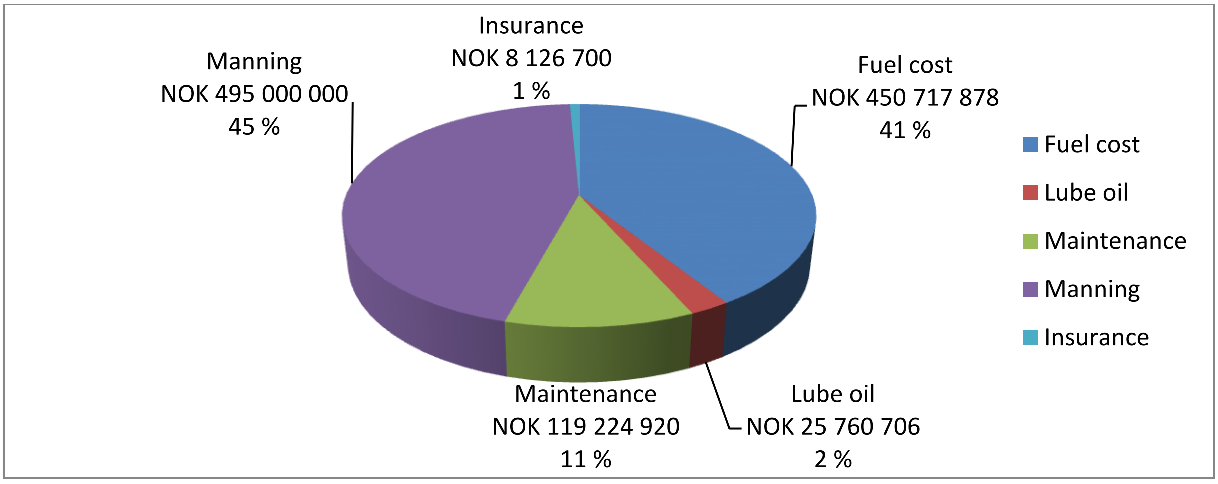

**Figure 5-8 Distribution of the conventional vessel's total operational expenditures**

***Manning***

Figure 5-8 illustrates that costs related to manning is the single most important cost element also for the conventional vessel. It makes 45 % of the total operational expenditures. However, as already mentioned, this study emphasises the costs generated by the vessel. Hence, further studies are not carried out of this cost element, and they are therefore not included in the total life cycle costs.

***Fuel costs***

The total cost of fuel represents 41 % of the total operational expenditures and 59 % of the total life cycle cost. Costs related to fuel are the most significant cost element for the vessel's life cycle cost if manning costs are disregarded. The yearly cost is increasing gradually over the time span due to the modelling of increasing MGO prices in the central scenario, which is discussed in section 4.2.1. According to figure 5-7, fuel costs are increasing more over the time span than any other cost element, and therefore drive the increase of the total life cycle costs per year. However, there is extreme uncertainty related to forecasting of fuel prices.

***Maintenance***

Costs related to maintenance are modelled to be constant over the time span of this study, which explains why the total maintenance cost per year doesn't vary. It accounts for 11 % of the total operational expenditures and 16 % of the total life cycle cost. It has therefore significant influence on the total life cycle cost.

***Lube oil***

Consumption of lube oil forms 2 % of the total operational expenditures, and has also little influence on the total life cycle cost. The yearly cost of lube oil is increasing over the time span according to the central scenario for MGO. This means that the significance of lube oil costs is increasing over the time period, but is nevertheless small.

***Insurance***

Costs generated by insurances make only 1 % of the total operational expenditures and are also of little importance for the total life cycle cost.

### 5.2.3 REGEX

The conventional vessel is modelled to have a constant downtime level, which result in a constant downtime cost. It represents 10 % of the total life cycle cost and is therefore of significant importance. Calculation of downtime is nevertheless associated with uncertainty.

### 5.2.4 ENVEX

The NOx emission from the type of engine installed in M/F Tysfjord is high, as discussed in section 4.4.1. M/F Tysfjord's NOx emission cost is primarily dependent on the amount of fuel burned by the main engine and its NOx emission factor. All the fuel consumed by the vessel is assumed to be burned by the vessel's main engine. The main engine has a high NOx emission factor, which means that all power produced by the vessel's machinery are produced at high NOx emission rates. This results in a high NOx emission cost, which accounts for 9 % of the total life cycle costs.

### 5.2.5 DISPEX

Figure 5-5 illustrates that the income due to scrapping is estimated to be about 6 million NOK when the vessel lengthening is taken into account. The income generated by scrapping reduces the total life cycle costs with less than 1 %, and is therefore of little significance with respect to the total life cycle costs. This is even though there is extreme uncertainty related to the scrapping price.

## 5.3 Comparison

According to section 5.1 and 5.2, capital costs, maintenance cost, downtime costs, fuel costs and NOx emission costs are the cost elements that have the most significant influence on the total life cycle cost for both vessels. These cost elements and the total life cycle costs as such are in this section compared.

### 5.3.1 Capital expenditures

Figure 5-9 illustrates the difference between procuring a new LNG ferry like M/F Lødingen and a 20 year old conventional vessel like M/F Tysfjord, in form of yearly capital expenditures. There is a 19 years difference in repay time. Due to the long repay- and depreciation time, inflation lowers the real value of the LNG vessel's capital cost significantly compared to the nominal value, which is presented in section 4.1.3. Over the time period, a difference of about 30 % is accumulated between the nominal value and the 2013 real value. The effect of inflation with respect to the capital costs' real value relative to the total life cycle costs is not as significant for the conventional vessel. This is due to the vessel's low value.

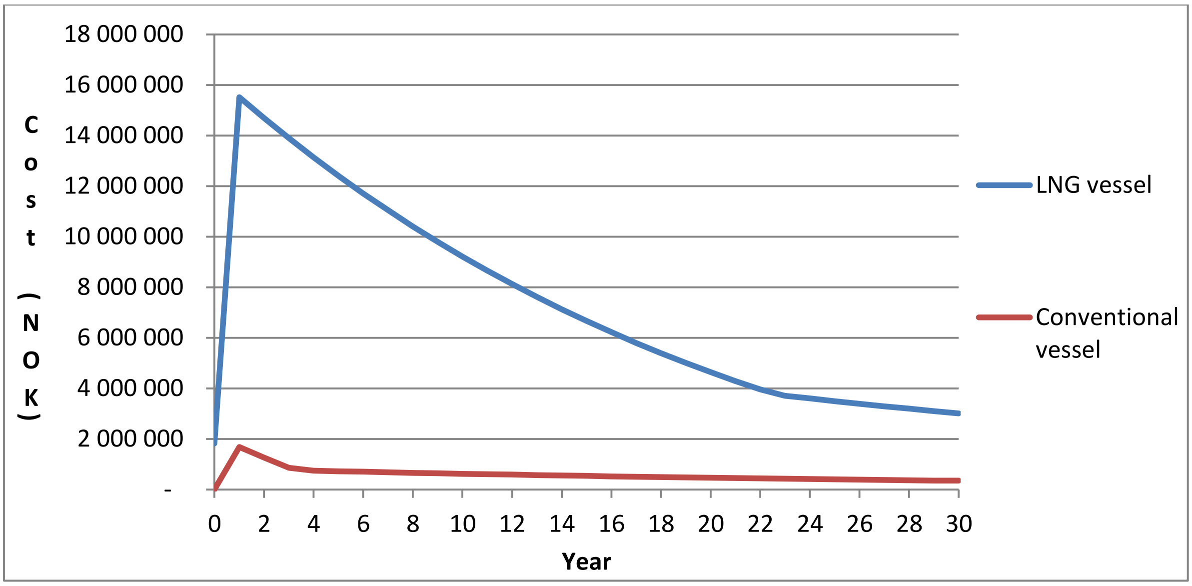

**Figure 5-9 Capital expenditures. Costs related to the test period are included for the LNG vessel.**

According to table 5-3, the total difference regarding the capital expenditures is about 206 million NOK. This difference is of major importance with respect to the total life cycle costs.

**Table 5-3 Capital expenditures**

| Cost category | LNG ferry | Conventional ferry |
|---|---|---|
| **CAPEX** | 223 856 305 NOK | 17 770 300 NOK |

### 5.3.2 Fuel costs

***Energy demand***

A key factor regarding the fuel costs is obviously the vessels' demand for energy. According to table 5-4, the conventional vessel is estimated to have about 19 % lower energy demand than the LNG vessel. There are mainly two factors that affect the energy demand, namely the vessels' hydrodynamic resistance and the efficiency of the propulsion system. The information given in section 2.1.2 and 4.2.1, indicates that both contribute to a higher energy demand for the LNG vessel. A single ended ferry tends to be more full-bodied than a double ended ferry, which increases the hydrodynamic resistance. The efficiency of the propulsion system is nevertheless difficult to assess in detail without a further study. This issue is thoroughly discussed in chapter 6.

***Total fuel costs***

In the beginning, the yearly cost of fuel is slightly higher for the LNG vessel even though the cost of LNG is 26 % lower than MGO. The main reason for this is that the LNG vessel has a significantly higher energy demand, and the fact that 19 % of this demand is related to MGO driven engines. Figure 5-10 illustrates that the yearly costs of fuel follow each other until year 8. After year 5, the LNG price is forecasted to flatten out according to the central scenario in chapter 4.2.1. Since 81 % of LNG vessel's energy demand is covered with LNG, the total fuel cost tends to flatten out as well. This creates a gap between the vessels' total fuel costs. Over time a significant difference between the fuel costs is generated, mainly due to the forecasted price increase of MGO relative to LNG. Table 5-4 shows that the resulting total fuel cost is about 9 % higher for the conventional vessel over a time period of 30 years. In other words, the total fuel cost is higher for the conventional vessel even though the LNG vessel demands a significantly higher amount of energy. However, it is important to underline that it is extreme uncertainty related to the forecasting of future energy prices.

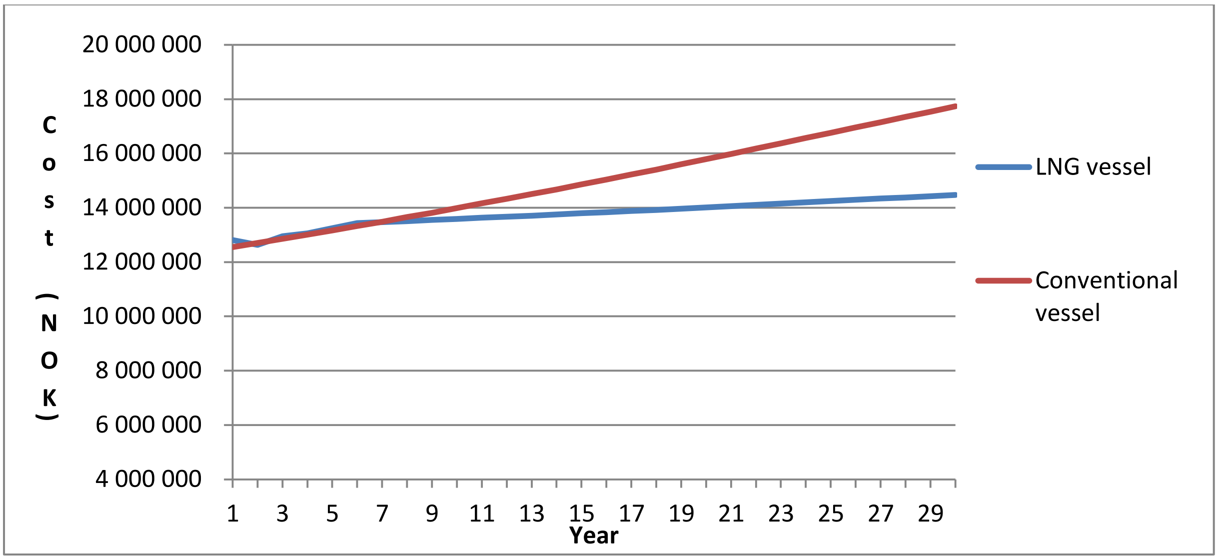

**Figure 5-10 Fuel costs**

**Table 5-4 Energy consumptions and fuel costs**

| Category | LNG ferry | Conventional ferry |
|---|---|---|
| **Energy consumption** | 28 924 373 (kWh/year) | 23 302 453 (kWh/year) |
| **Fuel cost** | 413 103 903 NOK | 450 717 878 NOK |

### 5.3.1 Maintenance cost

Figure 5-11 illustrates that the LNG vessel's yearly maintenance cost is estimated to be significantly lower than for the conventional vessel, in particular in year 1 and 2. In this period, the maintenance cost is forecasted to be reduced due to among other the guarantee on several important components and a reduced need for preventive maintenance actions.

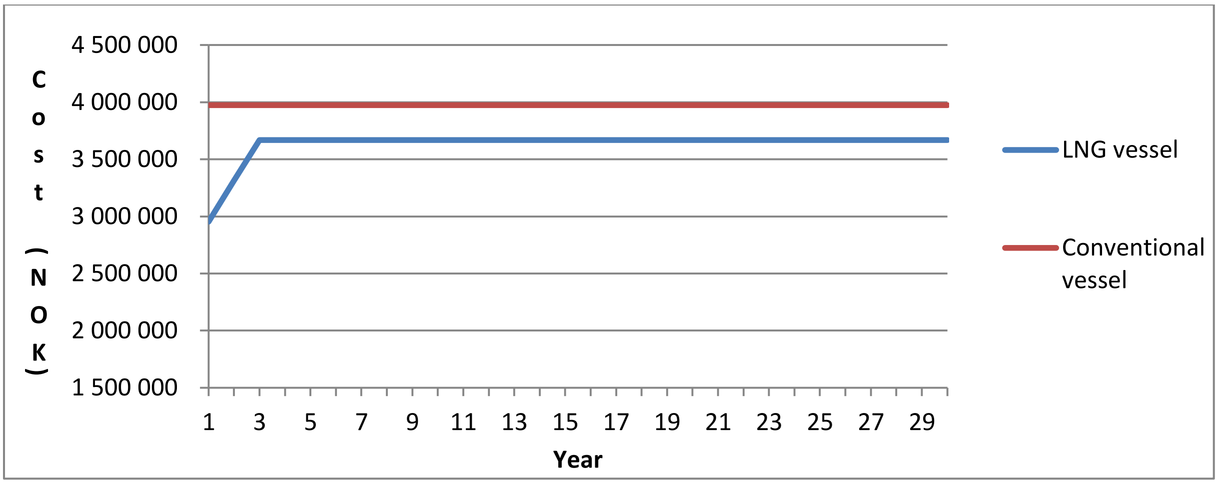

**Figure 5-11 Maintenance costs**

Table 5-5 illustrates that the total maintenance cost is about 9 % lower for the LNG vessel. However, there is extreme uncertainty both related to the modelling of maintenance costs and the data. The issue is discussed further in the sensitivity analyses.

**Table 5-5 Maintenance costs**

| Cost category | LNG ferry | Conventional ferry |
|---|---|---|
| **Maintenance cost** | 109 000 323 NOK | 119 224 920 NOK |

### 5.3.2 Downtime costs

Figure 5-12 illustrates the development of yearly downtime costs over the time period. The yearly cost is estimated to be higher for the LNG vessel while it is still in the burn-in phase. This is caused by the increased downtime in this period. The downtime cost is slightly lower for the LNG vessel from year 3. This is mainly because of the lower downtime level.

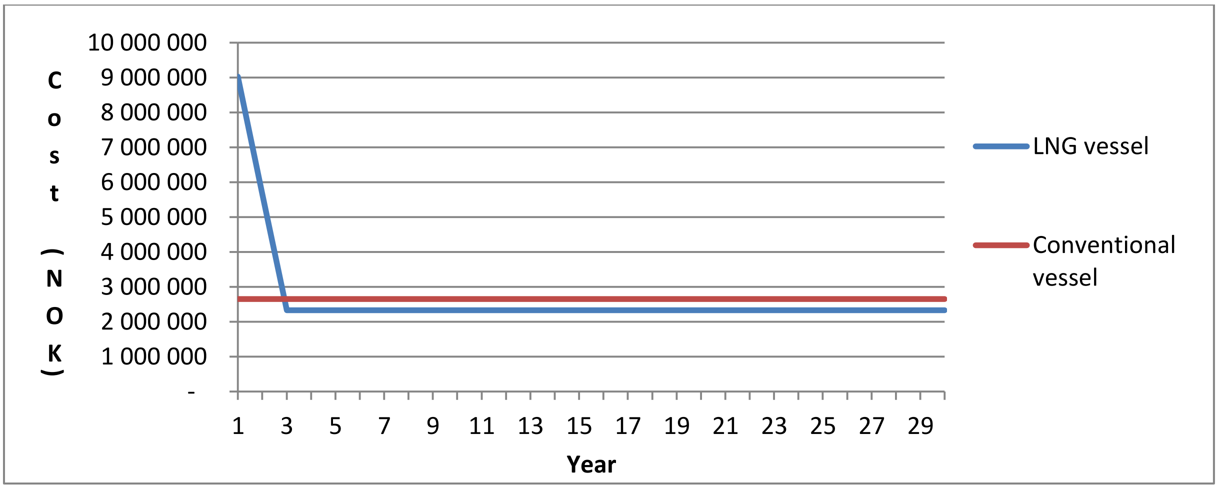

**Figure 5-12 Downtime costs**

According to table 5-6, there is no significant difference between the total downtime costs. The main reason for this is that the cost of the extra downtime in the burn-in period is regained afterwards due to a lower "normal" downtime level. It is nevertheless important to emphasise that there is extreme uncertainty related to the forecasting of future downtime.

**Table 5-6 Downtime costs**

| Cost category | LNG ferry | Conventional ferry |
|---|---|---|
| **Downtime cost** | 80 069 405 NOK | 79 546 688 NOK |

### 5.3.3 NOx emission cost

One of the most frequently used arguments to promote LNG propulsion systems have been that there are significant savings with respect to NOx emissions. Figure 5-13 illustrates that the LNG vessel has only a fraction of the conventional vessel's yearly NOx emission cost. This accumulates a difference of about 55 million NOK, which is approximately 6 % of the LNG vessel's total life cycle cost. It has only about 15 % of the NOx emission cost despite of its high energy consumption relatively to the conventional vessel, as shown in table 5-7. The vessel's low NOx emission lowers without doubt the environmental expenditures significantly.

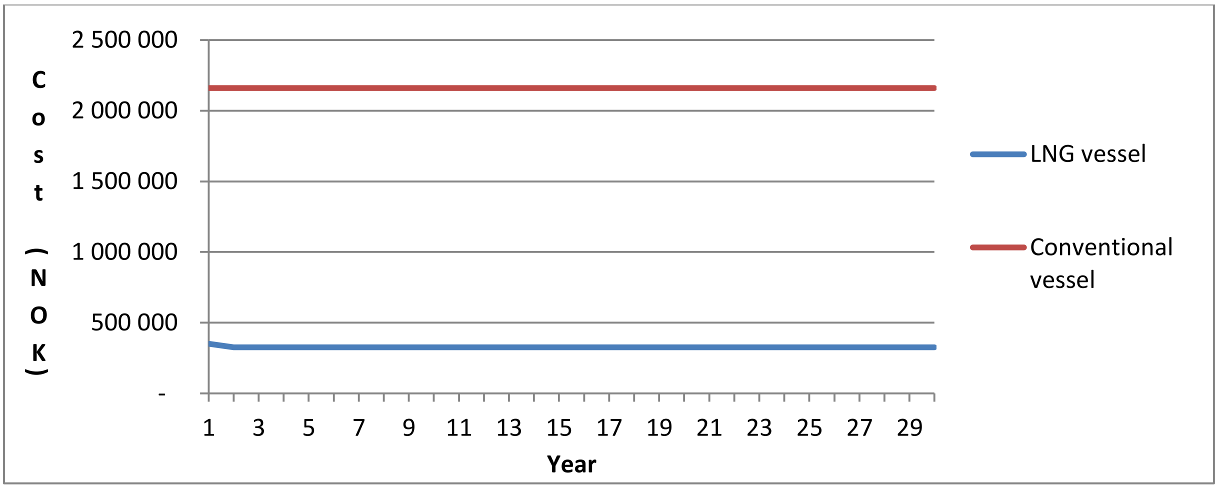

**Figure 5-13 NOx emissions costs**

**Table 5-7 NOx emission costs**

| Cost category | LNG ferry | Conventional ferry |
|---|---|---|
| **NOx emission cost** | 9 779 815 NOK | 64 812 825 NOK |

### 5.3.4 Total life cycle costs

In this section, the vessel's total life cycle costs are addressed. As already mentioned, manning costs are not included. Figure 5-14 illustrates the yearly total cost for each vessel. By the end of year 1, the gap is about 18 million NOK. This gap is generated by several factors. The capital cost related to the LNG vessel is at this point significantly higher than for the conventional vessel due to the vessel's high interest costs and depreciation costs. The difference in capital expenditures is about 14 million NOK. Costs related to downtime are in year 1 very high for the LNG vessel, and results in a difference of about 6 million NOK. However, the maintenance costs and the NOx emission costs are higher for the conventional vessel and reduce the gap by about 3 million NOK. These are the main factors that contribute to the total difference in year 1.

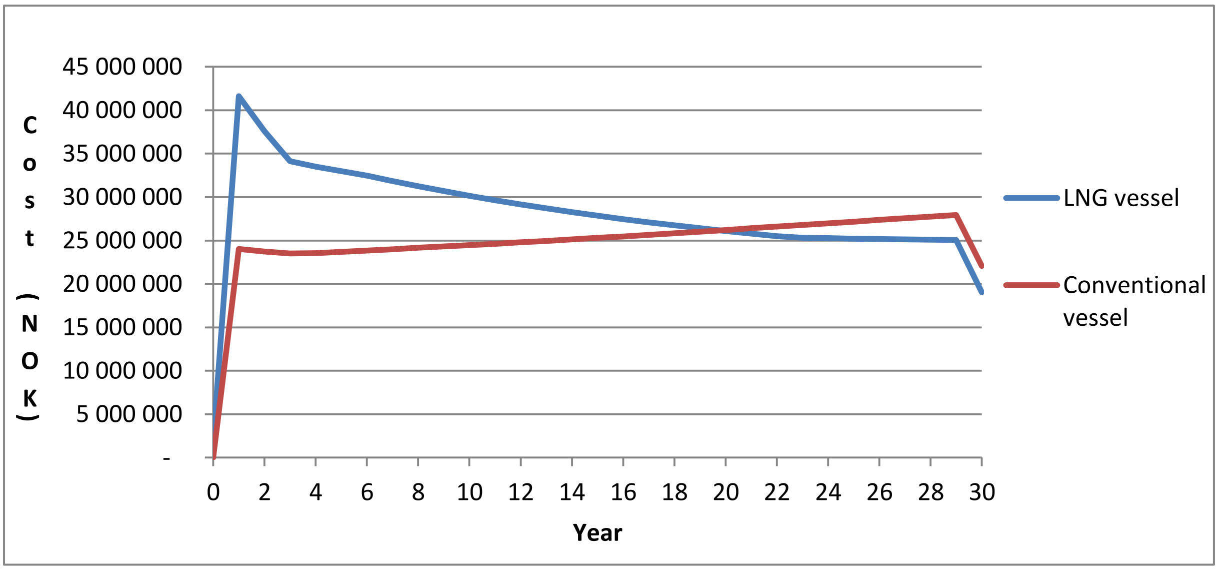

**Figure 5-14 Total life cycle cost**

The yearly cost of the conventional vessel is declining until the end of year 3, mainly due to the reduction of interest costs. Afterwards, the increase of the MGO prices results in a steadily increasing yearly cost.

Reduced downtime- and interest costs cause the LNG vessel's steep declining of the total yearly costs from year 1 to 3. The further development is complex, but the most significant factors are the fuel costs and the capital costs. The LNG prices are forecasted to flatten out after year 5, which limits the increase of fuel costs, while the capital costs are reduced continuously until year 22 due to the yearly reduction of interest costs. From year 23, it's only the effect of the inflation that lowers the LNG vessel's yearly capital costs.

The last instalment on the LNG vessel is estimated to fall due in year 22, which causes the yearly total cost to stabilise due to the cancellation of interest costs. The curves are crossing in year 20. This indicates that the LNG vessel is more cost efficient than the conventional vessel the last ten years of the time period.

According to table 5-8, the LNG vessel is not sufficiently cost efficient to regain the differences in life cycle costs, which have accumulated in the first 20 years in service. It is estimated that the conventional vessel has 12 % lower total life cycle costs than the LNG vessel, which is a significant difference. It is nevertheless important to underline that there is extreme uncertainty related to the result, which is addressed in the sensitivity analysis.

**Table 5-8 Total life cycle costs**

| Cost category | LNG ferry | Conventional ferry |
|---|---|---|
| **Total life cycle cost** | 862 080 946 NOK | 759 880 727 NOK |

### 5.3.5 Effect of internal rate of return

A nominal internal rate of return in the order of 8 % gives a real rate of return equal to 4.9 %, given 3 % inflation. See section 2.2.4 for more information. The main principal is that future costs are assessed to have lower value than costs which have to be paid today. This reduces the value of future costs according to the discount factor presented in equation ( 2.3 ). Figure 5-15 illustrates the effect of implementing an internal rate of return. The longer a cost is into the future, the more is the cost reduction. However, most of the LNG vessel's capital expenditures are paid at an early stage in the time span. At the same time the downtime costs peak. These costs are therefore relatively high compared to the costs later, which are reduced significantly due to the internal rate of return. As a result, the importance of the capital and downtime costs is increased and the conventional vessel's high fuel cost at the end of the time period is reduced. Table 5-9 indicates this. The total life cycle cost for both vessels is significantly reduced due to the internal rate of return, but the difference between them is only to a small extent affected. This means that the conventional vessel has about 19 % lower life cycle cost with 8 % nominal internal rate of return.

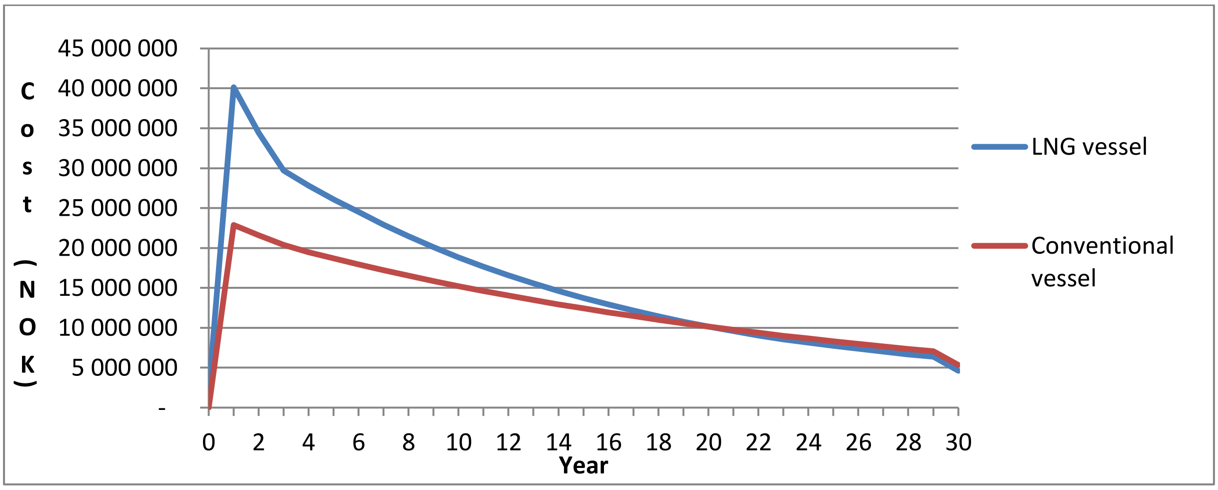

**Figure 5-15 Yearly total cost given 8 % nominal internal rate of return**

**Table 5-9 Total life cycle costs given 8 % nominal internal rate of return**

| Cost category | LNG ferry | Conventional ferry |
|---|---|---|
| **Total life cycle cost** | 478 582 901 NOK | 388 944 920 NOK |

To investigate this further, the models have been run with 12 % nominal internal rate of return. The total life cycle costs are both significantly reduced, but the difference is almost not influenced, which is similar to the result with 8 % nominal internal rate of return. With this internal rate of return, the conventional vessel has approximately 23 % lower total life cycle cost. This shows that the LNG vessel's drawback with respect to high initial capital- and downtime costs is increasing with increasing internal rate of returns. It also indicates that the favourability of the conventional vessel is increasing with increasing internal rate of returns as well.

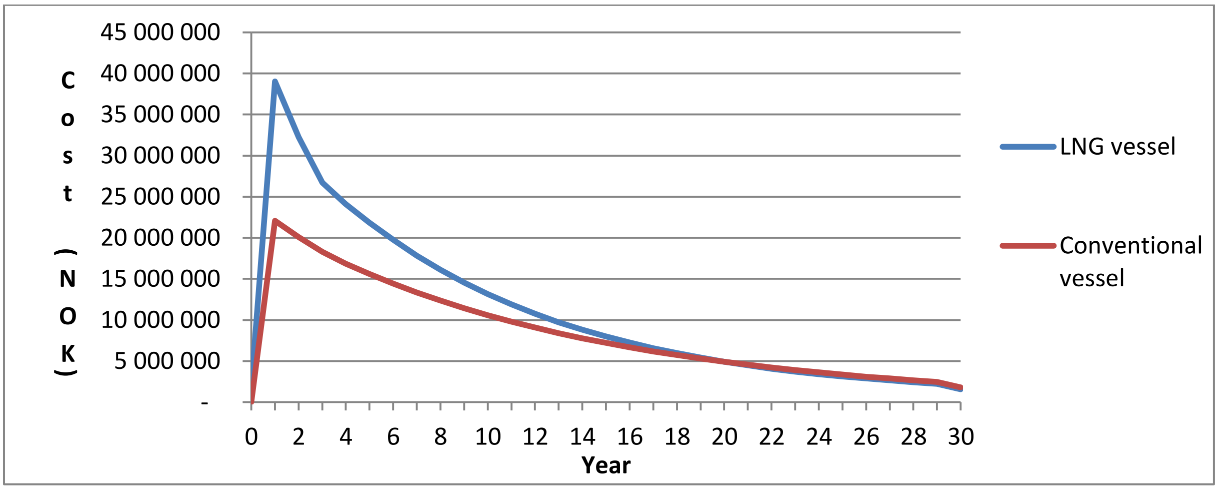

**Figure 5-16 Yearly total cost given 12 % nominal internal rate of return**

**Table 5-10 Total life cycle costs given 12 % nominal internal rate of return**

| Cost category | LNG ferry | Conventional ferry |
|---|---|---|
| **Total life cycle cost** | 336 872 401 NOK | 258 532 213 NOK |

## 5.4 Sensitivity analysis

Capital expenditures, fuel costs, downtime costs and maintenance costs are already identified as four of the most important factors with respect to the total life cycle cost. However, there is significant uncertainty related to all of them. This uncertainty will be addressed in this section. One low and one high scenario are established for each of the factors in addition to the central scenarios, which have already been discussed in section 5.1, 5.2 and 5.3. It's is important to underline that there is no probabilities included in this analysis.

### 5.4.1. Capital expenditures

Capital costs in real terms are, as already described in section 4.1.3, dependent on a variety of factors such as the size of the instalments, the own risk, the interest rate, the inflation rate and the depreciation time. The size of these is based on information given from the shipping company (Torghatten Nord, 2009). The interest rate and the inflation rate vary over time and the mechanisms are indeed complex. In the central scenario the interest rate is set to 5 %. However, generally in periods when the inflation is high, the key policy rate and thereby also the bank's interest rates are raised to lower the inflation and vice versa (Norges Bank, Frøyland, 2007). However, it is beyond the scope of this study to perform an economic analysis to provide a forecast of these rates. As a simplification, the two scenarios are based on a constant inflation.

***Low scenario***

The bank's interest rate is assumed to over time not remain lower than the inflation. Therefore, this scenario takes basis in an interest rate of 4 %.

***High scenario***

To decide a proper high scenario for the purpose of this study is rather difficult since high interest rates often occur when the inflation is high to "cool down" the economy. Since the inflation is set to be constant, too high interest rates may result in unrealistic high capital costs. Based on this, the high scenario is set to be 8 %.

***Results***

Table 5-11 shows that the uncertainty related to the interest rate mainly affects the LNG vessel, where the difference between the low- and the high scenario is 28 %. This difference has a significant influence on the total life cycle cost for the LNG vessel since capital costs account for about 26 % of the total life cycle cost.

**Table 5-11 Total capital costs**

| | LNG vessel | Conventional vessel |
|---|---|---|
| **Low scenario** | 208 100 733 NOK | 17 482 980 NOK |
| Relative reduction | -7 % | -2 % |
| **High scenario** | 271 123 022 NOK | 18 632 259 NOK |
| Relative increase | 21 % | 5 % |

### 5.4.2. Fuel costs

There is extreme uncertainty related to long term forecasting of fuel costs. The fuel price scenarios, which this sensitivity analysis is based on, have already been discussed in section 4.2.1. See this section for more information about the background for these scenarios.

***Results***

Table 5-12 illustrates the extreme uncertainty that is related to forecasting of future fuel prices. The uncertainty gives a span of 40 % for the LNG vessel and 56 % for the conventional vessel with respect to fuel costs. This is indeed extreme uncertainty especially since fuel costs account for about 75 % of the operational expenditures for both vessels when manning costs are excluded. Therefore, the future fuel prices are of the outmost importance for the outcome of the life cycle costs for both vessels. It may nevertheless be noticed that the relative difference between the high and the low scenarios is significantly lower for the LNG vessel than for the conventional vessel. However, as figure 1-1 illustrates, the energy prices tend to follow similar patterns independently of fuel type. Hence, it may not be likely that MGO will follow a high scenario while LNG follows a low scenario and vice versa. After all, the development of different fuels' prices is dependent on several common factors such as economic growth (DECC, 2013). Therefore, it may be most appropriate to carry out a comparison between fuel costs based on the same scenario. Based on this assumption, it may be noticed that the LNG vessel's fuel cost is 3 % higher than the conventional vessel's in the low scenario and 14 % lower in the high scenario. Thus, the vessel's performance relative to each other when it comes to fuel costs is heavily dependent on the development of future fuel prices.

**Table 5-12 Total fuel costs**

| | LNG vessel | Conventional vessel |
|---|---|---|
| **Low scenario** | 319 385 335 NOK | 309 864 413 NOK |
| Relative reduction | -23 % | -31 % |
| **High scenario** | 482 839 649 NOK | 562 555 974 NOK |
| Relative increase | 17 % | 25 % |

### 5.4.3. Downtime costs

To estimate the level of downtime are for both vessels associated with extreme uncertainty. The level of downtime for the conventional vessel is based on historical records, while the LNG vessel's is founded on the limited data available and expert opinions. Any extensive reliability analyses of the vessels are not carried out, which may be the preferable way to estimate the future amount of downtime.

The modelling of downtime is mainly dependent on the cost of one day of downtime and the number of downtime days per year. As described in section 4.3.1, the cost of one day of downtime is dependent on the fee issued for cancellation of trips, the lost income from passenger tickets and the savings due to reduced fuel consumption. The lost income from passenger tickets is assumed to vary insignificantly over time, while the savings due to reduced fuel consumption may fluctuate due to changing fuel prices. However, savings due to the reduction of fuel consumption lowers the cost of one day of downtime with only 10 %, which is a relatively low contribution compared to the other factors. Hence, variations of the fuel prices in the magnitude of those presented in table 5-12 will not significantly influence the downtime cost. The fee issued from Statens Vegvesen is assumed not to change over time. Based on this, it is natural to investigate the uncertainty related to the downtime level.

***Low scenario – conventional vessel***

There are many factors that may result in a lower level of downtime. The crew and the shipping company are familiar with the vessel and its equipment. They may therefore be able to improve the vessel's performance with respect to reliability by utilizing this experience and knowledge in the future operation of the vessel. Hence, a 20 % constant reduction of downtime over the time period compared to the central scenario may be a reasonable assumption.

**High scenario – conventional vessel**

As described in section 4.3.1, the assumption of perfect repair is somewhat uncertain. Equipment may deteriorate over time even though it is regularly maintained. Components which do not require maintenance and normally are assessed to last for 20 – 30 years may fail during the time span of this study due to their age. The high scenario therefore takes basis in a linear increase of downtime, which culminates in a total increase of 40 % yearly downtime at the end of the time span, compared to the central scenario.

***Low scenario – LNG vessel***

Modern engines and propulsion systems in general are often claimed to have improved reliability in relation to previous generations. In addition, the LNG system has several benefits with respect to reliability as for example reduced deterioration of the fuel – and exhaust system. This issue is already discussed in section 4.2.4 and 4.3.1. These arguments found the basis for the low case scenario, which implies that the downtime after the burn-in period is reduced by 20 % in relation to the central scenario.

***High scenario – LNG vessel***

In section 2.1.6, 4.2.4 and 4.3.1, the increase of systems and components compared to the propulsion system in the conventional vessel is discussed. The standby generator, which is made use of during port manoeuvring, is required to be functioning at all times when the vessel is in operation. In other words a diesel electric system has to be in a functioning state in addition to the LNG system. This increases the total amount of failure modes significantly. Therefore the high scenario, which is based on this argument, accounts for a 30 % increase of downtime after the burn-in period relative to the central scenario.

***Results***

Not surprisingly, the uncertainty may significantly affect the total downtime cost. It results in a span of 40 % for both the LNG vessel and the conventional vessel. The downtime costs account for respectively 10 and 9 % of the total life cycle cost for the conventional vessel and the LNG vessel. Hence the uncertainty may to some degree affect the total life cycle cost.

**Table 5-13 Total downtime costs**

| | **LNG vessel** | **Conventional vessel** |
|---|---|---|
| **Low scenario** | 66 996 849 NOK | 63 637 351 NOK |
| Relative reduction | -16 % | - 20 % |
| **High scenario** | 99 678 239 NOK | 95 456 026 NOK |
| Relative increase | 24 % | 20 % |

### 5.4.4. Maintenance cost

As described in section 4.2.4, the estimation of the maintenance cost for the conventional vessel is based on the shipping company’s financial statements. The LNG vessel’s maintenance cost is founded on calculations carried out in relation to the tender competition in 2009, four years before the vessel was put into operation. Therefore, it is significantly more uncertainty related to the maintenance cost of the LNG vessel.

***Low scenario – conventional vessel***

The data that the maintenance costs are based on are from 2009-2012. M/F Tysfjord had a major overhaul in 2008, which reduced the maintenance cost significantly in the following period. The maintenance cost in the central scenario may therefore also be considered as a low case scenario. For more information see section 4.2.4.

***High scenario – conventional vessel***

To assume perfect repairs are, as already discussed, an assumption which incorporates uncertainty. Equipment, systems and the steel structure tend to deteriorate over time despite of regular maintenance and may require additional maintenance or have to be replaced. The need of changing equipment that is obsolete due to age comes on top of this. See section 4.2.4 and 4.3.1 for a more thorough discussion. These factors may result in increased maintenance costs as the vessel accumulates additional age. Therefore, the high scenario accounts for a linear increase of maintenance costs. The increase is set to be 35 % at the end of the time span.

***Low scenario – LNG vessel***

The low case scenario is founded on that modern equipment and systems are often claimed to be more sustainable and thereby have longer maintenance intervals. Over time this reduces the demand for man hours with respect to maintenance, which again reduces the maintenance cost. Reduced deterioration of among other fuel - and exhaust system comes in addition to this. Hence a 10 % constant reduction of maintenance costs after year 2 is assumed. See section 4.2.4 for more information about the maintenance on the LNG system.

***High scenario –LNG vessel***

As described in relationship to the sensitivity analysis of the downtime costs, the LNG vessel has an increased number of systems and components compared to propulsion system in the conventional vessel. The standby generator, which originally wasn’t intended to be used in normal operation, is made used of in almost all port manoeuvring situations. Therefore, a significant amount of running hours is accumulated on the standby generator and the fuel supply system as such. This is in addition to the maintenance on the LNG engine and its fuel supply system. There is also uncertainty related to the maintenance of the LNG system. Components may demand more maintenance and be less reliable than expected. Costs related to spare parts may also be higher than foreseen. The high case scenario is based on this argumentation, and therefore forecasts a 30 % constant increase of the yearly maintenance costs. This increase is, as for the low case scenario, implemented after year 2 when the maintenance costs are assumed to stabilise.

***Results***

The span of possible total maintenance costs is significantly higher for LNG vessel. According to table 5-14, the uncertainty results in a span of 37 % for the LNG vessel and 18 % for the conventional vessel. Maintenance costs account for 20 % of the operational expenditures for the LNG vessel, if manning costs are excluded. Therefore, the uncertainty related to the maintenance cost may in particular affect the life cycle cost for the LNG vessel. It should nevertheless be noticed that all the uncertainty regarding the conventional vessel’s maintenance cost is related to whether or not the central scenario is too low.

**Table 5-14 Total maintenance costs**

| | LNG vessel | Conventional vessel |
|---|---|---|
| **Low scenario** | 98 726 836 NOK | 119 224 920 NOK |
| Relative reduction | -9 % | 0 % |
| **High scenario** | 139 820 783 NOK | 140 089 28 NOK |
| Relative increase | 28 % | 18 % |

### 5.4.5. Summary

Figure 5-17 clearly illustrates that uncertainty related to the fuel prices has the most significant effect on the total life cycle costs.

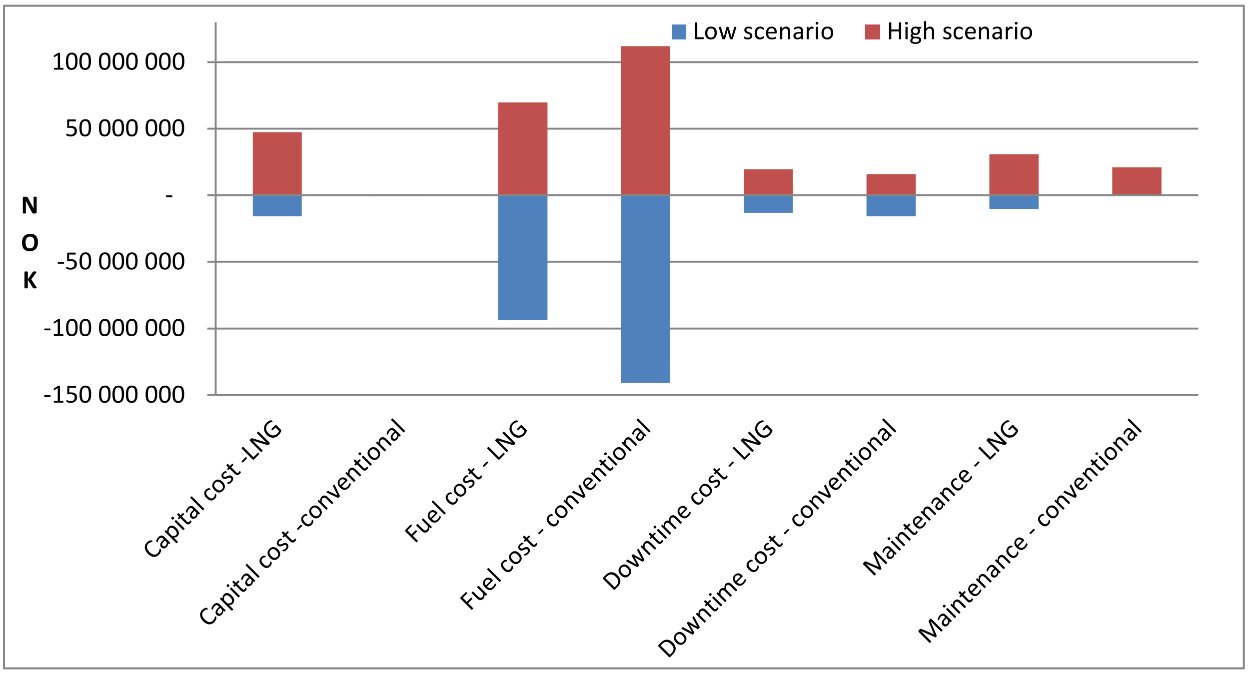

**Figure 5-17 Summary of deviations from central scenarios**

Table 5-15 shows the extreme situation if only low case- or high case scenarios occurred. The results indicate that the span between the low and the high scenario are significant for both vessels. However, the trend remains the same. The conventional vessel has a favourable lower total life cycle in both extreme situations. Its total life cycle cost is about 17 % lower in the extreme low case scenario and approximately 12 % lower in the high case scenario.

**Table 5-15 Total life cycle cost**

| | LNG vessel | Conventional vessel |
|---|---|---|
| **Low scenario** | 729 260 762 NOK | 602 830 604 NOK |
| Relative reduction | -15 % | -21 % |
| **High scenario** | 1 029 512 702 NOK | 909 354 481NOK |
| Relative increase | 19 % | 20 % |

# 6. POSSIBILITY FOR REDUCTION OF LIFE CYCLE COSTS

As described in section 2.2.2, the majority of the life cycle costs are constrained when the vessel embark its maiden voyage. However, the study has revealed that the LNG vessel's energy consumption is relatively high compared to the conventional vessel. The standby generator is made use of in almost all port manoeuvring situations due the shaft generators limited capacity. A central question is whether or not the extensive use of the standby generator has negative consequences for the vessel's life cycle cost, and if any cost reductions are achieved if a larger shaft generator is installed. This is assessed to be the measure which has the most promising prospects with respect to reducing the vessel's life cycle cost. Hence, the measure is analysed in this section with respect to potential savings and limitations. Savings may be generated due to the following relations:

- Lower cost of natural gas energy versus MGO.

- Reduced maintenance costs.

- Increased efficiency of electricity production.

## 6.1 Cost of energy

The cost of energy and emissions has already been discussed. If the cost of fuel per energy unit is added to the cost of NOx emissions per energy unit for the respective engines, we get the specific cost of energy for each engine. The results are presented in the table below.

**Table 6-1 Cost of energy ink. NOx tax. Based on input data from Norwegian Martime Authority (2011/2013), Norwegian Ministry of Taxes (2013), Torghatten Nord (2014e), Barents naturgass (2014)**

| Engine | Cost of energy |
|---|---|
| **MTU 8V 8000 M235** | 0.58 NOK/kWh |
| **RR C26:33L9PG** | 0.40 NOK/kWh |

According to table 6-1, the specific cost of energy, when the NOx emission cost is taken into account, is about 31 % lower for the LNG engine compared to the conventional standby generator.

## 6.2 Maintenance cost of standby generator

Over time when the standby generator is made use of in almost all port manoeuvring situations, a large amount of running hours is accumulated. As described in section 4.2.4, running hours generates maintenance costs for a conventional engine. According to the standby generator's supplier, the engine accumulates a maintenance cost of 10 – 12 Euros per running hours, which corresponds to 84 – 100.8 NOK, given an exchange rate 8.4 NOK/Euro (Bertel O. Steen, 2014). For information about the exchange rates applied in this study, see section 2.2.7. This cost includes the cost of spare parts and the cost of man hours for maintenance procedures that requires partly or complete disassembly of the engine (Bertel O. Steen, 2014). Maintenance costs related to for example deterioration of fuel feeder pumps, MGO filters, valves etc. are not taken into account. The cost per running hour is hence assessed to be a lower limit for the maintenance cost of the standby generator and its upstream systems. Therefore, in this study a maintenance cost of 92.4 NOK per running hour is assumed. This is assessed to be a conservative value based on the above given argumentation.

Table 6-2 is based on print-outs from M/F Lødingen's power management system. They reveal that the vessel utilizes the standby generator for 17.5 minutes in average per trip to provide extra power during manoeuvring. The standby generator is not shut down during short port stays, therefore 5 minutes is added per trip. Each time the generator is shut down, it enters a "cool-down" mode to provide proper cool down of the engine. The engine then runs at low load for about 4 minutes, hence 4 minutes extra running time is added per trip. The calculation is based on the number of trips that is given in section 3.1. The estimation indicates that a potential shaft generator change may reduce the maintenance cost by at least 206 000 NOK per year. Since deterioration of the fuel supply system isn't taken into account in this number, the value may be treated as a lower limit. However, it is important to underline that the calculation is only based on data from a very limited amount of trips. The use of the standby generator may vary significantly according to the weather conditions and the crew's practice (Torghatten Nord, 2014b).

**Table 6-2 Calculation of accumulated maintenance cost. Based on input data from Torghatten Nord (2014b), Bertel O. Steen (2014)**

| | **Time (min)** | **"In port" addition** (min) | **Shut down add.** (min) | **Total (hours)** | **Cost** |
|---|---|---|---|---|---|
| **Lødingen-Bognes** | 21 | 5 | 4 | 0.5 | 46.2 NOK |
| **Bognes - Lødingen** | 14 | 5 | 4 | 0.38 | 35.4 NOK |
| **Average** | 17.5 | 5 | 4 | 0.44 | 40.8 NOK |
| **Pr. year** | 88 270 | 25 220 | 20 176 | 2 228 | **205 846 NOK** |

## 6.3 Engine efficiency at constant versus variable speed

It is a commonly known fact that most engines accomplish a better overall efficiency when running on variable speed contra constant speed in low load situations (Haberg, 2014). The main switchboard is a conventional AC switchboard, which is designed to be supplied with constant 60 Hz voltage frequency directly from the generator. Since the generator is of 4 pol type, the prime mover has to run at the speed calculated by use of equation ( 6.1 ) (Rolls Royce, 2014b, Ådnanes, 2003):

$$S_{Pm} = \frac{f * 2 * 60}{p} \tag{6.1}$$

Here denotes $S_{Pm}$ the rotational speed of the prime mover, $f$ the switchboard frequency and $p$ the generators number of pols.

From equation ( 6.1 ), it is estimated that the prime mover has to run with 1800 rpm. This is the maximum rated speed of the standby generator (MTU, 2014). A generator operated at constant speed has to be running at its maximum rated speed to be able to reach its maximum power production limit. To illustrate this, M/F Tysfjord's BRM-6's power range diagram is used as an example in figure 6-1.

The blue line illustrates the operational curve, which a prime mover at constant speed operates according to. The orange line illustrates the potential for fuel savings when the speed can be varied. There are several reasons for this and the relations between them are complex. However, increasing specific fuel consumption with increasing speed at a constant load is mainly due to the increase of friction resistance in the engine (Heywood, 1988). Therefore, a generator running at constant speed has poor overall efficiency at low loads.

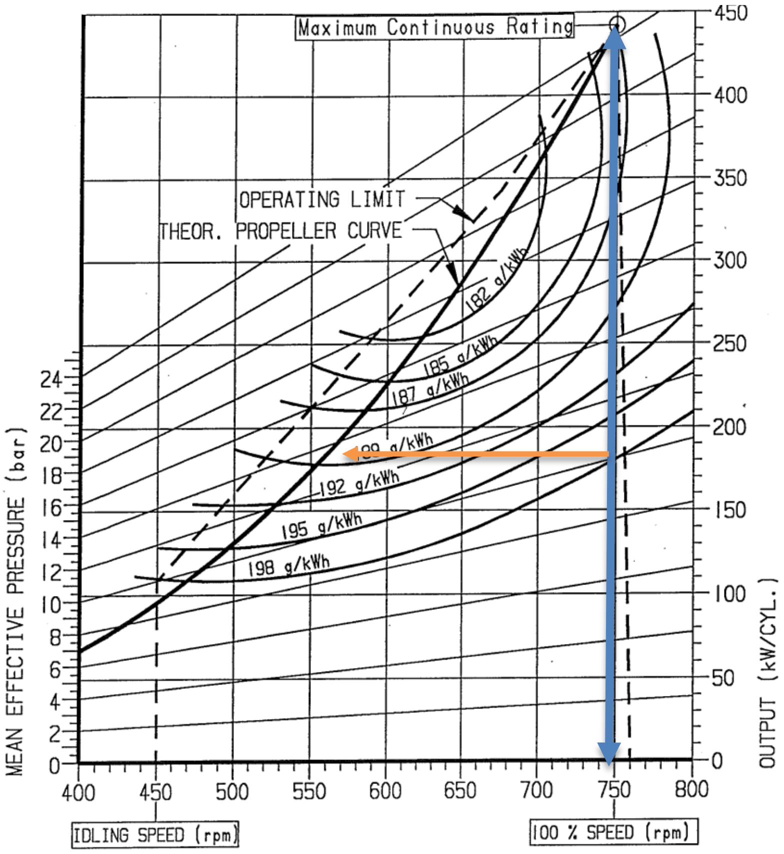

Figure 6-1 BRM-6 power range diagram (Ulstein Bergen Diesel, 1991)

The main engine is on the other hand operated at variable speed. Rolls Royce's lean burn gas engines are well renowned for its high efficiency at a large span of engine loads. The engines are able to perform at high overall efficiencies even at loads down to 25 % given variable speed operation. There are several complex factors that enables this performance (Rolls Royce, 2012, Haberg, 2014). However, a thorough discussion of combustion theory is beyond the scope of this study. The gas engines performance at variable speed is given in table 6-3.

The engine efficiencies are provided by testing carried out by the engine's manufacturer. However, the efficiencies are not corrected with respect to the extra load from engine driven pumps as for example the water pump. The efficiency is to be reduced by a factor of 0.5 % for each engine driven pump. This engine has three engine driven pumps. Therefore engine driven pump losses reduces the efficiency with a factor of 1.5 % (Haberg, 2014).

To get the actual overall efficiency, the test results have to be adjusted for a deviation margin. According to the prevailing standard for such engine testing, higher specific fuel consumption in the order of 5 % is permitted when the engine is in its real operational environment, and not at the test site (International Standard Organization, 2002). Hence, to get the actual overall efficiency, the given engine efficiency is reduced further with a factor of 5 %. This means that to be on the conservative side, the engine's efficiency has to be reduced by 6.5 % to get the actual overall efficiency (Haberg, 2014). The results are shown in table 6-3. They confirm that the LNG engines performs at high overall efficiencies over a large load span given variable load.

**Table 6-3 Gas engine's efficiency. Based on input data from Haberg (2014), Rolls Royce (2012)**

| **Load** | **100 %** | **85 %** | **75 %** | **50 %** | **25 %** |
|---|---|---|---|---|---|
| **Load (kw)** | 2430.0 | 2065.5 | 1822.5 | 1215.0 | 607.5 |
| **Engine efficiency** | 0.47682 | 0.47431 | 0.47182 | 0.45831 | 0.42338 |
| **Engine driven pump losses** | 0.0072 | 0.0071 | 0.0071 | 0.0069 | 0.0064 |
| **ISO margin** | 0.0238 | 0.0237 | 0.0236 | 0.0229 | 0.0212 |
| **Actual overall efficiency** | **44.6 %** | **44.3 %** | **44.1 %** | **42. 9 %** | **39.6 %** |

As discussed in section 4.2.1, the main engine is operating according to a so-called combination curve. However, the calculated overall efficiency given in table 6-3 is assessed to be conservative compared to the engines actual operation on board the vessel (Haberg, 2014).

## 6.4 Analysis of potential shaft generator replacement

As already described in section 2.1.6, a shaft generator produces electricity power out of mechanical energy gathered from the main engines reduction gear. The shaft generator installed in M/F Lødingen has a max capacity of 800 kW, while the bow- and stern thrusters together demand 1000 kW at full throttle. The power demand from other consumers such as lights, pumps, heating etc. comes in addition. These consumers are commonly referred to as "the hotel load". The hotel load for this vessel is normally in the magnitude of 100 – 300 kW (Torghatten Nord, 2014b). Based on this data a shaft generator with a capacity of 1500 kW will be able to supply all the consumers and thereby eliminate the need of running the standby generator during port manoeuvring.

### 6.4.1 Efficiencies

All the components that are shown in figure 6-2 are associated with energy losses. The efficiencies of the following components are discussed in this section: shaft generator, variable speed drive and reduction gear.

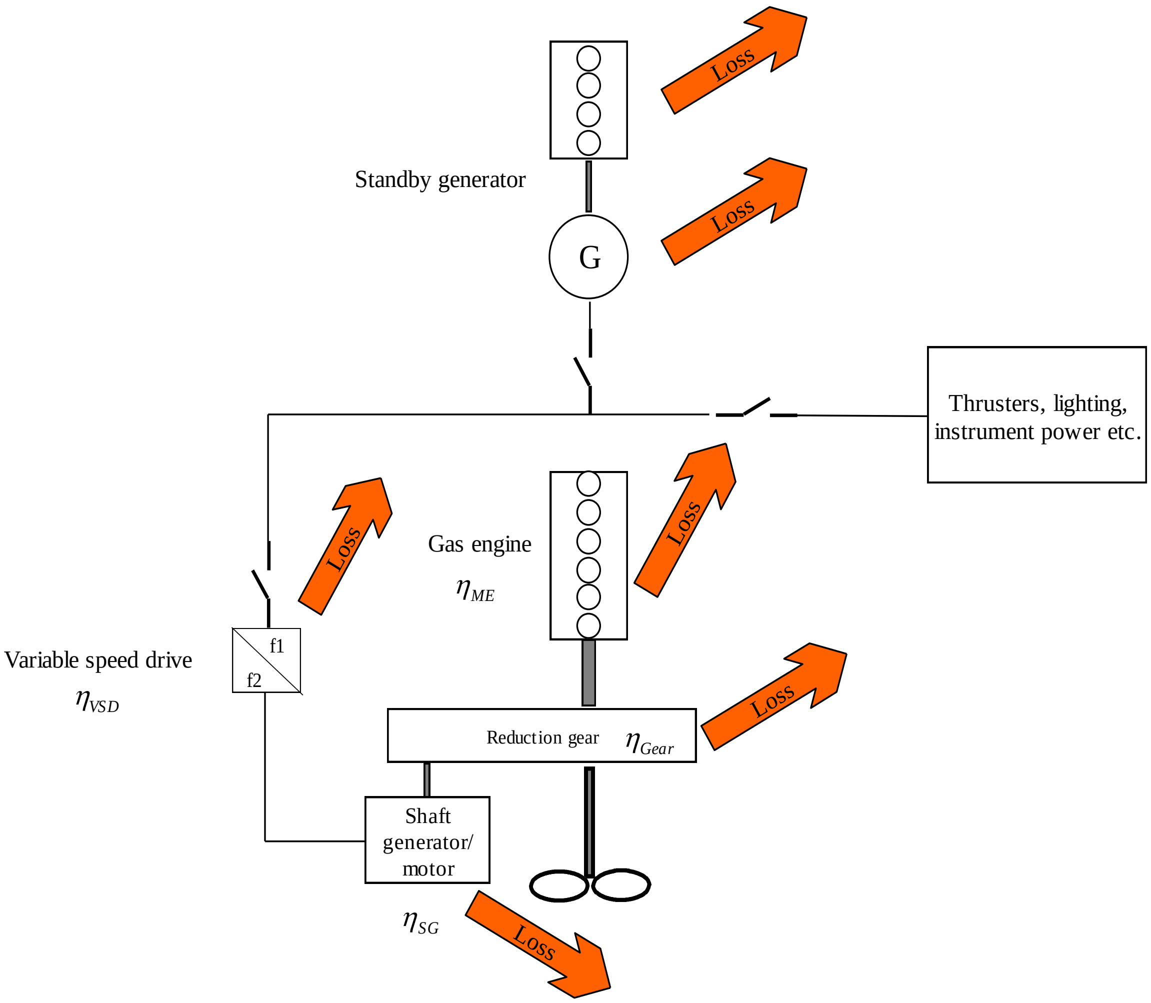

**Figure 6-2 Illustration of the losses in the hybrid system**

### *Shaft generator*

The existing generator will have a beneficial efficiency up to its 800 kW maximum continuous rating. At 800 kW production rate, the existing generator has about 2.5 % better efficiency, which is a relatively small difference. Data regarding the shaft generators' efficiency at lower loads are not specified by the producers. However, the reduction of the shaft generators' efficiency from 50 % load to 10 % load may unofficially be in the order of 5-6 % (Erstdal, 2014). Hence, the shaft generators efficiency at very low loads such as 150 kW will be of approximately the same magnitude.

**Table 6-4 Shaft generators' efficiency. Based on data from Rolls Royce (2014b)**

| | Existing | Marelli B5J 500 LC6 |
|---|---|---|
| **Max continuous rating** | 800 kW | 1500 kW |
| **Efficiency at 100 % load** | 96.9 % | 97.5 % |
| **Efficiency at 75 % load** | 95.9 % | 96.5 % |
| **Efficiency at 50 % load** | 93.8 % | 94.4 % |

***Variable speed drive***

To be able to run a 1500 kW shaft generator in this system, the variable speed drive has to be changed to handle the increased power output from the shaft generator. The voltage frequency of the power produced by the shaft generator will vary since the speed of the shaft generator depends on the speed of the main engine. The variable speed drive's function is to transform the voltage frequency into a constant 60 Hz frequency (Ådnanes, 2003). The losses associated with the VSD are about 5 % of the supplied power. They are assumed to be unaffected by the change of VSD (Rolls Royce, 2014b).

***Reduction gear***

According to the supplier, the reduction gear mounted to the main engine is dimensioned to deliver at least 1500 kW to the shaft generator, and is therefore not influenced by the replacement. The losses related to the reduction gear are normally assessed to be less than 3 % (Rolls Royce, 2014b).

### 6.4.2 Costs

The budget price of a 1500 kW shaft generator of the type B5J 500 LC6, is according to the supplier 670 000 NOK, while a VSD dimensioned for this shaft generator costs about 1 500 000 NOK. Cost of installation, cables etc. are not included in these prices, but are nevertheless relatively small compared to the two components (Rolls Royce, 2014b).

### 6.4.3 Data gathering

To assess the possibility for cost reductions, it is necessary to obtain data which describes the operation of the propulsion system. Ideally, the data should reflect the average operation of the vessel over a long time period. This is because the operation of the vessel is dependent on among other the crew’s practice and the weather conditions. However, due to the time limitation of this study data are only obtained from a very limited time period.

Data for this analysis is provided by print-outs from the M/F Lødingen’s power management system. The purpose is to be able to assess the effect of a potential shaft generator replacement. This analysis takes basis in three trips, which were carried out 18.03.2014. One of these is from Lødingen to Bognes (08:00-09:11) and two are from Bognes to Lødingen (06:40 -07:47 and 09:15-10:22). Data from two trips were needed to be able to get a complete set of data for the crossing from Bognes to Lødingen. The weather conditions were very good during this time period. However, it is important to underline that the data for this analysis are only based on a very limited time span and are transferred to spreadsheets by use of manual readings. Hence, uncertainty and inaccuracy are implemented into the calculation.

In total, four types of data are made use of:

- Standby generator’s fuel consumption
- Standby generator’s power production
- Shaft generator’s power production
- Gas engine’s gas consumption

### 6.4.4 Current efficiency of standby generator

Figure 6-3 illustrates the efficiency of the standby generator under normal operational conditions. It is based on the vessel’s logging of the standby generators fuel consumption and the produced power. The figure indicates that the generator is mostly running with an overall efficiency in the region of 20-30 %. The average efficiency is calculated to be 25.9 % and 21.9 % for each crossing direction. As figure 6-3 illustrates, the standby generator is made use of twice in one direction and only once in the other. This is due to the need of turning the vessel, which is discussed in section 2.1.4. Increased demand for manoeuvring power increases the efficiency of the generator. This is due to the reasons discussed in section 6.3. Hence, the average efficiency differs according to the crossing direction.

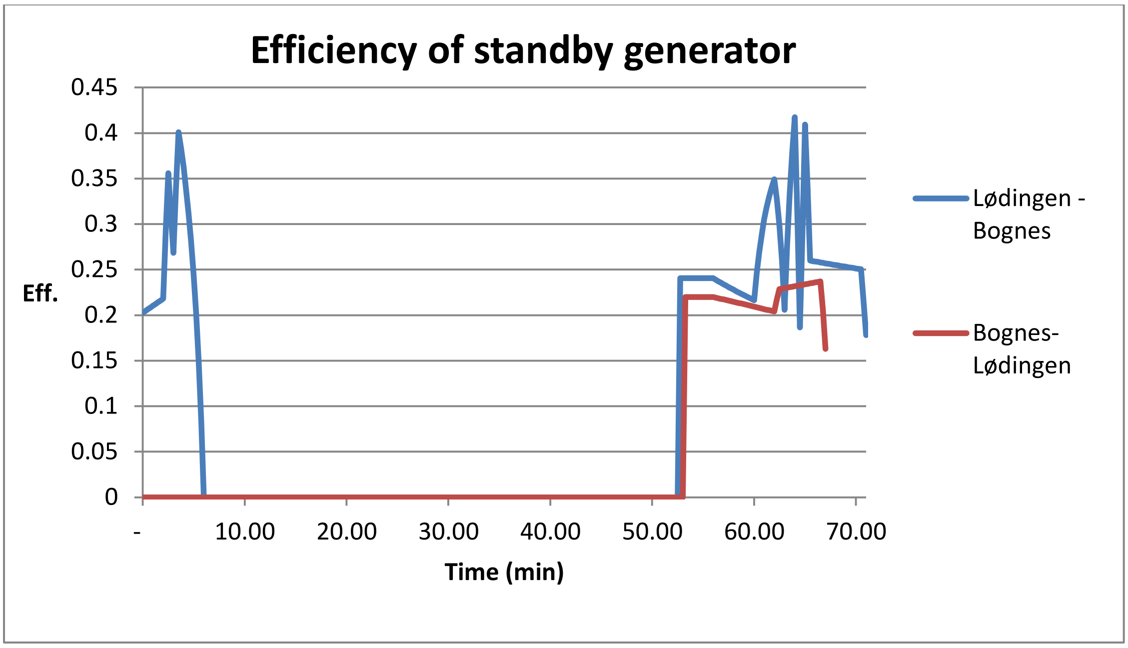

**Figure 6-3 Current efficiency of standby generator. Based on input data from Torghatten Nord (2014b)**

### 6.4.5 Hybrid system efficiency

$$\eta_{hybrid} = \eta_{ME} * \eta_{gear} * \eta_{SG} * \eta_{VSD} \tag{6.2}$$

Equation ( 6.2 ) describes the efficiency of electricity production by use of the “new” hybrid system. $\eta_{ME}$ denotes the main engine efficiency, $\eta_{gear}$ the gear efficiency, $\eta_{SG}$ the 1500 kW shaft generator’s efficiency and $\eta_{VSD}$ the variable speed drive efficiency. As already discussed, the different component’s efficiencies are highly dependent on the power production rate. However, if we assume the efficiency at 50 % load for the shaft generator and 50 % load on the main engine, the system’s overall efficiency will be about 37 % percent.

As an exemplification, an increase in the efficiency of the electricity production from 25 % to 37 % will reduce the energy consumption with more than 32 %. In addition, LNG energy (included cost of NOx emissions) is at the moment 31 % cheaper than MGO. This gives a potential of reducing the total amount of NOx and fuel cost, generated by the standby generator during manoeuvring, with about 53 %. Table 6-2 shows that on top of this reduction, the maintenance costs may be reduced with at least 206 000 NOK per year. This indicates that it may be valuable to study the potential savings.

### 6.4.6 Main engine capacity

It is necessary to investigate whether or not the main engine is able to handle the extra load, which this replacement will involve within its limitations. Since the main engine is mechanically connected to the propeller shaft, the engine power production is not measured directly (Haberg, 2014). It is therefore estimated by use of the gas flow and the engines efficiency according to the equation below:

$$P_{ME\_EX}(t) \qquad = \qquad P_{gflow\_EX}(t) * \eta_{ME}(P_{ME\_EX}) \tag{6.3}$$

Here denotes $P_{ME\_EX}$ the main engine's existing power production as a function of time *t*, $P_{gflow\_EX}$ the existing supplied gas power as a function of time, and $\eta_{ME}$ the main engine's efficiency, which again is a function of the main engine's power production.

To determine the main engine's power production, it is necessary to carry out an iteration process with respect to $\eta_{ME}$. The values for $\eta_{ME}$ is based on those given in table 6-3. The variation between the efficiency values given in table 6-3 is modelled to be linear due to the limited data available. All power production below 25 % of the main engine capacity is set to be produced at 39.6 %. This is a simplification which implements uncertainty. However, the uncertainty is assessed to be relatively small. The reason is that the engine seldom produces less than 25 % of its maximum continuous rating. Therefore, this assumption is evaluated to be good enough for the purpose of this study. The iteration process is carried out by use of the computer software MATLAB. The script can be found in "Appendix G – MATLAB script: Main engine efficiency".

Figure 6-4 clearly indicates that the main engine load is at its highest when the vessel is manoeuvring at Bognes. The reason is that the vessel is turned 180 degrees by use of both thrusters and the main propeller.

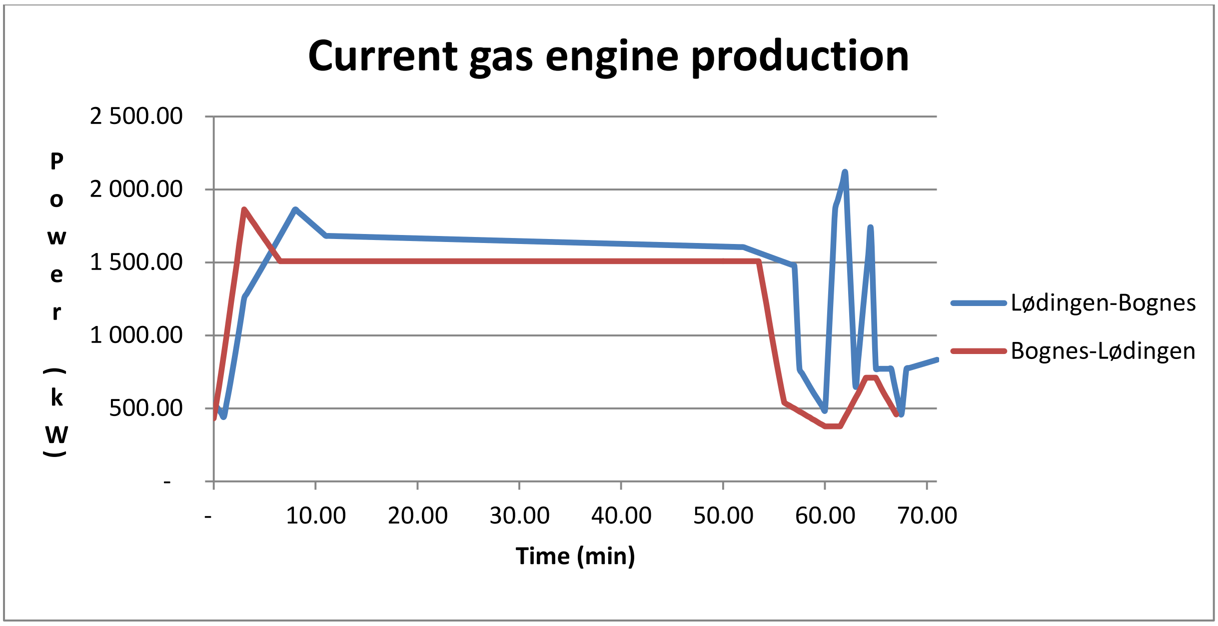

**Figure 6-4 Current gas engine production. Based on input data from Torghatten Nord (2014b), Rolls Royce (2012)**

To calculate the new gas engine production, it is necessary to determine the main engine's propeller load. This is done according to the equation below.

$$P_{propeller}\,(t) \quad = \quad P_{ME\_EX}(t) * \eta_{gear} - \frac{P_{SG\_EX}(t)}{\eta_{SG_{Ex}}(P_{SG_{EX}}) * \eta_{VSD}} \qquad (6.4)$$

Here denotes $P_{ME\_EX}$ the existing main engine power as a function of time, $P_{SG\_EX}(t)$ the produced shaft generator power as a function of time, $\eta_{gear}$ the gear efficiency, $\eta_{SG\_Ex}$ the existing shaft generator's efficiency as a function of $P_{SG_{EX}}$ and $\eta_{VSD}$ the VSD efficiency. $P_{propeller}$ represents the propeller load as a function of time.

The existing shaft generator's efficiency is modelled to vary linearly according to the data given in table 6-4. Production below 50 % of the shaft generator's maximum capacity is set to be 93.8 %. This assumption implements uncertainty. However, a shaft generator's efficiency varies only to a small extent even at low loads (Erstdal, 2014). Hence, the assumptions are assessed to be good enough for the purpose of this study even though it is non-conservative. MATLAB is applied to model the variation of $\eta_{SG_{Ex}}$. See "Appendix F – MATLAB script: Existing shaft generator efficiency" for more information about the script.

The new shaft generator load can then be calculated according to the equation below.

$$P_{SG\_NEW}(t) = P_{SG\_EX}(t) + P_{ST}(t) \qquad (6.5)$$

Here represents $P_{SG\_NEW}$ the new shaft generator load, $P_{SG\_EX}$ the existing shaft generator load and $P_{ST}(t)$ the standby generator load. All are functions of time.

Figure 6-5 illustrates the new accumulated shaft generator production for one crossing direction. It may be noticed that it peaks above 800 kW for two short time periods. This shows that the existing shaft generator is not able to carry the total thruster and hotel load even at good weather conditions.

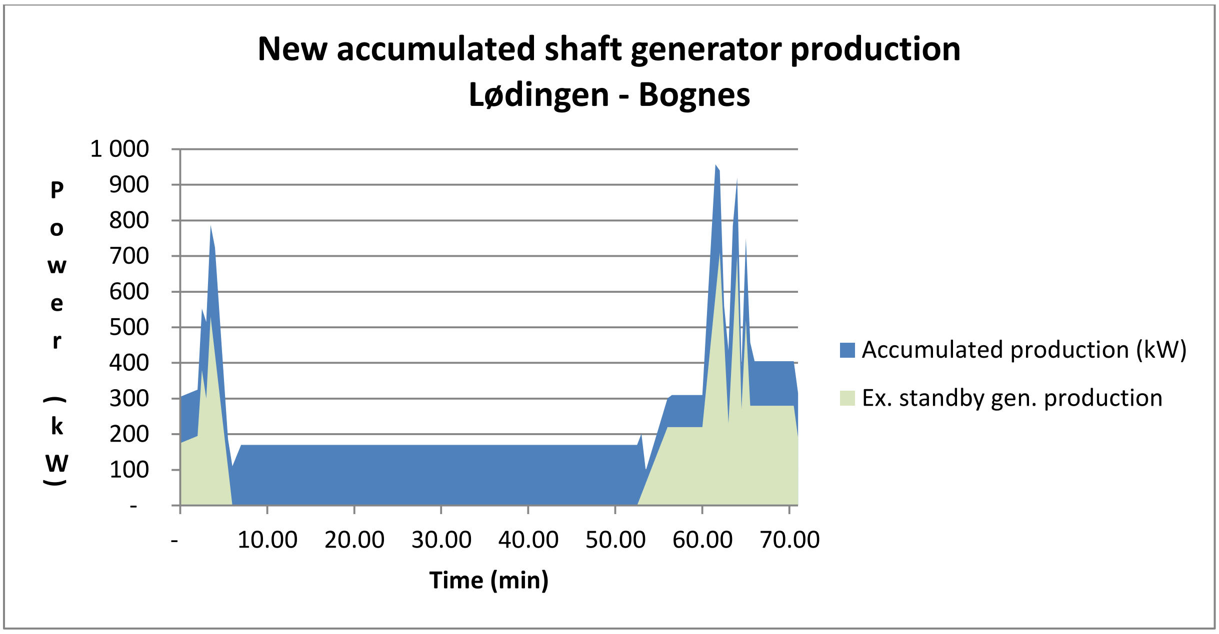

**Figure 6-5 New accumulated shaft generator production. Based on input data from Torghatten Nord (2014b)**

The main engine's new load can then be calculated according to the equation below.

$$P_{ME\_NEW}\,(t) = \frac{P_{SG\_NEW}(t)}{\eta_{gear} * \eta_{SG_{NEW}}(P_{SG\_NEW}) * \eta_{VSD}} + \frac{P_{propeller}\,(t)}{\eta_{gear}} \qquad (6.6)$$

Here denotes $P_{ME\_NEW}$ the main engine's new load, $P_{SG\_NEW}$ the new shaft generator load and $P_{propeller}$ the propeller load. All are functions of time. $\eta_{gear}$ represents the gear efficiency, $\eta_{SG_{NEW}}$ the new shaft generator's efficiency as a function of $P_{SG\_NEW}$ and $\eta_{VSD}$ the VSD efficiency.

The new shaft generator's efficiency is modelled to vary linearly according to the data given in table 6-4. Production below 50 % of the shaft generator's maximum capacity is set to be 94.4 %. As discussed already in relation to the existing shaft generator, this type of assumption implements uncertainty into the calculation, but are assessed to be good enough for the purpose of this study. It is nevertheless important to underline that the assumption is non-conservative. MATLAB is applied to model the variation of $\eta_{SG_{NEW}}$. See "Appendix H – MATLAB script: New shaft generator efficiency" for more information about the script.

Figure 6-6 illustrates the estimated main engine's new production. It is important to notice that the engine maximum continuous rating of 2430 kW is exceeded for a short time period during manoeuvring at Bognes. This means that the crew has to change its practice during port manoeuvring at Bognes and reduce either the propeller load or the thruster load with about 400 kW. As mentioned already, the measurements that form the basis for this study were gathered during good weather conditions. The required load reduction may be significantly higher in bad weather conditions. However, a source claims that it is achievable to change the crew's manoeuvring practice and manoeuvre the vessel within the main engine's limits (Sletteng, 2014).

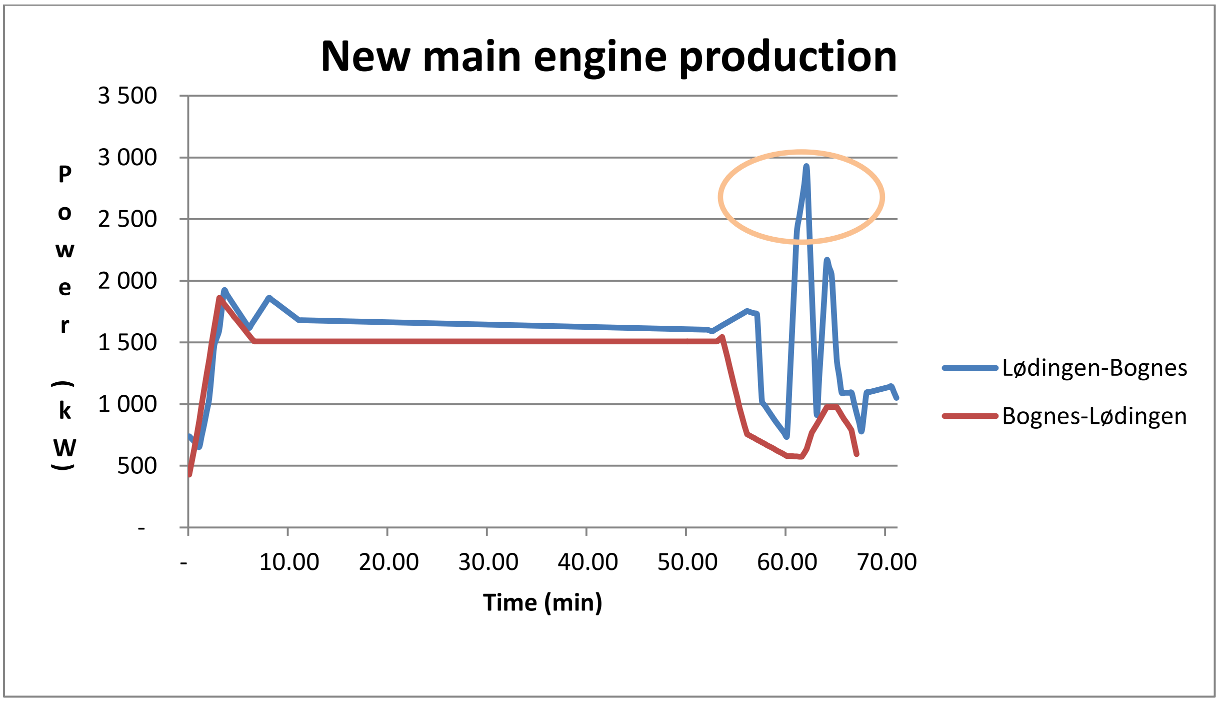

**Figure 6-6 New main engine production**

### 6.4.7 Reduction of energy expenditures

To estimate the reduced cost of energy (included NOx tax), it is necessary to determine the main engine's new gas consumption. This is done according to the equation below.

$$P_{gflow\_NEW}(t) \quad = \quad \frac{P_{ME\_NEW}\,(t)}{\eta_{ME}(P_{ME\_NEW})} \tag{6.7}$$

Here denotes $P_{gflow\_NEW}$ the new gas flow as a function of time, $P_{ME\_NEW}$ the main engine's new load as a function of time and $\eta_{ME}$ the main engine efficiency as a function of $P_{ME\_NEW}$.

As for the initial calculation, the values for $\eta_{ME}$ is based on those given in table 6-3. The variation is modelled to be linear due to the limited data available. All power production below 25 % of the main engine capacity is set to be produced at 39.6 %. For more information see the discussion in relation to equation ( 6.3 ). MATLAB is made use of to model the variation of $\eta_{ME}$. See "Appendix I – MATLAB script: New main engine efficiency" for more information about the script.

***Existing MGO energy consumption***

The existing MGO energy consumption per trip is calculated according to the equation below.

$$Q_{MGO} \quad = \quad \left(\int_0^T P_{MGO\_flow}\;dt\right) + \left(\int_0^{Tcd} P_{MGO\_cd} * dt_{cd}\right) + \left(P_{MGO\_port} * t_{port}\right) \tag{6.8}$$

Here denotes $P_{MGO\_flow}$ the standby generator's energy supply as a function of time, $T$ the length of the trip. $P_{MGO\_cd}$ represents the standby generator's energy consumption during cool down as a function of the "cool down" time and $Tcd$ the length of the "cool down" period. The "cool down" time is measured to be 4 minutes (Torghatten Nord, 2014b). $P_{MGO\_port}$ denotes the standby generator's energy consumption in port. This is to take into account that the standby generator is not shut down during short port stays, therefore 5 minutes ($t_{port}$) is added per trip. See "Appendix E – "In port" loads" for more information about the standby generator's MGO energy supply in port.

***Existing gas energy consumption***

The existing gas energy consumption per trip is estimated according to equation ( 6.9 ).

$$Q_{GAS\_EX} \quad = \quad \left(\int_0^T * P_{gflow_{EX}}\;dt\right) + \left(P_{gas\_EX\_port} * t_{port}\right) \tag{6.9}$$

$P_{gflow_{EX}}$represents the main engine's existing gas energy supply as a function of time, $T$ the length of the trip, $P_{gas\_EX\_port}$ the main engine's gas energy supply in port and $t_{port}$ the time of the port addition. See “Appendix E – “In port” loads” for more information about the main engine’s existing gas energy supply in port.

### *New gas energy consumption*

The new gas energy consumption per trip is calculated according to the equation below.

$$Q_{GAS\_NEW} \quad = \quad \left(\int_0^T * P_{gflow_{NEW}}\, dt\right) + \left(P_{gas\_NEW\_port} * t_{port}\right) \qquad (6.10)$$

Here denotes $P_{gflow_{NEW}}$ the main engine’s estimated new gas energy supply as a function of time, $T$ the time of the trip, $P_{gas\_NEW\_port}$ the gas engine’s new energy supply in port and $t_{port}$ the time of the port addition. See ”Appendix E – “In port” loads**”** for more information about the main engine’s new gas energy supply in port.

### *Estimation of existing energy cost*

Since the energy consumption per trip differs according to the crossing direction, the following application of $Q_{MGO}$, $Q_{GAS\_EX}$ and $Q_{GAS\_NEW}$ is based on an average value per trip.

$$Cost_{EX} \quad = \quad n_{trips} * \left(Q_{MGO} * C_{MGO} + Q_{GAS_{EX}} * C_{GAS}\right) \qquad (6.11)$$

$Cost_{EX}$ represents the existing yearly energy cost, $n_{trips}$ the yearly amount of trips, $Q_{MGO}$ the existing MGO energy consumption per trip. $Q_{GAS_{EX}}$ denotes the existing gas energy consumption per trip, $C_{MGO}$ the cost of MGO per energy unit and $C_{GAS}$ the cost of gas per energy unit. The total amount of trips can be found in table 3-1, while the energy prices are found in table 6-1.

### *Estimation of new energy cost*

The new energy cost is estimated according to equation ( 6.12 ).

$$Cost_{NEW} \quad = \quad n_{trips} * \left(Q_{GAS_{NEW}} * C_{GAS}\right) \qquad (6.12)$$

Here denotes $Cost_{NEW}$ the new yearly energy cost, $n_{trips}$ the yearly amount of trips, $Q_{GAS_{NEW}}$ the new gas energy consumption per trip and $C_{GAS}$ the cost of gas per energy unit.

### *Results*

According to table 6-5 the yearly reduced energy cost (including NOx tax) is in the order of 720 000 NOK. Combined with the reduced maintenance costs, the yearly saving is estimated to be about 926 000 NOK. It is important to underline that these energy costs, given in table 6-5, don't represent the vessel's total fuel and NOx expenditures, which are discussed in relation to the LCC study. These numbers are only obtained to be able to assess the reduction of fuel costs due to the shaft generator replacement, and not to assess the total fuel and NOx expenditures.

**Table 6-5 Summary of potential savings**

| **Value/Total** | **Existing total fuel cost** | **New total fuel cost** | **Reduced MTU maintenance** | **Sum savings per year** |
|---|---|---|---|---|
| **Cost** | NOK 8 859 963.91 | NOK 8 139 628.05 | NOK 205 845.64 | **NOK 926 181.50** |
| **Value pr. km** | NOK 75.39 | NOK 69.26 | NOK 1.75 | **NOK 7.88** |

Figure 6-7 illustrates how the energy savings are generated. It describes the efficiency that the power produced by standby generator is produced at, and the efficiency which the same power will be produced at by use of the hybrid system. On top of this difference in system efficiencies comes the price difference per energy unit.

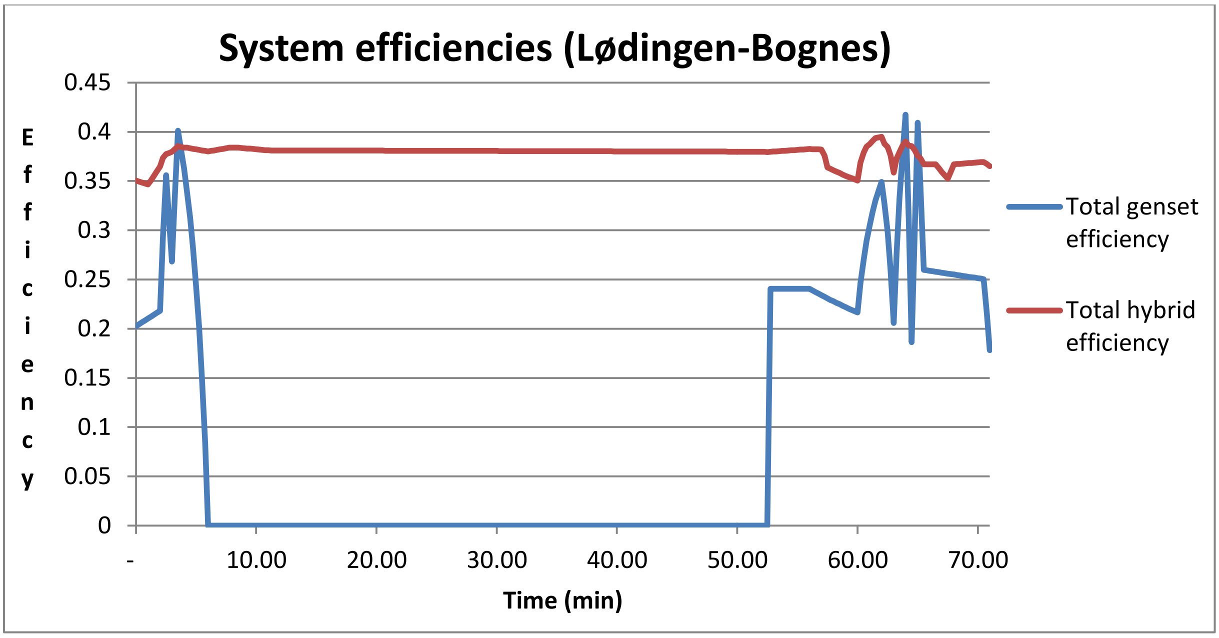

**Figure 6-7 Comparison of system efficiencies**

It may be noticed that the increased load on the main engine gives a beneficial increase of the engines efficiency. This means that the main engines efficiency is improved by the measure in relation to the main engine's existing operation.

### *Summary of uncertainty in analysis*

It's important to emphasise the factors that contributes to uncertainty in this analysis. The applied data regarding the efficiencies of the main engine and the shaft generators are limited, which constrains the model's accuracy. In addition the components' variation in efficiency at given loads is modelled to vary linearly and to be constant below the lowest given load. This simplification implements uncertainty. However, the main engine has very seldom lower load than 25 % of its maximum continuous rating. In addition, the shaft generators' efficiency vary little even at low loads. The reduction of the shaft generators' efficiency from 50 % load to 10 % load may unofficially be in the order of 5-6 % (Erstdal, 2014). However, the effect of this uncertainty in relation to the calculated reduction of energy costs is expected to be less than 5-6 %. This is because the reductions in energy consumption are only gained in the time periods where the standby generator is running. Consequently, the accumulated production rates on the new shaft generator are increased during this period (see figure 6-5). This results in improved quality of the results. In addition, the energy consumptions from the thrusters during manoeuvring may be significantly higher at rougher weather conditions.

The data gathered from the power management system is transferred to a spreadsheet by use of manual readings, which always introduces a risk of reading errors and inaccuracy. It also constrains the study's detail level. Integral operations are carried out by summing up the area of rectangular sections. One minute operation is divided into four sections which are 15 seconds long. This also implements uncertainty. However, considered the inherent uncertainty and the low detail level of the input data, in addition to the modelled linear variation over time, this contribution is evaluated to be small.

This data were nevertheless gathered during very good weather conditions, which again reduced the manoeuvring time and the power demand from the standby generator. These are factors indicating that the results may be conservative even though there are implemented some non-conservative simplifications.

As already discussed, the applied assumptions in this study are assessed to be sufficiently accurate for the purpose of this study. However, the uncertainty regarding the limited data of several key components and the input data should be investigated in detail. This should constitute the foundation of a more accurate modelling in any further studies.

### 6.4.8 Financial support

In Norway, companies may apply for financial support which may partly finance so-called NOx reduction measures. Each kg yearly reduction in NOx emissions is awarded with 225 NOK in financial support to the investment. This financial support may finance up to 80 % of the total cost of the measure (Norewegian NOx fund, 2014). Calculations of NOx emissions are thoroughly discussed in section 4.4.1, hence only the results are presented in this section.

Table 6-6 indicates that a replacement of the existing shaft generator may generate a financial support of 1.1 million NOK. If we take basis in the budget prices given in section 6.4.2, the resulting cost of the replacement is reduced to about 1 million NOK. Based on the estimated yearly reduction in NOx tax, energy costs and maintenance cost, the replacement may be repaid in about one year, which is a relatively short time period.

**Table 6-6 Financial support**

| | **Gas engine (Ex)** | **DG (Ex)** | **New gas engine calculation** | **Reduction** |
|---|---|---|---|---|
| **Mass fuel** | 1399 tons | 170 tons | 1 446 tons | |
| **Nox emission** | 4113 kg | 5 169 kg | 4 251 kg | 5 031 kg |
| **Total NOX reward** | | | | **1 132 030 NOK** |

However, as already discussed, there are several factors that implements uncertainty to the analysis. These are related to the applied analytical method and the limitations given by the limited input data. In addition, the replacement raises challenges when it comes to the manoeuvring of the vessel. Further studies are therefore needed to fully understand the potential and limitations of this measure.

### 6.4.9 Effect on total life cycle cost

The measure is estimated to reduce the yearly energy expenditures by 720 000 NOK. Based on the 2013 values, it will lower the total expenditures related to NOx emissions and fuel cost by about 5.5 %, and the maintenance expenditures by about 7 %. This will have a significant impact on the LNG vessel’s total life cycle cost. However, due to the time limitation of this study, the total life cycle cost savings over the 30 year time span are not analysed.

# 7. DISCUSSION

## Life cycle cost comparison study

A LCC comparison study arises several issues and challenges when it comes to among other study boundaries, data, modelling, uncertainty etc. The most important of these are discussed in this section as well as the results.

### *Study objects*

It is important to underline that this study only provides information regarding two specific vessels, hence the results are only representative for these vessels. The study of the conventional vessel's life cycle cost is based on an imaginary lengthening of the vessel in the order of 18.5 m. The purpose of the lengthening is to get an improved reference cost from the conventional vessel, and thereby satisfy the three defined requirements for a comparison study between two car ferries. However, it's important to stress that the imaginary lengthening creates uncertainty with respect to cost elements as for example fuel costs, NOx emissions and disposal expenditures.

### *Data*

Most of the cost data for this study is gathered from the shipping company Torghatten Nord, which is also the owner of the two vessels. Technical information and data are mainly collected from the shipping company's suppliers. An important limitation of this study is the lack of detailed maintenance cost data.

### *Environmental aspect*

The study focuses only on costs. LNG engines have several beneficial factors when it comes to its emissions. Combustion of natural gas has a significantly lower emission of CO2 per energy unit. In addition, modern LNG engines have a performance when it comes to emissions of particles and NOx, which is below 10 % of what conventional diesel engines can cope with.  Only the effect of NOx emissions is captured by this study and then only in the form of costs. Therefore the study doesn't fully address the environmental aspect, which is an important limitation. However, the study shows that the LNG vessel has only a fraction of the NOx emission cost of the conventional vessel.

### *Maintenance costs*

LNG propulsion systems in general have several promising aspects when it comes to maintenance costs. This is due to among other the expectation of reduced deterioration of the fuel supply system and other components such as engine nozzles and exhaust valves. The LNG vessel is estimated to have 9 % lower maintenance costs. However, M/F Lødingen struggles with a large amount of running hours on the standby generator, which accumulates a significant maintenance cost on the MGO system. This is not taken into account in the estimation. Due to the limited data available, the modelling of maintenance costs is carried out on a low detail level. Hence, quantitative information about each components/systems importance with respect to maintenance costs is not provided by this study. The validity of assuming constant maintenance expenditures is also debatable. There is in particular uncertainty related to whether or not the conventional vessel will demand increased maintenance cost due to its mature age. It is nevertheless not basis for saying that the LNG vessel has a clearly lower maintenance cost than the conventional vessel due to the uncertainty related to these calculations. The maintenance costs are also to some degree dependent on the shipping company's maintenance policy. A shipping company that practices a different maintenance policy may experience maintenance costs that varies from those applied in this study.

### *Modelling of downtime*

Due to the lack of reliability data, the modelling of downtime costs is of a relatively simple nature. Ideally, such an assessment should be based on a detailed reliability analysis, which involves the vessels' critical components. These simplifications reduce the amount of information that potentially could have been drawn out from this analysis. For example, the model doesn't take into account the LNG vessel's reduced need of preventive maintenance, which may reduce the downtime level significantly. No other RAMS parameters than the availability is incorporated in the model. Therefore, valuable information such as the mean time to failure, mean time to repair and the variation of these over time are not captured by the model. Such information may be utilized not only to estimate the downtime cost, but also to support a detailed analysis of risk expenditures.

### *Downtime costs*

The results regarding the downtime costs imply that the total cost of downtime are approximately equal over the time span. An important difference is that a significant proportion of the LNG vessel's downtime cost is generated during the first two years in service, while the conventional vessel has a constant yearly downtime cost. Hence, if an internal rate of return is applied in the calculation, the LNG vessel's downtime cost will be significantly higher than the conventional vessel's. Increasing internal rates of return will therefore increase the conventional vessel's favourability when it comes to downtime costs. However, it is important to underline that there is indeed uncertainty related to these numbers. The sensitivity analysis reveals that this uncertainty may be in the order of 40 %. The model doesn't take into account risk expenditures that are related to critical failures and the costs associated with poor media publicity. This is a drawback that is important to emphasise since it may have affected the outcome of the study.

### *Capital costs*

An important cost element is the capital costs, which are the costs related to the acquisition. The cost of the LNG vessel is heavily dependent on the newbuilding prices, while the price of the conventional vessel is dependent on the second-hand prices. The market situation dictates both. Therefore, the prices vary over time. Hence, the costs applied in this analysis are only representative for a specific market state. The LNG vessel significantly suffers from high capital cost the first 22 years in service. It is uncertainty related to the vessels' capital costs in real terms, which primarily is dependent on the inflation, the bank's interest rate and the depreciation time. This uncertainty mainly affects the total capital cost of the LNG vessel.

***Insignificant cost elements and manning costs***

Costs related to lube oil and insurance, as well as the income generated by the disposal, is of minor significance for the total life cycle costs. This is even though there is extreme uncertainty related to forecasting of lube oil prices and scrapping prices. Lube oil and insurance costs accounts for less than 4.5 % of the total life cycle cost of both vessels, while income from scrapping reduces it by less than 1 %. On the other hand, manning costs are revealed to be the largest cost element if it's included, and it is therefore important for the shipping companies. However, the crew costs are assessed to be the same for both vessels.

***Fuel costs***

Fuel costs are beyond doubt the most important cost element of those studied in this analysis. It accounts for 48 % and 59 % of the total life cycle cost for respectively the LNG vessel and the conventional vessel. The total fuel cost is estimated to be 9 % higher for the conventional vessel despite of its 19 % lower energy consumption. The main reason for this is that the MGO price applied in this study is forecasted to remain high and increase over time compared to the LNG price. This generates a high MGO cost in particular at the end of the time period. It is very important to underline that there is extreme uncertainty related to the forecasting of future energy prices. The sensitivity analysis shows that the uncertainty related to the MGO fuel price may change the fuel cost with as much as 56 %, which is an extreme potential deviation. The uncertainty implemented by the "lengthening" of the conventional vessel is relatively small compared to the uncertainty regarding the fuel prices.

However, energy prices are to some degree linked. Hence, it may be unlikely that the LNG price will follow a low scenario and the MGO a high scenario or vice versa. The sensitivity analysis indicates that if both fuels follow the same scenario category, the difference between the fuel costs will change significantly. If both low scenarios occur, the conventional vessel will have a lower fuel cost than the LNG vessel and thereby increase its favourability with respect to life cycle costs. On the other hand, a high scenario will benefit the LNG vessel and reduce the gap in life cycle costs significantly.

***Effect of internal rate of return***

In such analyses, an internal rate of return is often implemented. The reason is that money earned today is valued more than money earned several years into the future. As a result, the LNG vessel's capital costs and downtime costs, which initially are high, are of increased importance for the total life cycle cost. On the other hand, the significance of the conventional vessel's high fuel costs in the end of the time span is decreased. The difference in total life cycle costs between the vessels is almost maintained with nominal internal rates of return up to 12 %. This means that LNG vessel's drawback with respect to total life cycle costs increases relatively to the conventional vessel with raising internal rate of returns. The internal rate of return is in particular favourable for the conventional vessel's life cycle cost, since it is low in the beginning and increases over the time period. In other words, the higher internal rate of return a shipping company bases its investment on, the more favourable is the conventional vessel.

### *Uncertainty related to external factors*

To assess the life cycle cost of two ferries over a time span of 30 years introduces several issues when it comes to the assumptions needed to conduct the study. This study takes basis in the assumption that the study objects are to be operating the same ferry service for the entire time span. This is seldom the case. A vessel may very well be sold or used at another ferry service during a thirty year period, and thereby change the operational premises. Over such a long time period, national and international regulations will be changed. Such changes may make the vessels superfluous or obsolete. This is with respect to stricter environmental regulations in particular. For example, older engines such as the conventional vessel's main engine may be prohibited and hence require expensive renewals of the vessel's machinery, which aren't taken into account in this study.

## Possibility for reduction of life cycle costs

The main proportion of a ship's life cycle cost is constrained when the vessel embark its maiden voyage. However, the LNG vessel has significantly higher energy consumption than the conventional vessel. This is even though there is uncertainty related to the estimation of the conventional vessel's energy consumption. The extensive use of the standby generator has been identified as one of the reasons for this difference. It has been indicated that the standby generator produces electricity to the main switchboard with a very low average efficiency.

In this study, the possibility of reducing the energy and NOx costs by replacing the existing shaft generator is analysed. The new shaft generator applied in this study has 1 500 kW production capacity. This will cancel the need of running the standby generator during manoeuvring. The analysis is based on data gathered from the LNG vessel's power management system and from the suppliers. The results indicate that the combined reduction of NOx tax and energy costs may be in the order of 720 000 NOK per year. However, there are several issues in this analysis that is important to emphasise. One of them is that the analysis shows that the main engines maximum continuous power rating is exceeded by the power demand generated by today's manoeuvring practice. This means that the crew has to change their manoeuvring practice if this measure is implemented.

### *Maintenance*

The extra amount of running hours that accumulates on the MGO system and the standby generator generates an additional maintenance cost. It has been calculated that the maintenance cost regarding the extra use of the standby generator is in the order of 206 000 NOK per year. The costs related to the deterioration of the fuel supply system come in addition to this. Hence, the reduction of maintenance costs given here may be assumed to be a lower limit.

***Payback time***

It has been found that the measure will significantly reduce the vessel's NOx emissions. This may generate 1.1 million NOK in financial support from the Norwegian NOx Fund, which reduces the investment cost of the equipment needed to about 1 million NOK. Consequently, the payback time is approximately one year. This cost includes nevertheless only the cost of a new shaft generator and a VSD. Costs such as the cost of man hours for the replacement and the cost of downtime are not included. Therefore, further studies of the potential savings, the investment cost and any limitations are needed to reduce the uncertainty regarding this investment.

***Uncertainty***

The data gathered from the power management system is representing a very limited time period. Hence, the results are only valid for the prevailing weather conditions and crew practice that were present in the time period when the data were generated. However, the weather conditions were good when the measurements were carried out, which reduced the manoeuvring time and the power demand from the standby generator. Therefore, the data gathered from the power management system are assessed to be conservative in relation to the average power consumptions.

Uncertainty is also generated due to the limited data available regarding the efficiency of the main engine and in particular the shaft generators. The shaft generators' efficiency is modelled to be constant at production rates below 50 % of the generators' capacity. Hence, the analysis doesn't capture the shaft generators' reduction in efficiency at lower power production rates. This is a drawback for the study. However, the shaft generators' efficiency varies only to a small extent even at low loads. Another important detail which contributes to the total uncertainty in this analysis is that the efficiencies are modelled to vary linearly.

# 8. CONCLUSION

In this study, a life cycle cost comparison study between a newly built single ended LNG ferry and a 21 year old double ended conventional ferry is carried out. The study's time span is 30 years, and it's assumed that both vessels are to be procured from respectively the newbuilding market and the second-hand market. Another assumption is that the vessels' are to be producing according to the LNG vessel's current production pattern for the whole time period. A life cycle cost analysis that spans over a 30 year time period is indeed associated with uncertainty. It is therefore important that the results are treated carefully.

It has been estimated that the life cycle cost of the LNG vessel is 862 million NOK and 760 million NOK for the conventional vessel. Hence, the conventional vessel is estimated to have a 12 % lower total life cycle cost. In this context, the most important cost elements are capital costs, fuel costs, maintenance costs, NOx emission costs and downtime costs.

The results show that the capital cost of the conventional vessel is only 8 % of the LNG vessel's in real term value. This constitutes a significant disadvantage for the LNG vessel in a life cycle cost context.

It has been found that the conventional vessel has 19 % lower energy consumption than the LNG vessel. Despite of this, the conventional vessel is estimated to have a higher total fuel cost in the order of 9 %. The main reason is that the existing gap between the two energy prices is forecasted to increase over the time period.

Maintenance generated costs are assessed to be 9 % lower for the LNG vessel. This is due to among other the expected reduced deterioration of the fuel supply system and other components such as engine nozzles and exhaust valves. This is relative to a conventional system. However, the data material in particular which the maintenance costs for the LNG vessel are based on is very limited and uncertain.

Despite of a high amount of initial downtime, the downtime cost is estimated to be approximately the same for both vessels. It represents 9 and 10 % of the total life cycle cost for respectively the LNG and the conventional vessel. However, the modelling of downtime is based on a constant downtime rate for the conventional vessel from year 1, and for the LNG vessel from year 3, which are extreme simplifications.

Due to the LNG engine's low NOx emission rates, the LNG vessel's NOx emission cost is only 15 % of the conventional vessel's NOx emission cost. This is one of the most significant differences between the vessels.

Costs related to lube oil consumptions and insurances, as well as income generated from disposal, are estimated and assessed to be of insignificant importance for the total life cycle cost. This is even though there is extreme uncertainty related to some of these numbers.

If 8 % nominal internal rate of return is implemented, the total life cycle costs are 479 million NOK and 389 million NOK for respectively the LNG vessel and the conventional vessel. It may be noticed that the difference between the vessels is only to a small extent affected by the internal rate of return, while the relative difference has increased significantly. This is because a significant portion of the LNG vessel's capital costs are paid at an early stage. At the same time, the vessel has high downtime costs due to so-called "childhood diseases". These high initial costs combined are important factors that maintain the gap between the two life cycle costs.

A sensitivity analysis is performed in order to assess the uncertainty related to this study. Two extreme scenarios (high and low) are established for each of the cost elements that are important for the total life cycle cost, and which there are extreme uncertainty related to. These cost elements are the fuel cost, the capital cost, the maintenance cost and the downtime cost. The sensitivity analysis indicates that the uncertainty related to the fuel costs is most important with respect to the total life cycle cost for both vessels. For example, the uncertainty related to the conventional vessel's fuel cost may change the total fuel cost in the order of 56 %. This uncertainty is mainly related to the difficulty in forecasting future energy prices. Hence, large deviations from the fuel prices' central scenarios may change the outcome of the study.

A potential measure to reduce the LNG vessel's life cycle cost is also analysed. It has been found that the crew makes use of the vessel's standby generator during manoeuvring. The standby generator, which is a conventional diesel generator that is running at constant speed, has a very low average load in these situations. This gives a low overall efficiency. If the existing 800 kW shaft generator is replaced with a Marelli B5J 500 LC, which has 1 500 kW production capacity, the need of running the standby generator during manoeuvring is cancelled. It has been estimated that the engine accumulates about 2 200 extra running hours per year due to the extra need of power production during manoeuvring. As a result, the prime mover alone generates a maintenance cost that is in the order of 206 000 NOK per year. In addition comes the contribution from fuel feeder pumps, filters etc.

The potential for savings with respect to NOx taxes and fuel costs by replacing the existing shaft generator has been estimated. Data for this study has been provided by use of print-outs from the LNG vessel's power management system and technical specifications from the suppliers. It has been found that the vessel may save about 720 000 NOK on yearly basis in form of reduced fuel costs and NOx taxes. This is due to the improved efficiency of the vessel's electricity production and the price difference per energy unit between LNG and MGO. However, there is uncertainty in these calculations which is important to consider. The uncertainty is related to the applied analytical method and the limitations given by the input data.

The reduction of yearly NOx emissions, which this measure may achieve, qualifies to a financial investment support of about 1.1 million NOK from the Norwegian NOx fund. Based on budget prices, the remaining cost of the equipment needed is then 1 million NOK. This gives the investment a payback time of approximately one year. However, further studies are needed to fully understand the potential and the limitations of this measure.

# 9. RECOMMENDATIONS FOR FURTHER WORK

The results of this study indicate that the life cycle cost of a 21 year old conventional double ended ferry is 12 % lower than for a newly built LNG ferry with the same capabilities. From an economic point of view, these results may question whether it's beneficial to replace older tonnage. However, this study is only based on two vessels. Therefore it may provide valuable information to study a larger amount of vessels and investigate whether this is a trend or only a special case. In addition, this study only emphasises costs. It would be of interest if further studies are able to implement the environmental aspect in form of life cycle analyses (LCA) as well. After all, the environmental aspect has increasing importance in many business sectors.

LNG propulsion systems incorporate a lot of extra components and systems compared to a conventional system. This increases the system's complexity. Only a very brief assessment of the LNG vessel's reliability performance compared to the conventional vessel is carried out in this study. A thorough reliability assessment may provide interesting information regarding the vessels' reliability performance. Such an analysis should aim to pin-point the components, systems and dependencies that are of major importance for the vessels' reliability. It may also emphasise on obtaining detailed information about the maintenance costs of these propulsion systems.

A thorough reliability assessment may further on be used as input to a risk assessment. As already mentioned, the LNG vessel has experienced blackouts while it was in service, and had cars and passengers on board. Risk expenditures are not estimated in this study, but there are indications which imply that the cost category may be of great interest. Hence, further studies of this issue may obtain interesting knowledge of the risk expenditures associated with these vessels.

Significant amounts of downtime often impair a company's reputation. This effect is not taken into account in this study. The study shows that the LNG vessel suffered heavily from so-called "childhood diseases" in its first year in service, which frequently generated poor media publicity. If the actual cost of this publicity had been known, the company may rethink their practice when it comes to testing and training of vessels and crews.

The analysis of the potential savings and limitations obtained by a shaft generator replacement is based on a limited amount of data. In addition, the cost of the replacement is only based on budget prices of the equipment. Therefore, further studies of this measure are needed. These studies should focus on improving the data inputs and the detail level of the analysis. The analysis should be able to model the variations of the components' efficiency more accurate than the linear variation that this study is based on. In addition, it is crucial to fully understand the total cost of the investment and the challenges that may arise when it comes to the operation of the vessel, before the measure is implemented. If the measure is implemented, it may be interesting to study the LNG vessel's new performance in relation to the LCC comparison study.

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# 11. APPENDICES

# Appendix A – Terms and definition

**AC**

Alternating current

**CAPEX**

Short for “capital expenditures”. The term is in general used to describe the acquisition costs of physical elements.

**Cash flow**

Currents of costs and revenues.

**CBS**

Cost breakdown structure.

**Cost driver**

Major cost element which, if changed, will have significant impact the total life cycle cost of an item (International Standard Organization, 2006).

**DC**

Direct current

**DECC**

UK Department of Energy and Climate Change.

**DISPEX**

Costs related to disposal, retirement, and decommissioning (Utne, 2009).

**EIAPP**

Engine international air pollution prevention

**HPP**

Homogenous Poisson process

**HVAC**

Heating, ventilation and air conditioning

**IMO**

International maritime organization

**Life cycle**

All development stages of an item, from the study commences and until the item is disposed.

(International Standard Organization, 2006)

**Life cycle cost (LCC)**

The sum of all costs incurred during the life cycle of an item (Dhillon, 2010).

**Life cycle costing**

A process which evaluates two or more alternatives based on life cycle costs (International Standard Organization, 2006).

**LNG**

Liquefied natural gas.

**MGO**

Marine gas oil

**MTD**

Mean downtime

**MTTF**

Mean time to failure.

**MTTR**

Mean time to repair.

**NHPP**

Non homogenous Poisson process

**NPV**

Short for “net present value”. The present value of an annual or single payment today or in the future.

**OPEX**

Short for “operational expenditure”. The expression in general describes all the costs which are related to operation and maintenance of an object.

**PMS**

Short for power management system.

**RAMS**

Short for “reliability, availability, maintainability and safety”.

**REGEX**

Short for “regularity expenditure”.  The term is used to describe the costs related to the item’s ability to meet the demand for delivery and performance (Kawauchi and Rausand, 1999).

**RISKEX**

Short for risk expenditure. The term is used to describe the costs related to accidents.

**SG**

Shaft generator

**THN**

Short for Torghatten Nord

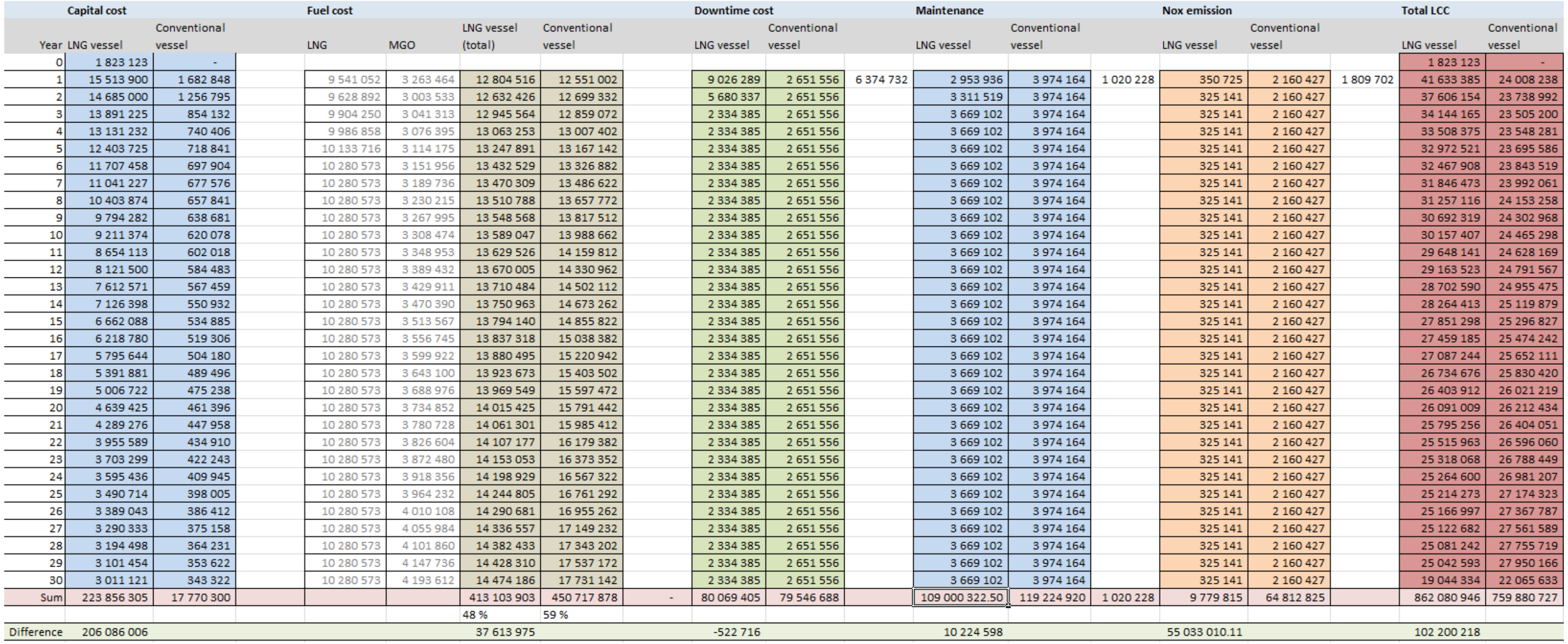
**TLCC**

Short for total life cycle cost analysis. Mode of analysis (Ruegg, 1987).

**VSD**

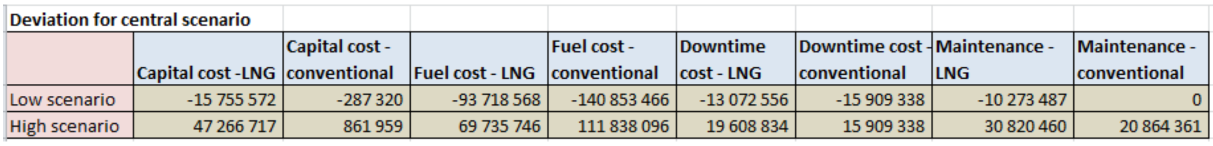
Variable speed drive (Ådnanes, 2003)

# Appendix B – Comparison study table



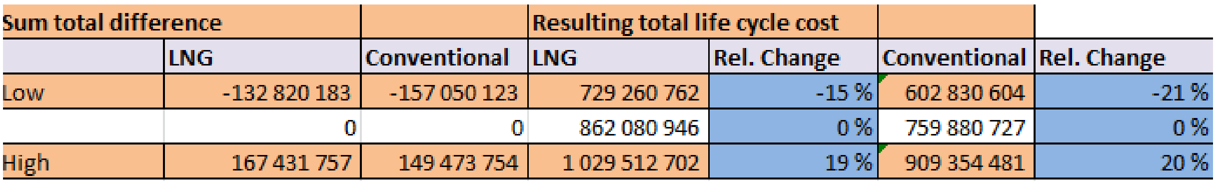
| | Capital cost | | | Fuel cost | | | | | Downtime cost | | | Maintenance | | | Nox emission | | | Total LCC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | LNG vessel | Conventional vessel | | LNG | MGO | LNG vessel (total) | Conventional vessel | | LNG vessel | Conventional vessel | | LNG vessel | Conventional vessel | | LNG vessel | Conventional vessel | | LNG vessel | Conventional vessel |
| 0 | 1 823 123 | - | | | | | | | | | | | | | | | | 1 823 123 | - |
| 1 | 15 513 900 | 1 682 848 | | 9 541 052 | 3 263 464 | 12 804 516 | 12 551 002 | | 9 026 289 | 2 651 556 | 6 374 732 | 2 953 936 | 3 974 164 | 1 020 228 | 350 725 | 2 160 427 | 1 809 702 | 41 633 385 | 24 008 238 |
| 2 | 14 685 000 | 1 256 795 | | 9 628 892 | 3 003 533 | 12 632 426 | 12 699 332 | | 5 680 337 | 2 651 556 | | 3 311 519 | 3 974 164 | | 325 141 | 2 160 427 | | 37 606 154 | 23 738 992 |
| 3 | 13 891 225 | 854 132 | | 9 904 250 | 3 041 313 | 12 945 564 | 12 859 072 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 34 144 165 | 23 505 200 |
| 4 | 13 131 232 | 740 406 | | 9 986 858 | 3 076 395 | 13 063 253 | 13 007 402 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 33 508 375 | 23 548 281 |
| 5 | 12 403 725 | 718 841 | | 10 133 716 | 3 114 175 | 13 247 891 | 13 167 142 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 32 972 521 | 23 695 586 |
| 6 | 11 707 458 | 697 904 | | 10 280 573 | 3 151 956 | 13 432 529 | 13 326 882 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 32 467 908 | 23 843 519 |
| 7 | 11 041 227 | 677 576 | | 10 280 573 | 3 189 736 | 13 470 309 | 13 486 622 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 31 846 473 | 23 992 061 |
| 8 | 10 403 874 | 657 841 | | 10 280 573 | 3 230 215 | 13 510 788 | 13 657 772 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 31 257 116 | 24 153 258 |
| 9 | 9 794 282 | 638 681 | | 10 280 573 | 3 267 995 | 13 548 568 | 13 817 512 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 30 692 319 | 24 302 968 |
| 10 | 9 211 374 | 620 078 | | 10 280 573 | 3 308 474 | 13 589 047 | 13 988 662 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 30 157 407 | 24 465 298 |
| 11 | 8 654 113 | 602 018 | | 10 280 573 | 3 348 953 | 13 629 526 | 14 159 812 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 29 648 141 | 24 628 169 |
| 12 | 8 121 500 | 584 483 | | 10 280 573 | 3 389 432 | 13 670 005 | 14 330 962 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 29 163 523 | 24 791 567 |
| 13 | 7 612 571 | 567 459 | | 10 280 573 | 3 429 911 | 13 710 484 | 14 502 112 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 28 702 590 | 24 955 475 |
| 14 | 7 126 398 | 550 932 | | 10 280 573 | 3 470 390 | 13 750 963 | 14 673 262 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 28 264 413 | 25 119 879 |
| 15 | 6 662 088 | 534 885 | | 10 280 573 | 3 513 567 | 13 794 140 | 14 855 822 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 27 851 298 | 25 296 827 |
| 16 | 6 218 780 | 519 306 | | 10 280 573 | 3 556 745 | 13 837 318 | 15 038 382 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 27 459 185 | 25 474 242 |
| 17 | 5 795 644 | 504 180 | | 10 280 573 | 3 599 922 | 13 880 495 | 15 220 942 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 27 087 244 | 25 652 111 |
| 18 | 5 391 881 | 489 496 | | 10 280 573 | 3 643 100 | 13 923 673 | 15 403 502 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 26 734 676 | 25 830 420 |
| 19 | 5 006 722 | 475 238 | | 10 280 573 | 3 688 976 | 13 969 549 | 15 597 472 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 26 403 912 | 26 021 219 |
| 20 | 4 639 425 | 461 396 | | 10 280 573 | 3 734 852 | 14 015 425 | 15 791 442 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 26 091 009 | 26 212 434 |
| 21 | 4 289 276 | 447 958 | | 10 280 573 | 3 780 728 | 14 061 301 | 15 985 412 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 795 256 | 26 404 051 |
| 22 | 3 955 589 | 434 910 | | 10 280 573 | 3 826 604 | 14 107 177 | 16 179 382 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 515 963 | 26 596 060 |
| 23 | 3 703 299 | 422 243 | | 10 280 573 | 3 872 480 | 14 153 053 | 16 373 352 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 318 068 | 26 788 449 |
| 24 | 3 595 436 | 409 945 | | 10 280 573 | 3 918 356 | 14 198 929 | 16 567 322 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 264 600 | 26 981 207 |
| 25 | 3 490 714 | 398 005 | | 10 280 573 | 3 964 232 | 14 244 805 | 16 761 292 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 214 273 | 27 174 323 |
| 26 | 3 389 043 | 386 412 | | 10 280 573 | 4 010 108 | 14 290 681 | 16 955 262 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 166 997 | 27 367 787 |
| 27 | 3 290 333 | 375 158 | | 10 280 573 | 4 055 984 | 14 336 557 | 17 149 232 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 122 682 | 27 561 589 |
| 28 | 3 194 498 | 364 231 | | 10 280 573 | 4 101 860 | 14 382 433 | 17 343 202 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 081 242 | 27 755 719 |
| 29 | 3 101 454 | 353 622 | | 10 280 573 | 4 147 736 | 14 428 310 | 17 537 172 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 25 042 593 | 27 950 166 |
| 30 | 3 011 121 | 343 322 | | 10 280 573 | 4 193 612 | 14 474 186 | 17 731 142 | | 2 334 385 | 2 651 556 | | 3 669 102 | 3 974 164 | | 325 141 | 2 160 427 | | 19 044 334 | 22 065 633 |
| Sum | 223 856 305 | 17 770 300 | | | | 413 103 903 | 450 717 878 | - | 80 069 405 | 79 546 688 | | 109 000 322.50 | 119 224 920 | 1 020 228 | 9 779 815 | 64 812 825 | | 862 080 946 | 759 880 727 |
| | | | | | | 48 % | 59 % | | | | | | | | | | | | |
| Difference | 206 086 006 | | | | | 37 613 975 | | | -522 716 | | | 10 224 598 | | | 55 033 010.11 | | | 102 200 218 | |

# Appendix C – Sensitivity analysis tables



Deviation for central scenario

| | Capital cost -LNG | Capital cost - conventional | Fuel cost - LNG | Fuel cost - conventional | Downtime cost - LNG | Downtime cost - conventional | Maintenance - LNG | Maintenance - conventional |
|---|---|---|---|---|---|---|---|---|
| Low scenario | -15 755 572 | -287 320 | -93 718 568 | -140 853 466 | -13 072 556 | -15 909 338 | -10 273 487 | 0 |
| High scenario | 47 266 717 | 861 959 | 69 735 746 | 111 838 096 | 19 608 834 | 15 909 338 | 30 820 460 | 20 864 361 |



| Sum total difference | | | Resulting total life cycle cost | | | |
|---|---|---|---|---|---|---|
| | LNG | Conventional | LNG | Rel. Change | Conventional | Rel. Change |
| Low | -132 820 183 | -157 050 123 | 729 260 762 | -15 % | 602 830 604 | -21 % |
| | 0 | 0 | 862 080 946 | 0 % | 759 880 727 | 0 % |
| High | 167 431 757 | 149 473 754 | 1 029 512 702 | 19 % | 909 354 481 | 20 % |

# Appendix D – Applied constants

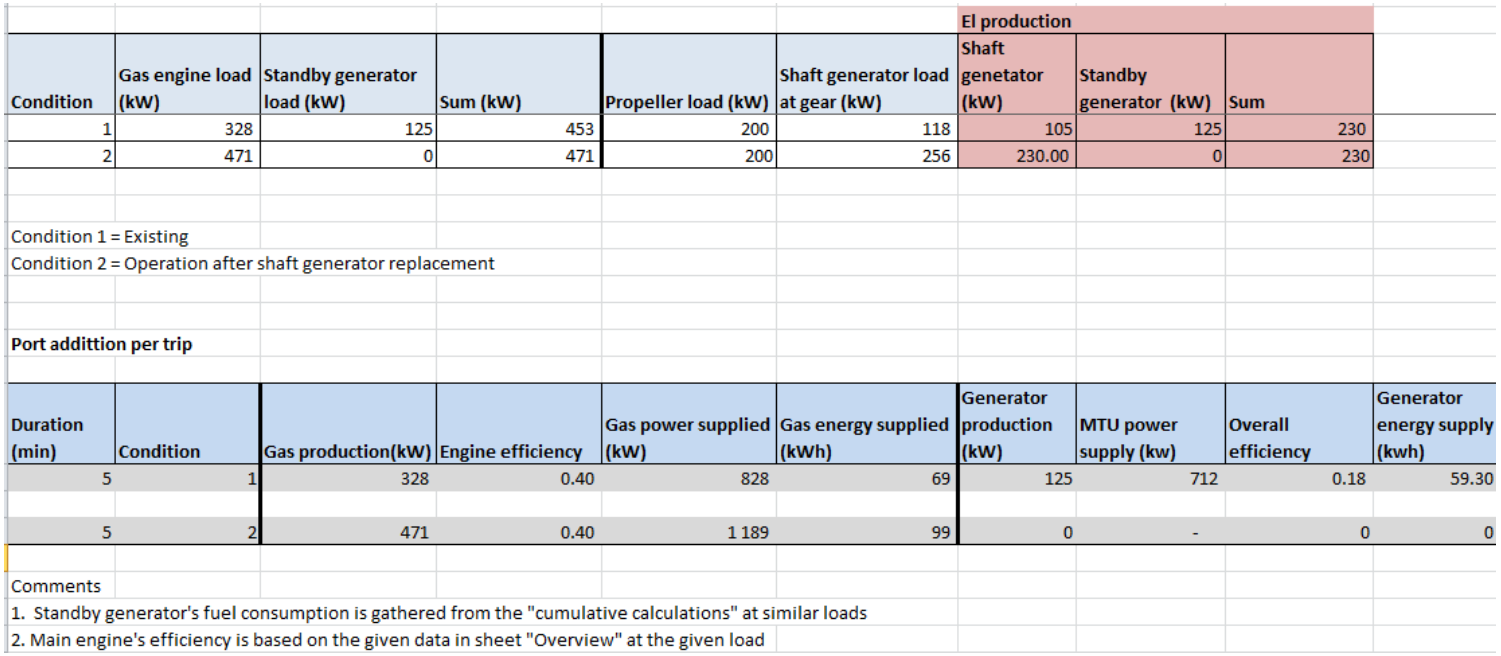
| **LNG properties** | | | | |
|---|---|---|---|---|
| Lower Calorific Value | 36.21 | MJ/sm^3 | 49.00 | MJ/kg |
| Specific weight LNG | 450.66 | kg/$m^3$ | | |
| Density | 0.74 | kg/sm^3 | | |
| 1 $m^3$ LNG | 6134 | kWh LCV | 6.13359393 | kwh/l |
| 1 kg LNG | 13.61 | kwh | | |

(Barents naturgass, 2014)

| **MGO properties** | | |
|---|---|---|
| Lower Calorific Value | 42.8 | MJ/kg |
| Density | 0.855 | kg/l |
| | 11 889 | kwh /ton |

(Statoil, 2008)

# Appendix E – "In port" loads



| | | | | | | El production | | |
|---|---|---|---|---|---|---|---|---|
| Condition | Gas engine load (kW) | Standby generator load (kW) | Sum (kW) | Propeller load (kW) | Shaft generator load at gear (kW) | Shaft genetator (kW) | Standby generator (kW) | Sum |
| 1 | 328 | 125 | 453 | 200 | 118 | 105 | 125 | 230 |
| 2 | 471 | 0 | 471 | 200 | 256 | 230.00 | 0 | 230 |

Condition 1 = Existing

Condition 2 = Operation after shaft generator replacement

**Port addittion per trip**

| Duration (min) | Condition | Gas production(kW) | Engine efficiency | Gas power supplied (kW) | Gas energy supplied (kWh) | Generator production (kW) | MTU power supply (kw) | Overall efficiency | Generator energy supply (kwh) |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 1 | 328 | 0.40 | 828 | 69 | 125 | 712 | 0.18 | 59.30 |
| 5 | 2 | 471 | 0.40 | 1 189 | 99 | 0 | - | 0 | 0 |

Comments

1. Standby generator's fuel consumption is gathered from the "cumulative calculations" at similar loads
2. Main engine's efficiency is based on the given data in sheet "Overview" at the given load

# Appendix F – MATLAB script: Existing shaft generator efficiency

```
clc
clear

%Existing shaft generator calculation

t=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',3,'O4:O569')


k=length(t)

P=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'L49')


ef_1=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'L65')

ef_0_75=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'M65')

ef_0_5=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'N65')

I_SG=[]

for i=1:k


    if  (t(i)>=(P*0.75))

        s=(ef_1-ef_0_75)/(P*0.25)

        a=ef_1-(P*s)

        I_SG(i)=a+s*t(i);


    elseif ((P*0.75)>t(i))&(t(i)>=(P*0.5))

        s=(ef_0_75-ef_0_5)/(P*0.25)
```

```
        a=ef_0_75-(P*s*0.75)


         I_SG(i)=a+s*t(i);



    elseif ((P*0.5)>t(i))&(t(i)>=(P*0))

        I_SG(i)=ef_0_5;
    else

        I_SG(i)=NaN;
    end


end


I_SG=xlswrite('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',I_SG','In_Matlab','B4')
```

# Appendix G – MATLAB script: Main engine efficiency

```
clc
clear

%Current main engine efficiency

t=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',3,'E4:E569')


k=length(t)

P=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'B51')


ef_1=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'B67')

ef_0_85=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'C67')

ef_0_75=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'D67')

ef_0_50=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'E67')

ef_0_25=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'F67')

y=t




for j=1:10

for i=1:k


     if  (y(i,j)>=(P*0.85))
```

```
        s=(ef_1-ef_0_85)/(P*0.15)

        a=ef_1-(P*s)

        Ex_Me(i)=a+s*y(i,j);


     elseif ((P*0.85)>y(i,j))&(y(i,j)>=(P*0.75))

        s=(ef_0_85-ef_0_75)/(P*0.1)

        a=ef_0_85-(P*s*0.85)


         Ex_Me(i)=a+s*y(i,j);

     elseif ((P*0.75)>y(i,j))&(y(i,j)>=(P*0.5))

        s=(ef_0_75-ef_0_50)/(P*0.25)

        a=ef_0_75-(P*s*0.75)


         Ex_Me(i)=a+s*y(i,j);

     elseif ((P*0.5)>y(i,j))&(y(i,j)>=(P*0.25))

        s=(ef_0_50-ef_0_25)/(P*0.25)

        a=ef_0_50-(P*s*0.5)


         Ex_Me(i)=a+s*y(i,j);

     elseif ((P*0.25)>y(i,j))&(y(i,j)>(P*0))

        Ex_Me(i)=ef_0_25;



    else

       Ex_Me(i)=NaN;
    end


end

  y(:,j+1)=t.*Ex_Me'
```

```
end

  Ex_Me'



Ex_Me=xlswrite('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',Ex_Me','In_Matlab','D4')
```

# Appendix H – MATLAB script: New shaft generator efficiency

```
clc
clear

%New shaft generator calculation

t=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',3,'AF4:AF569')


k=length(t)

P=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'R49')


ef_1=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'R65')

ef_0_75=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'S65')

ef_0_5=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'T65')

Nw_SG=[]



for i=1:k


     if  (t(i)>=(P*0.75))

        s=(ef_1-ef_0_75)/(P*0.25)

        a=ef_1-(P*s)

        Nw_SG(i)=a+s*t(i);


    elseif ((P*0.75)>t(i))&(t(i)>=(P*0.5))

        s=(ef_0_75-ef_0_5)/(P*0.25)

        a=ef_0_75-(P*s*0.75)
```

```
         Nw_SG(i)=a+s*t(i);



    elseif ((P*0.5)>t(i))&(t(i)>(P*0))

        Nw_SG(i)=ef_0_5;
    else

        Nw_SG(i)=NaN;
    end


end

Nw_SG'
Nw_SG=xlswrite('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',Nw_SG','In_Matlab','C4')
```

# Appendix I – MATLAB script: New main engine efficiency

```
clc
clear

%New main engine calculation

t=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',3,'AL4:AL569')



k=length(t)

P=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'B51')



ef_1=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'B67')

ef_0_85=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'C67')

ef_0_75=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'D67')

ef_0_50=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'E67')

ef_0_25=xlsread('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',2,'F67')

Nw_Me=[]



for i=1:k


     if  (t(i)>=(P*0.85))
```

```
    s=(ef_1-ef_0_85)/(P*0.15)

    a=ef_1-(P*s)

    Nw_Me(i)=a+s*t(i);



 elseif ((P*0.85)>t(i))&(t(i)>=(P*0.75))

    s=(ef_0_85-ef_0_75)/(P*0.1)

    a=ef_0_85-(P*s*0.85)


     Nw_Me(i)=a+s*t(i);


 elseif ((P*0.75)>t(i))&(t(i)>=(P*0.5))

    s=(ef_0_75-ef_0_50)/(P*0.25)

    a=ef_0_75-(P*s*0.75)


     Nw_Me(i)=a+s*t(i);


 elseif ((P*0.5)>t(i))&(t(i)>=(P*0.25))

    s=(ef_0_50-ef_0_25)/(P*0.25)

    a=ef_0_50-(P*s*0.5)


     Nw_Me(i)=a+s*t(i);

 elseif ((P*0.25)>t(i))&(t(i)>(P*0))

    Nw_Me(i)=ef_0_25;



else

   Nw_Me(i)=NaN;
```

```
    end


end

  Nw_Me'
Nw_Me=xlswrite('C:\Users\Svein\Dropbox\Master\Model\Data til
beregninger\Driftsprofil Loedingen\Propulsion plant analysis
U2.xlsx',Nw_Me','In_Matlab','E4')
```

# Appendix J – Print-outs from M/F Lødingen's PMS

18.03.2014 05:57:23:957

02:28:56.684

18.03.2014 08:26:20:641

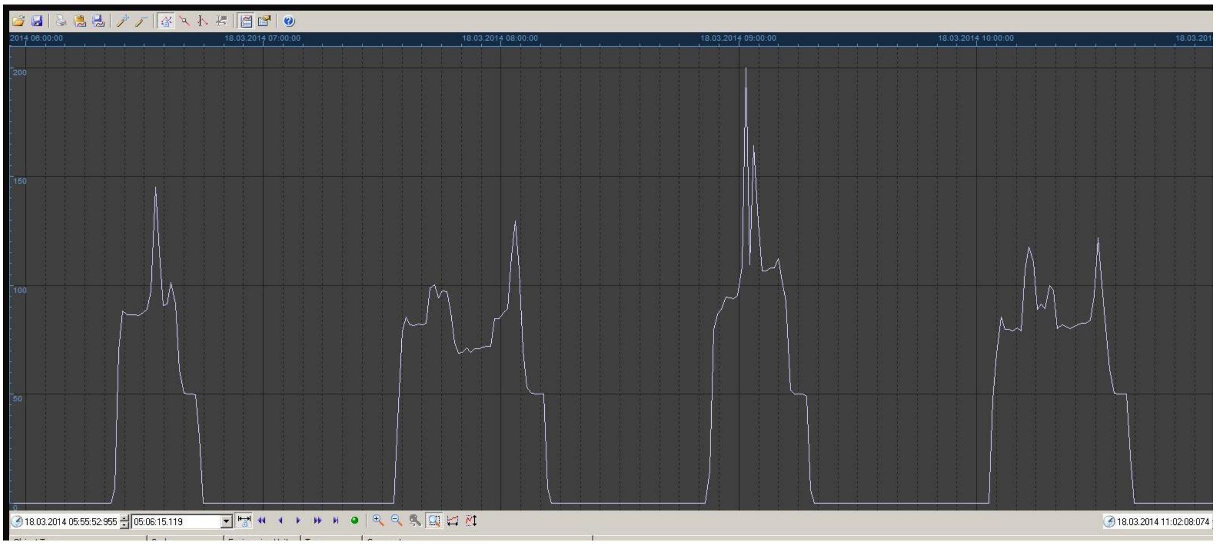
**Appendix figure 1 – Gas consumption part 1**

18.03.2014 07:25:32:008

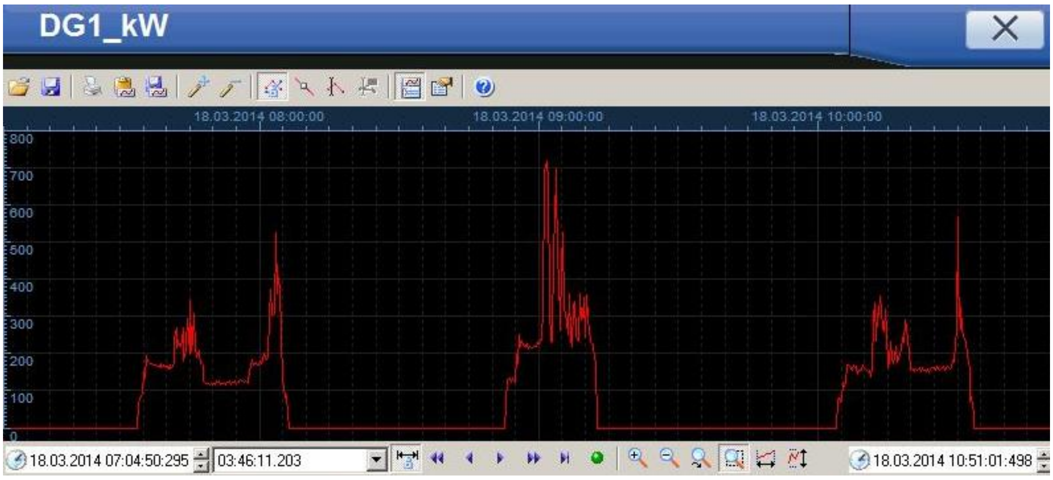
02:34:22.311

18.03.2014 09:59:54:319

**Appendix figure 2 – Gas consumption part 2**



Appendix figure 3 – MGO consumption



Appendix figure 4 - Standby generator electricity production

18.03.2014 07:09:47:593

03:50:10.634

18.03.2014 10:59:58:227

Appendix figure 5 - Shaft generator electricity production

# Appendix K – Electronic attachments

| **Estimation/model** | **File name** |
|---|---|
| Study of the conventional vessel's increased fuel consumption due to lengthening | Driftsprofil Tysfjord 2.xlsx |
| Study of fuel prices and the trend for inflation, currencies etc. | Price development scheme.xlsx |
| LCC model for the LNG vessel | LCC model Lødingen.xlsx |
| LCC model for the conventional vessel | LCC model Tysfjord.xlsx |
| Analysis of the potential savings gained by a replacement of the LNG vessel's shaft generator | Propulsion plant analysis U2.xlsx |