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Contractual and Economical Consequences of LNG Boil-Off Quality

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Background

The gas evaporating from the LNG, usually called Boil-off Gas (BOG), has previously been out of focus regarding its composition and corresponding heating value. A concentration of the BOG has been assumed to be identical to the loaded LNG, or has been given by another constant value, as the gas has been something to the carrier has “to get rid off”. However, these assumptions have seemed to give deviating results in reported fuel consumption for the vessel in some cases. This is interesting as the assumed concentration of the BOG is used to calculate its heating value, which further is used to estimate the over all fuel consumption reported as amount of Heavy Fuel Oil (HFO).

Each vessel has a given chartering contract specifying upper limits of total fuel consumption for the vessel per day. Deviating values by assumed concentration of the BOG might result in breach of contract, and corresponding economical consequences. Thereby, it is very important to understand the properties of the BOG by a given LNG concentration, and the corresponding contractual consequences by deviations in reported fuel consumption for the vessel.

Overall aim and focus

The overall aim is to understand the changing quality of the boil-off gas (BOG) during voyage, how it affects the heating value per day for an LNG Carrier, and what contractual and economical consequences this will have from a ship owner’s perspective.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Gathering some information on today's practice to calculate the heating value of the BOG.*
2. *Develop a mathematical model to calculate concentration of the BOG during voyage compared to the transported LNG.*
3. *Validate the results from the mathematical model.*
4. *Look into corresponding contractual and economical consequences by assuming a wrong concentration of the BOG*

Modus operandi

The work shall follow the guidelines given by NTNU for an MSc Master thesis. The workload shall be in accordance with 30 ECTS, corresponding to 100% of one semester.

This master thesis is written with inputs from Golar Wilhelmsen Management (GWM).

At NTNU, Professor Stein Ove Erikstad will be the responsible supervisor.



Stein Ove Erikstad
Professor/Responsible Advisor

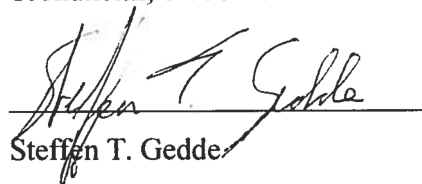
Preface

This Master thesis was written in the spring of 2014 at the Norwegian University of Science and Technology, NTNU, Department of Marine Technology, with inputs from Golar Wilhelmsen Management (GWM). They gave helpful suggestions regarding topic of the thesis, and made available useful numbers from their vessels.

This thesis treats some of the topics presented in my project thesis from fall 2013, and can somehow be seen as a continuation of that project. The topic then focused on properties of LNG in general, in addition to different engine solution for an LNG Carrier. During the work of that project thesis some differences in concentration of the evaporating gas versus the LNG itself was discovered. Thereby, it was interesting to focus more on that area in this master thesis, since the gas is used as fuel for the vessel.

I wish to thank Professor Stein Ove Erikstad, who acted as my supervisor at the Department of Marine Technology, NTNU, for his support throughout the project. Many thanks to GWM for access to useful numbers from their vessels, and the Project Engineer in Golar LNG, Kristin Haugbraaten, for great guidance on the gas-liquid behaviour of the LNG. Finally, I wish to thank Henriette Linna for great help with structuring the report.

Trondheim, 02/06-2014



Steffen T. Gedde

Abstract

The gas evaporating from the Liquefied Natural Gas (LNG), usually called Boil-off Gas (BOG), has previously been out of focus regarding its composition and corresponding heating value. A concentration of the BOG has been assumed to be identical to the loaded LNG, or has been given by another constant value, as the gas has been something to the carrier has “to get rid off”. However, these assumptions have seemed to give deviating results in reported fuel consumption for the vessel in some cases. This master thesis is therefore investigating the difference in concentration of the BOG evaporating from the transported LNG during voyage, and corresponding deviations in reported fuel consumption by assumed characteristics of the BOG.

To do this, a dynamic model is developed to see the change in concentration of the BOG per day of the voyage by a given loaded LNG quality. By knowing the change in concentration of the BOG, the model calculates the corresponding change in Higher Heating Value (HHV), since the BOG is used as fuel for the vessel. Any changes in concentration of the LNG during the loading process is taken into account as well, as it will influence the initial concentration of the product at the first day of the voyage.

To report the total fuel consumption for an LNG Carrier (LNG/C), a Fuel Oil Equivalent (FOE) is used to convert amount LNG to tons of Heavy Fuel Oil (HFO). This equivalent depends on the HHVs of both the BOG and the HFO, which is also calculated by the dynamic model. Since it has been a normal procedure for a ship owner to assume a value for this FOE, the last part of the master thesis looks into deviations in reported fuel consumption by different assumptions, and corresponding economical consequences.

The results from the model showed a significant increase in fraction of nitrogen in the BOG by only a small increase of nitrogen in the transported LNG. Since nitrogen is

highly volatile at the given cargo temperature of -162°C , the LNG tended to contain a lower fraction of nitrogen when finally loaded. The difference in concentration of the BOG during voyage caused a lower HHV compared to the LNG, as the fraction of nitrogen in the BOG was higher. This affected the calculated FOE of the BOG, and caused significant deviations in reported fuel consumption when utilizing common ways to assume the FOE. By having a HFO price of 600 USD/ton, this led to an unnecessary cost of 366,000 USD for one voyage of 28 days, when transporting LNG with approximately 1 Mole% nitrogen.

Sammendrag

Gass som koker av fra LNG har tidligere ikke vært i fokus hva gjelder dens komposisjon og korresponderende brennverdi. Før har den avkokte gassens konsentrasjon vanligvis blitt antatt å være identisk med den lastede LNGen, da denne har blitt ansett som noe skipet kun skal ”kvitte seg med”. Imidlertid ser det ut til at slike antagelser kan føre til feilrapportering av skipets drivstofforbruk ved noen tilfeller. I denne masteroppgaven vil derfor konsentrasjonen av gass avkokt fra LNG under transport med LNG-skip undersøkes, samt eventuelle avvik i rapportert forbruk grunnet gassens *antatte* egenskaper.

En dynamisk modell er utviklet for å undersøke konsentrasjonen av den avkokte gassen, hvorav denne viser gassens konsentrasjonsendringer per dag ved en gitt kvalitet på LNGen som er lastet ombord. Etterfulgt av dette regner modellen ut hvordan dette påvirker gassens brennverdi, ettersom denne brukes som drivstoff til skipet. Videre tas det hensyn til endringer av LNGen under lasting, da slike konsentrasjonsendringer kan forekomme.

For å rapportere et LNG-skips totale drivstofforbruk benyttes en såkalt Fuel Oil Equivalent (FOE). Den regner om mengden LNG brukt som drivstoff til tilsvarende mengde tungolje (HFO). Denne ekvivalenten avhenger av både HFOen og den avkokte gassens brennverdi, og blir også beregnet i den dynamiske modellen. Det har vært vanlig prosedyre at rederen antar verdien for denne ekvivalenten, ettersom gassens konsentrasjonen ikke har vært i fokus. Avslutningsvis vil derfor avvik i rapportert forbruk ved slike antagelser belyses, samt deres påfølgende økonomiske konsekvenser.

Resultatene fra modellen viste en betydelig større andel av nitrogen i den avkokte gassen enn i LNGen i lastetankene. Dette fordi nitrogen er svært flyktig ved normal transporttemperatur. Samtidig førte dette til en lavere brennverdi for den avkokte gassen enn for LNGen. Dette hadde videre påvirkning på FOEens virkelige verdi, og

førte til store avvik i rapportert forbruk ved bruk av antatte verdier. Ved å benytte en drivstoffpris for HFO på 600 USD/tonn førte eksempelvis én slik antagelse til en unødvendig kostnad på 366,000 USD for kun én reise på 28 dager, når man fraktet LNG med et nitrogeninnhold på omtrent 1 mol%.

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Nomenclature

BOG	-	Boil-off Gas
BOR	-	Boil-off Rate
FOE	-	Fuel Oil Equivalent
GWM	-	Golar Wilhelmsen Management
HFO	-	Heavy Fuel Oil
HHV	-	Higher Heating Value
LHV	-	Lower Heating Value
LNG	-	Liquefied Natural Gas
LNG/C	-	LNG Carrier
LPG	-	Liquefied Petroleum Gas
NG	-	Natural Gas
SPB	-	Self-supporting Prismatic Type B
BOG	-	Boil-off Rate

1. Introduction

The global transport of Liquefied Natural Gas (LNG) has grown rapidly during the last decades and thereby the competition in the market. By 1st of October 2013 there was a fleet of 380 LNG Carriers. The total fleet compromised 56.1 cubic metres, while the orderbooks was equivalent to 35.2 per cent of the total fleet capacity (Novikova, 2013). Many ship owners have joined the LNG transport sector, which makes efficiency more important in order to provide the lowest freight rates. Some of the transported LNG will vaporize during voyage, which is normally used as fuel for the vessel. As the insulation of the cargo tanks become better the rate of evaporations decreases, and thereby requires a more efficient fuel economical carrier for transport.

The gas evaporating from the LNG, usually called Boil-off Gas (BOG), has previously been out of focus regarding its composition and corresponding heating value. A concentration of the BOG has been assumed to be identical to the loaded LNG, or has been given by another constant value, as the gas has been something to the carrier has “to get rid off”. However, these assumptions have seemed to give deviating results in reported fuel consumption for the vessel in some cases. This is interesting as the assumed concentration of the BOG is used to calculate its heating value, which further is used to estimate the over all fuel consumption reported as amount of Heavy Fuel Oil (HFO).

Each vessel has a given chartering contract specifying upper limits of total fuel consumption for the vessel per day. Deviating values by assumed concentration of the BOG might result in breach of contract, and corresponding economical consequences. Thereby, it is very important to understand the properties of the BOG by a given LNG concentration, and the corresponding contractual consequences by deviations in reported fuel consumption for the vessel.

Some studies have been conducted concerning the BOG. Hasan et al. (2009) have been focusing on minimizing boil-off losses during transport, while Dimopoulos and

1. Introduction

Frangopoulos (2008) have been focusing more on the changing evaporation rate per day of the voyage. Shin and Lee (2009), on the other hand, have studied the reliquefaction process of the BOG and corresponding design of a control system. However, these studies' main focuses have not been the change in concentration of the BOG by a given LNG quality, and corresponding deviations in reported fuel consumption. Therefore it was interesting to focus on the changing characteristics of the BOG itself and how it affects the ship owner.

1.1. Objective

The main objective of this thesis is to get a better understanding of the gas evaporating from the LNG during voyage, as the BOG's concentration has significant influence on the reported fuel consumption for the vessel. To accomplish this, a mathematical model to estimate day-to-day changes in concentration of the BOG by a given LNG concentration will be developed. The following output will be used to investigate changes in reported fuel consumption for the vessel by different LNG qualities, and to highlight deviations caused by assuming a concentration of the BOG to be constant or equal the loaded LNG. Finally, this will be analysed from a ship owner's perspective regarding contractual and economical consequences by assuming a wrong concentration of the BOG.

1.2. Limitations

There are several factors that could potentially influence the results that are not included in this master thesis. It is likely to think that the evaporation rate of the LNG will be affected by outside temperature and sea conditions. This may also affect the composition of the BOG. The thesis are focusing on the theoretical aspects, assuming a concentration of the BOG based on boiling points for the different substances. In reality, movements on the cargo tanks due to different sea conditions might affect the substances boiling off from the LNG. However, this is not included as it would be excessive in relation to the size of a master thesis. The validation of the model in Chapter 5 will reflect any deviations from the results of the theoretical model, and thereby reveal whether the theoretical model is sufficient for explaining the overall trends.

1.3. Structure of Report

To understand all the aspects of the LNG and the BOG, some theory of the transported LNG has to be known. Consequently, what LNG is and its properties will be introduced in Chapter 2. When all the basic theory of the product is established the next chapter will create a mathematical model to estimate changes in the BOG per day of the voyage by a given LNG quality. The results from the model will be analysed regarding different loading scenarios in order to compare changes in the BOG by different concentrations of the loaded LNG. Additionally, how this affects the reported fuel consumption for the vessel will be analysed. When having these results, the next chapter will compare the theoretical model with real measurement of the BOG for some of Golar Wilhelmsen Management's (GWM) vessels, to see how well they correlate. Finally, contractual and economical consequences of the given results will be presented, in addition to how this influences the chartering contract of the vessel.

Chapters	
2.	Theory
3.	Creating Model
4.	Model Results
5.	Validating Model
6.	Consequences
7.	Conclusion
8.	Further Work

2. Chemical and Physical Properties of LNG as Fuel

This chapter will look into different aspects of Liquefied Natural Gas (LNG). The main part of this section is obtained from the Project Thesis written as a pre-study for this master thesis in the fall 2013. The overall focus is to give an introduction to the product, and create a basis for further calculations in the thesis. Thermodynamic properties of the LNG will be introduced in addition to short descriptions of how it is handled as a product and later transported on an LNG Carrier (LNG/C).

The first part will discuss what LNG is, and its difference from the related product called Natural Gas (NG). Further, the liquefaction process of the LNG will be introduced, before moving on to the part concerning transport of the product. This will handle evaporation during voyage and corresponding heating values of the gas used as fuel.

2.1. What is LNG

Liquefied Natural Gas (LNG) is Natural Gas (NG) that has been cooled down to a liquefied state, but the mixture of the two products is not the same. The products contain different chemical substances, and thereby have different thermodynamic and chemical properties. However, not even LNG is a fixed mixture, which causes the heating value (described in Chapter 2.5) to change and thereby affect the total fuel consumption of the vessel transporting it. Before moving on with these aspects, it is important to distinguish LNG from NG.

2.1.1. Difference Between NG and LNG

Natural gas is often discovered during search for oil. It primarily consists of methane, but does also contain ethane, propane, butane and other heavier hydrocarbons, even small quantities of nitrogen, water, sulphur compounds and carbon dioxide (Foss, 2007). Liquefied Natural Gas (LNG) is natural gas (NG) that has been cooled to a temperature of about -162°C to make it liquefied.¹ The liquefaction process makes

¹ The temperature of -162°C is an approximate value, as it may differ slightly by some degrees Celsius.

the gas more economical to transport as it compromises the gas approximately 600 times (BP, 2012). Figure 1 illustrates a typical composition of the natural gas when discovered, but to prevent components from forming solids during liquefaction, as will happen with water and carbon dioxide at LNG temperature (-162°C), some non-methane components needs to be removed. In addition, much of the propane and butane will be removed and sold as a separate product called Liquefied Petroleum Gas (LPG). The result is a typical higher methane ratio in the LNG composition than in the discovered NG, as illustrated in Figure 1.

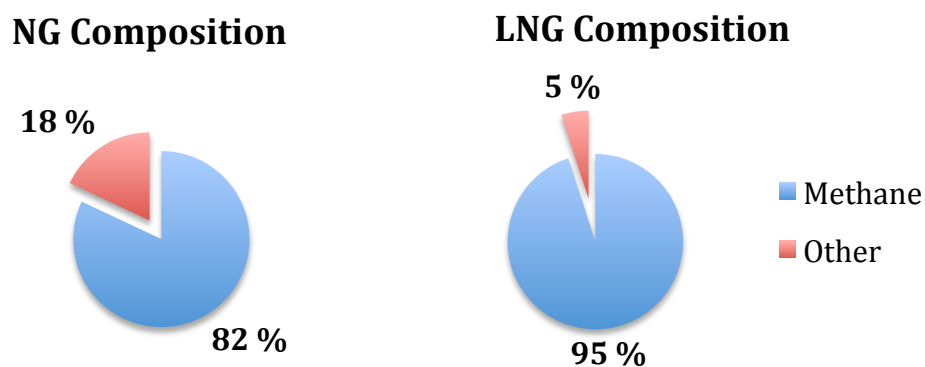


Figure 1: Composition of NG and LNG (Foss, 2007)

The figure only illustrates that the main part of methane increases and that other components are removed before the gas is transported as LNG. The exact ratio of methane compared to other substances will vary by location around the world and will differ from this value. It is just meant to be an illustration of how significant the change in composition is to make it transportable on LNG Carriers.

The product, LNG itself, is colourless, non-corrosive, odourless and non-toxic. Still, the natural gas that vaporizes from the LNG can cause asphyxiation in an unventilated room. Thereby safety is very important when handling the product, as leakage may result in hazardous consequences. However, the risk factor is not a focus area in this master thesis.

2. Theory

2.2. Liquefaction of the Gas

There are mainly two ways to liquefy gas: either by pressure or by lowering the temperature. The required pressure and temperature depends on the properties of the gas normally illustrated by a Pressure-Enthalpy Diagram, illustrated in Figure 2. Note that this figure is only used as an example to illustrate how a substance is changing phase by pressure or by temperature. It reflects what the diagram will look like for the substances in LNG, and illustrates the changing phase from liquid to vapour, but the figures exact shape will depend on given substance.

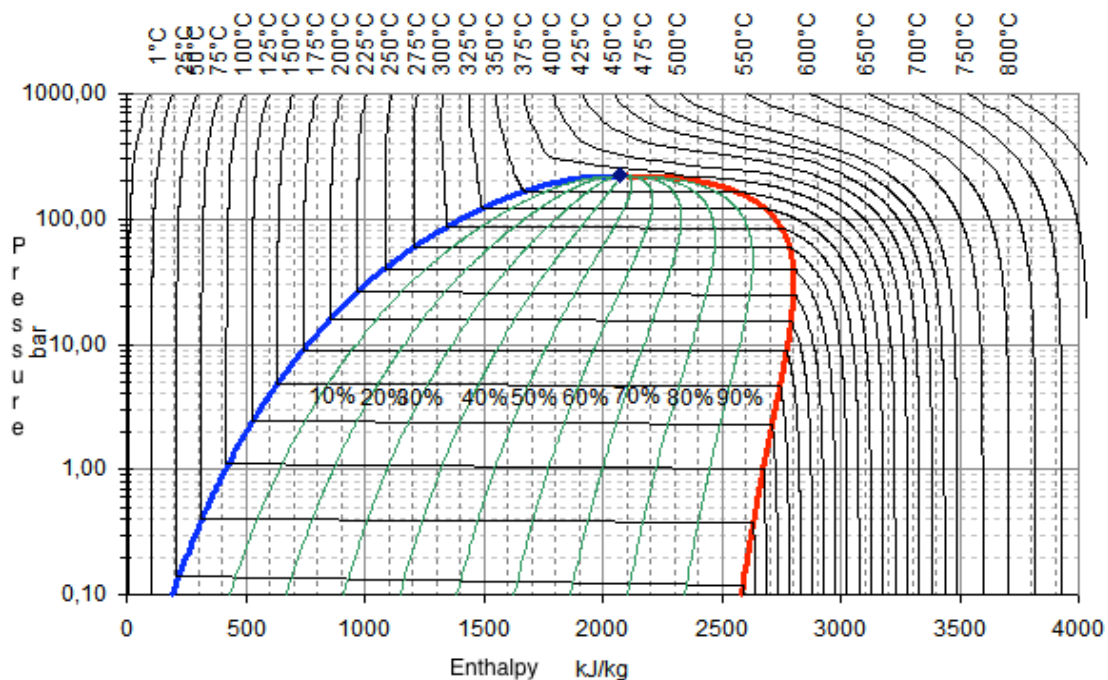


Figure 2: Pressure-Enthalpy Diagram, Example (Holmgren, 2007)

The horizontal axis corresponds to the enthalpy of the substance, while the vertical axis is the pressure.² The blue line is saturated liquid and the red line is saturated vapour.³ Between these two lines is where the liquid partly change phase, and finally become 100% gas at the red line. The black lines indicate the different temperatures. An important aspect of the diagram is the critical temperature illustrated by a black dot. Above this point no liquefaction is possible by just increasing the pressure, as the

² Enthalpy is the total energy of a thermodynamic product, measured in kJ/kg MORAN, M. J. & SHAPIRO, H. N. 2010. *Fundamentals of Engineering Thermodynamics*, Wiley.

³ Saturated *liquid* is liquid that is about to vaporize. Saturated *vapour* is the phase where no more liquid exists and the substance is in 100% gas phase.

temperature have to be decreased as well for the substance to become liquid (Moran and Shapiro, 2010).

As an example two different products transported by ship is compared; Liquefied Petroleum Gas (LPG), which is normally liquefied by pressure, and LNG, that has to be liquefied by lowering the temperature. In difference to LPG, which is mainly propane transported under high pressure, LNG is transported in cargo tanks with around atmospheric pressure and with no cooling system commonly used. It is interesting to highlight why these two products are handled differently. Methane has different thermodynamic properties and a different critical temperature, which is an essential difference to propane. Since LNG is mainly methane and LPG is mainly propane, the two different products have to be treated differently before transport. In Appendix A1 and A2 are the properties of both methane and propane illustrated in Pressure-Enthalpy Diagrams. Methane has a critical temperature of -82.7°C (Starling, 1973), which means methane has to be cooled to a temperature below -82.7°C to liquefy the gas by increased pressure. It is simply not possible to liquefy by pressure at temperatures above this point. On the other hand, propane has a critical temperature of 96.6°C (Starling, 1973), which enables liquefaction by increasing the pressure since the temperature normally is below this point. Therefore, LNG is liquefied by decreased temperature, and LPG by increased pressure. However, there exists combinations of both pressurized and cooled tanks, but this will not be further discussed, as it is not relevant for this thesis. The essential part is that LNG has to be cooled to a temperature below -82.7°C to become liquid, and thereby there is no reason to have pressurized tanks aboard.

2.3. Tank Concepts for Transport on LNG Carriers

Most of the LNG is transported around the world using specially designed ships, called LNG Carriers (LNG/C). This way the gas can be transported in a very efficient way and keep the total cost of the product as low as possible. Some may argue pipelines to be a more economically beneficial way to transport the gas, but that only counts for shorter distances. There will be an economically intersection between a gas pipeline and transport by an LNG Carrier, where transportation done by ship is more economically beneficial for longer distances (Foss, 2007).

2. Theory

There exist several different cargo tank designs for an LNG/C, which can be Cylinders (Type A, B, C), Esso design, Self-supporting Prismatic Type B (SPB), Membrane design or the Spherical Moss design (Novikova, 2013). However, the most commonly used designs, representing nearly all of the total world fleet of LNG Carriers, are the Membrane Design and the Spherical Moss design (Novikova, 2013). The spherical design by Moss is illustrated in Figure 3. This characteristic design has been the most commonly used on older vessels after it was introduced to the market in 1973 (Maritime, 2013), and can easily be recognized by its spherical dome tops visible above deck. However, the trend is now pointing in direction of membrane designs, illustrated in Figure 4.

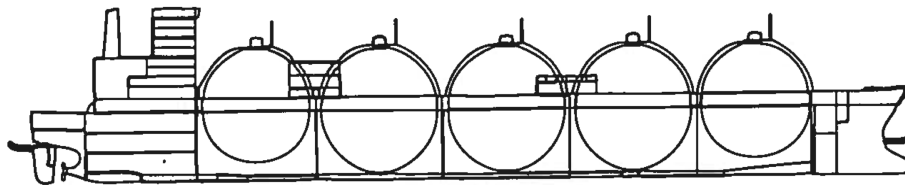


Figure 3: LNG Carrier of the Spherical (Moss) Type (MAN, 2009)

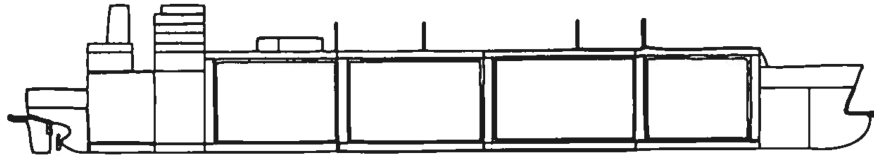


Figure 4: LNG Carrier of Membrane Type (MAN, 2009)

It is very interesting to compare the existing fleet by 2006 with the fleet by 2013 and corresponding newbuildings. It has been a significant trend of moving away from the spherical design, and the trend is still decreasing for newbuildings in 2013 (Foss, 2007). The trend of moving away from spherical tanks may have to do with the membrane tanks utilizing more of the void space between the cargo tanks and thereby requiring less hull space for transporting the same amount of LNG. Having less void

space between the cargo tanks makes it easier for the vessel's main dimension to fulfil different limitations, e.g. the Panamax.⁴

2.4. Boil-off Gas During Transport

Although the cargo tanks on the LNG Carriers are highly insulated, some heat exchange is inevitable. As illustrated in Figure 5, some of the liquid will vaporize and change into gas phase, known as boil-off gas (BOG). The rate the liquid vaporizes, called boil-off rate (BOR), mainly depends on the heat exchange through the tank walls, and thereby how well the tanks are insulated. More heat exchange means more energy stored in the tank, and thereof more vaporization. This phenomenon of vaporized LNG during transport is called ageing. The BOG will mainly consist of nitrogen and methane, but it may contain a very small amount of heavier hydrocarbons as well (Benito). The vaporization of LNG is not totally homogeneous; it depends on the mixture and the properties of the different components.

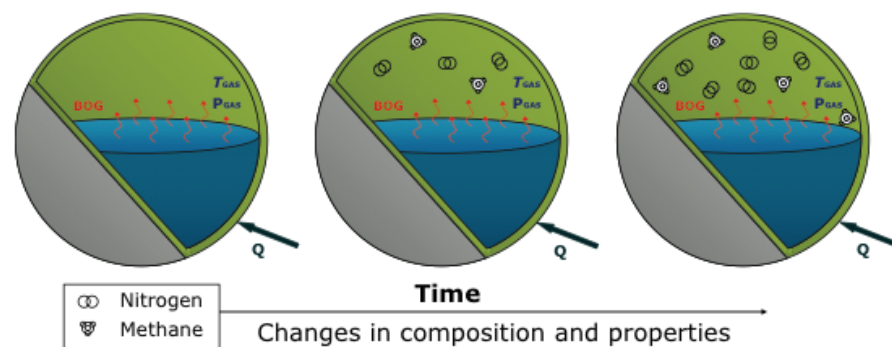


Figure 5: Change in composition and properties (Benito)

The boiling point at atmospheric pressure (the pressure during transport) is essential and individual for all the components. Methane, which is the main part of LNG, has a boiling point of -161.5°C . Only nitrogen has a lower boiling point (-196°C) among the important components in LNG. All the other heavier hydrocarbons as ethane, propane and butane have boiling points above the liquefaction temperature (-162°C) as illustrated in Table 1 (Aylward and Findlay, 2007).

⁴ Panamax defines the restrictions for maximum main dimensions of a ship that can transit the Panama Canal, i.e. a beam of 32.3m, a length of 294.1m and a draft of 12m. Note that a scheduled increase of the canal in 2014 will increase the allowed main dimensions (AUTHORITY, P. C. 2013. *This is the Canal* [Online]. Available: <http://www.panacanal.com/eng/acp/asi-es-el-canal.html>).

2. Theory

Table 1: Boiling Points (Aylward and Findlay, 2007)

Component	Boiling Point (Atmospheric pressure)
Nitrogen	-196°C
Methane	-161.5°C
Ethane	-88.6°C
Propane	-42.1°C
Butane	-0.5°C

The boiling point is the temperature at a given pressure where a substance is changing phase from liquid to vapour. Thereby, it is reasonable that the BOG only consists of methane and nitrogen as the temperature during transport is around -162°C.

During transport the LNG will be stirred and moved within the tanks caused by movements on the ship. This, together with heat exchange, causes some parts of the substances in LNG to vaporize and become BOG, but the amount of each substance in the BOG will be different and change during transport. The main part of the gas will always be methane as it is the main component of LNG, and it will contain some nitrogen if present. However, other substances will not have a significant impact on the mixture of the BOG since their boiling points are above the liquefaction temperature of -162°C.

In the beginning of the voyage the LNG will often contain some nitrogen (Dimopoulos and Frangopoulos, 2008), which has a boiling point below the liquefaction temperature. This causes nitrogen to boil off easily in the beginning of the voyage until there is nearly no nitrogen left. Therefore, nitrogen will be a more essential part of the BOG in an early stage of the voyage than in the end. This phenomenon of ageing causes the LNG to have slightly different properties at the destination port than the liquid originally loaded. It will contain less nitrogen when unloaded, and it may be a lower amount of methane compared to other heavier hydrocarbons. However, this difference will most likely be so small that it will be unnoticeable. Methane is still the main part of the product at the destination port. Nevertheless, it may affect the heating value of the LNG and the BOG and thereby the amount consumed as fuel for the vessel.

2.5. Heating Values

The heating value of a substance gives the amount of energy released when burning it (Moran and Shapiro, 2010). This is important since Boil-off Gas (BOG) is used as fuel, and the amount energy released when burning it (the heating value) affects the amount LNG needed to propel the vessel. The heating value of the BOG, given by Equation 2.5.1, is calculated as the mean value of all the substances in the product, and thereby depends on mixture. M is the total mass [kg] of the LNG transported in the cargo tanks, i is the index for all different substances, and h_i together with m_i is the heating value and the total mass of each substance respectively.

$$\text{Heating Value of LNG} = \frac{\sum_i (h_i * m_i)}{M} \quad (2.5.1)$$

M	Mass of LNG	[kg]
h_i	Heating Value of Substance i	[MJ/kg]
m_i	Mass of Substance i	[kg]

It is important to distinguish between a lower and a higher heating value, also called Gross and Net Calorific values. The higher heating value (HHV) includes the energy released when the vapour in the exhaust gas are condensing into liquid, while the lower heating (LHV) is obtained when all the water formed by combustion is still vapour (Moran and Shapiro, 2010). According to ISO 3046-1 (2002), specific fuel consumption is specified for a reference fuel with lower heating value, as sulphur in the fuel may cause corrosion if the exhaust gas is cooled to a temperature below 150-160°C. This is specified as a lower temperature limit for sulphur-containing fuels. The reason is that sulphur combines with oxygen in the combustion process to form sulphur dioxide (SO₂), which further may combine to form sulphur trioxide (SO₃). The sulphur trioxide reacts with moisture from the combustion process and forms sulphuric acid vapour. This can lead to corrosion if it condenses to sulphuric acid, caused by exhaust temperatures below the acid dew point of 160°C (Woodyard, 2009).

However, LNG does not contain any sulphur, which means more of the energy in the LNG can be utilized by cooling the exhaust gas below this limit. Therefore, some

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U.S. calculations tend to use the HHV, but it should be noted that it might cause problems when comparing utilization of different fuel types, as comparing with sulphur containing fuels will require use of the LHV.

Still, the HHV will be used in this thesis to compare changes in properties of the BOG, since Golar Wilhelmsen Managemnet (GWM) is using these values in their calculations. Thereby, it is easier to compare any results with values used by a company in the LNG business. To highlight the difference between LHV and HHV, both values are given in Table 2.

Table 2: Heating Values (Genapathy, 2002)

Substance	Formula	LHV [MJ/kg]	HHV [MJ/kg]
Methane	CH ₄	50.0	55.5
Ethane	C ₂ H ₆	47.5	51.9
Propane	C ₃ H ₈	46.4	50.4
n-Butane	C ₄ H ₁₀	45.8	49.6
Isobutane	C ₄ H ₁₀	45.7	49.4
n-Pentane	C ₅ H ₁₂	45.4	49.1
Isopentane	C ₅ H ₁₂	45.3	49.0
Nitrogen	N ₂	-	-

There will be a change in mixture of the LNG during voyage due to gas boiling off. This will affect the concentration of the BOG and thereby the total fuel consumption for the vessel. Dimopoulos and Frangopoulos (2008) have done some research regarding liquefied natural gas evaporation during marine transport.⁵ Even though their research mainly focuses on change in mass flow of gas boiling off per day, it includes some results of change in composition of both the LNG and the BOG during voyages as well.

⁵ These results are based on data from Kuver, Clucas & Fuhrmann (2002 in DIMOPOULOS, G. G. & FRANGOPOULOS, C. A. 2008. A dynamic model for liquefied natural gas evaporation during marine transportation. *International Journal of Thermodynamics*, 11, 123-131.

Their findings are based on a 25 days voyage with a fully loaded LNG vessel of 150,000 m³, without any forced boil-off or reliquefaction onboard.^{6 7} It confirms that the amount of methane in the final delivered product is nearly equal to the previous initial state for the loaded LNG. However, there is a noticeable difference in composition, and thereby properties of the BOG used as fuel. This affects the amount of gas needed to propel the vessel and thereby its fuel economy. Their results are given in Table 3.

Table 3: Changes in composition during voyage (Dimopoulos and Frangopoulos, 2008)

	LNG [Mole %]		BOG [Mole %]	
	Initial	Final	Initial	Final
Methane	89.9 %	89.7 %	92.7 %	96.8 %
Ethane	6.0 %	6.2 %	0.0 %	0.0 %
Propane	2.2 %	2.3 %	0.0 %	0.0 %
Butane	1.5 %	1.6 %	0.0 %	0.0 %
Nitrogen	0.4 %	0.2 %	7.4 %	3.2 %
LHV of LNG	49.5 [MJ/kg]	49.6 [MJ/kg]	46.4 [MJ/kg]	48.5 [MJ/kg]

Their results clearly indicate that the BOG includes a high percentage of 7.43% nitrogen at the beginning of the voyage before it decreases to 3.15% at the final destination. It is also interesting to see that the BOG almost does not include any ethane, propane or butane at all, which is reasonable since methane and nitrogen are the only substances around or above their boiling point during transport in the LNG Carrier. Thereby, only the change in composition of methane and nitrogen affects the heating value of the BOG used as fuel, which changes from 46.37 [MJ/kg] initially to 48.45 [MJ/kg] at final state (Note that the LHVs are used in their research). The reason is that nitrogen does not contribute to the total heating value at all, which makes the total value better during voyage since the amount of nitrogen in the BOG decreases by time.

⁶ Forced Boil-off means to extract LNG as liquid from the cargo tanks, and vaporize it by use of external energy. This can be done if more gas is needed as fuel.

⁷ Reliquefaction means to liquefy the gas by cooling it down to cargo temperature and send it back to the cargo tanks. This can be done if more LNG is vaporizing than the amount needed as fuel.

2. Theory

In addition, their results clearly shows that the total mixture of the final delivered LNG is almost identical to the initial loading state, while the BOG changes more significantly in composition. The mixture of the LNG itself tends to be better during voyage since much of the nitrogen has boiled off. However, the initial part of nitrogen in the LNG is very low (0.40%) compared to other substances, which only causes the heating value of LNG to change from 49.55 [MJ/kg] to 49.67 [MJ/kg]. As some methane and nitrogen has boiled off during voyage, the amount of other hydrocarbons in the mixture will slightly increase, but not by much. The overall understanding is that both the LNG itself and the resulting BOG becomes better during voyages.

It has been a normal procedure for a shipping company to assume a concentration of the BOG identical to the concentration of the loaded LNG or a fixed value, as the BOG has not been an area of focus. However, greater competition in the market and stricter limits on fuel consumption makes it more interesting to know the exact concentration of the BOG used as fuel. Especially as Dimopoulos and Frangopoulos (2008) have found a significant difference in composition of the BOG compared to the LNG. Therefore, the next chapter creates a model to identify the exact changes of the BOG per days of the voyage by a given concentration of the loaded LNG. The aim is to look for changes in the HHV of the BOG per day in order to highlight any deviations in reported fuel consumption due to assuming the concentration of the BOG.

3. Model to Estimate Change During Transport

The Boil-off Gas (BOG) has been out of the ship owner's focus regarding its changing concentration and thermodynamic properties compared to the loaded LNG. It has been common to assume a composition of the BOG identical to the loaded LNG when calculating its HHV and corresponding fuel consumption. Some of the substances in the LNG, as nitrogen and methane, are more volatile at the given loading temperature, which implies a higher fraction of these substances in the BOG than in the LNG itself. Any difference in composition of the BOG will influence the fuel consumption of the vessel since it is used as fuel during transport. It is therefore interesting to develop a dynamic mathematical model to gain a better understanding of the changes in physical and chemical properties of the BOG during transport, and to see how it affects the reported fuel consumption of the vessel. The model itself is divided into subsections, but the basis of all these sub-models is to understand the change in composition of the BOG per days of the voyage compared to the loaded LNG.

The following subsections will go through all the assumptions and equations that provide the foundation of the model. It is divided into subsections to illustrate all the aspects that underline the calculations to report the total fuel consumption for the vessel. The first part is about calculating change in concentrations of the BOG per day relative to the LNG in the cargo tanks. However, some of the LNG will be flashing off during the loading process and sent back to the terminal (Haugbraaten).⁸ This can cause change in composition of the finally loaded LNG compared to the product delivered by the terminal. In order to have the correct initial state of the LNG at the first day of the voyage, subsection two is focusing on changes in initial state of the LNG by gas flashing off during loading. The last two subsections are looking into

⁸ Gas flashing off means that parts of the LNG will evaporate and thereby be flashing off from the product.

3. Creating Model

changes in HHV and corresponding Fuel Oil Equivalent (FOE) of the BOG due to change in concentration of the BOG.⁹

However, to create this dynamic model it was required a good knowledge about the steady-state equilibrium between the LNG and the BOG. This aspect of the product had to be covered before moving on with the model, as it will be used as an input. Thereby, the following section will be handling this equilibrium phase before looking into the subsections of the dynamic model.

3.1. Steady-State Equilibrium of LNG and BOG

There will always be a steady-state equilibrium between liquid and vapour in a cargo tank containing LNG. This is important when further modelling the change in composition of the BOG. Even though liquid might vaporize by a changing rate per day, depending on heat exchange with the surroundings and the composition, there will always exist an initial state, which can be considered as a steady-state equilibrium. Different parts of the thermodynamic discipline was attempted analysed in an early phase of this thesis work to calculate this steady-state equilibrium, but it was too heavy and deviated from the focus of this master thesis. However, SINTEF at NTNU was contacted for advice, and they recommended the Design II software to simulate the concentration of gas and liquid in equilibrium phase.^{10 11} Simplified, this software gives the concentration of the gas when input parameters, as molar concentration of liquid added to the tank, the gas pressure and amount flashing off per time are given. The only problem was that this software only gives the instant concentration of the gas relative to the liquid. A dynamic model needs to recalculate this equilibrium phase for every day of the voyage, as the concentration of the LNG will change due to gas boiling off. Thereby, the solution was to run several cases of different LNG concentrations in the software to look for correlations in the results. The aim was to find corresponding functions that could be used in the following dynamic model in this thesis.

⁹ Fuel Oil Equivalent (FOE) – Used to calculate the amount of HFO the given LNG corresponds to.

¹⁰ A personal meeting with Senior Scientist Ole Oldervik at SINTEF OLDERVIK, O. 05.03.2014. *RE: Meeting with SINTEF, Ole Oldervik.*

¹¹ The Design II Software is an advanced engineering software developed by WinSim INC., W. 1996 - 2013. *Advanced Engineering Software* [Online]. Available: www.winsim.com.

To get accurate results by use of the software, good knowledge on usage and input parameters were required. Fortunately, The Project Engineer in Golar LNG, Kristin Haugbraaten, had access to this simulation tool and helped with the calculations in order to get correct results. To get an idea of the composition of the BOG, some cases of different concentration of the LNG were conducted. All these simulations supported the assumptions of only methane and nitrogen containment in the BOG, which corresponded very well with studies by Dimopoulos and Frangopoulos (2008). Some other hydrocarbons were present, but the fractions were approximately zero. This is illustrated in Table 4.

Table 4: Results from Design II Calculations (All Substances)

Input (LNG Mole%)					Output (BOG Mole%)				
CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀	N ₂	CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀	N ₂
89.9	6.0	2.2	1.5	0.4	89.6	0.0	0.0	0.0	10.4
91.5	6.3	2.0	0.2	0,03	99.2	0.0	0,0	0,0	7.9
88.0	8.4	2.0	0.6	1.0	75.8	0.0	0,0	0,0	24.2

The table clearly indicate that the BOG does almost exclusively contain methane and nitrogen. Additionally, since ethane has a heating value nearly equal to methane (Goodger, 1977), it was assumed that ignoring the fraction of ethane in the BOG would have nearly no impact on the overall results. Thereby, when running more simulations to cover several aspects of the LNG, it was assumed that the loaded LNG only contained methane and nitrogen. This means all the heavier hydrocarbons in the LNG was excluded and replaced by methane in the simulations.

However, it was suspected that including heavier hydrocarbons in the simulations could affect the evaporations rate of the nitrogen. By running some new test simulations, it appeared that this was actually the case. The fraction of nitrogen in the BOG tended to increase when including heavier hydrocarbons, even though the nitrogen content in the LNG was constant. Thereby, new simulations were preformed, including all the common substances in the LNG, in order to obtain correct functions for the concentration of the BOG. To illustrate these changes, both iterations are included in the following subsections.

3. Creating Model

3.1.1. First Iteration: Only methane and nitrogen in the LNG

It was expected that the calculations of the BOG would be independent of heavier hydrocarbons in the LNG. Therefore, for the first iteration in the software, it was assumed a loaded LNG containing only methane and nitrogen. Additionally, the Design II software required some assumptions, which were set to be equal common values for an LNG/C in GWM's fleet. These values were decided by guidance from the Project Engineer in Golar LNG. The gas pressure was set equal to a regular pressure in the cargo tanks of an LNG/C, an overpressure of 0.132 bars. Additionally, the amount of gas flashing off per day was set to be 0.12% of the total volume, which is a reasonable value for an LNG/C. Table 5 gives the results from this first iteration of the equilibrium phase.

Table 5: Results from Design II Calculations (Only Methane and Nitrogen)

Input (LNG Mole %)		Output (BOG Mole%)	
CH ₄	N ₂	CH ₄	N ₂
99.97	0.03	99.3	0.7
99.9	0.1	97.8	2.2
99.7	0.3	93.6	6.4
99.5	0.5	89.6	10.4
99.0	1.0	80.4	19.6

The results clearly indicate an increasing trend of nitrogen in the BOG by increased fraction of nitrogen in the loaded LNG. However, in order to use these results in a dynamic model to calculate changes per day, it was desirable to find a function corresponding to these results. To do this the results were plotted to look for correlations. Polynomial regression fitted perfectly and made it possible to determine a suitable function for the nitrogen content to be used in the dynamic model. The correlations in the results are illustrated in Figure 6, where the horizontal axis represents the fraction of nitrogen in the LNG, and the vertical axis represents the corresponding nitrogen in the BOG. Note that these values are fractions of 1 in total, not the percentage value.

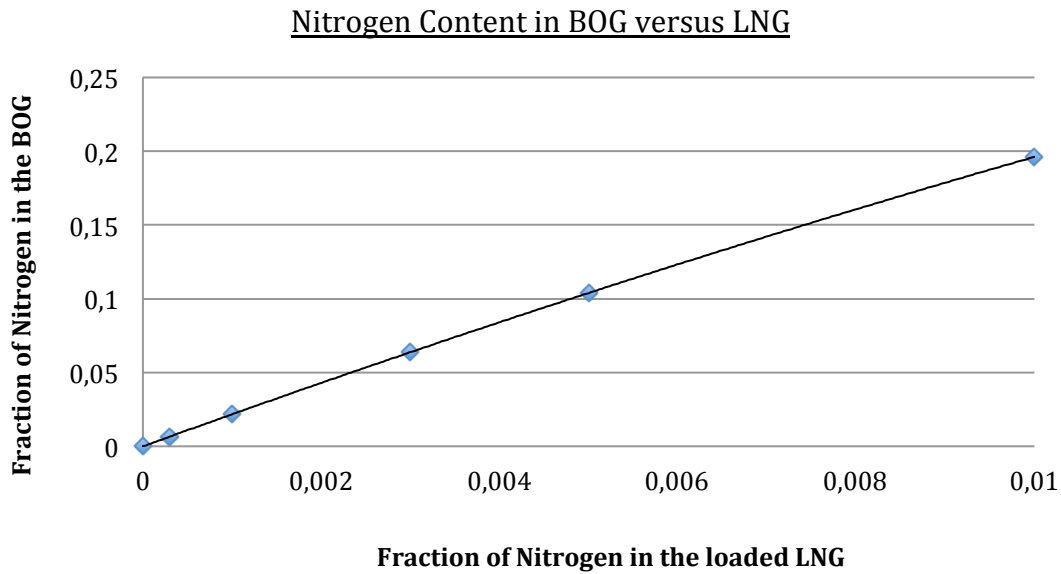


Figure 6: Regression of Nitrogen Content in BOG versus LNG

The resulting function of the nitrogen content in the BOG, found by polynomial regression is given by Equation 3.1.1:

$$f_N(x) = -233.7x^2 + 22.0x \quad (3.1.1)$$

This function gives the corresponding mole fraction of nitrogen in the BOG when the fraction of nitrogen in the LNG is known, which is very useful as the fraction of nitrogen in the LNG is provided by the loading papers from the terminal. It enables a dynamic illustration of changes per day, as the changing concentration of the LNG always will be a known value.

Even though the BOG mostly contains methane and nitrogen, it was suspected that the evaporation rate of methane and nitrogen could vary by the fraction of other substances in the loaded LNG. Since that was confirmed when running some test cases, more thoroughly simulations were performed in a second iteration.

3. Creating Model

3.1.2. Second Iteration: Including heavier hydrocarbons in the LNG

In the second iteration, it turned out that including ethane and heavier hydrocarbons in the simulations of the equilibrium had a significant influence on the results, yet only on the concentration of nitrogen in the BOG. Still, methane and nitrogen were the only main substances in the gas. This time, more systematic simulations were performed to look for differences by changing the amount of ethane in the cargo. 16 simulations were done in total, varying the fraction of ethane from 0% to 8% by a step length of 2. In addition, the fraction of nitrogen was varied from 0.03% to 1%, which is identical to the first iteration. Other heavier hydrocarbons as propane and butane were kept at a constant level of 2% and 0.5%, respectively. All these values were based on common values given by loading papers from terminals. It is normal for the LNG to contain some propane and butane, but the fractions are small according to provided loading papers for some vessels (see Appendix A3 and A4). Thereby, keeping the values at a constant level was assumed to not have a significant influence on the overall results.

All the results from the simulations in Design II due to changing the fraction of ethane, methane and nitrogen are given in Figure 7. The horizontal axis corresponds to the fraction of nitrogen in the loaded LNG, while the vertical axis gives the corresponding fraction of nitrogen in the BOG. Note that the values of the axis represent fractions of 1 in total, not the percentage values.

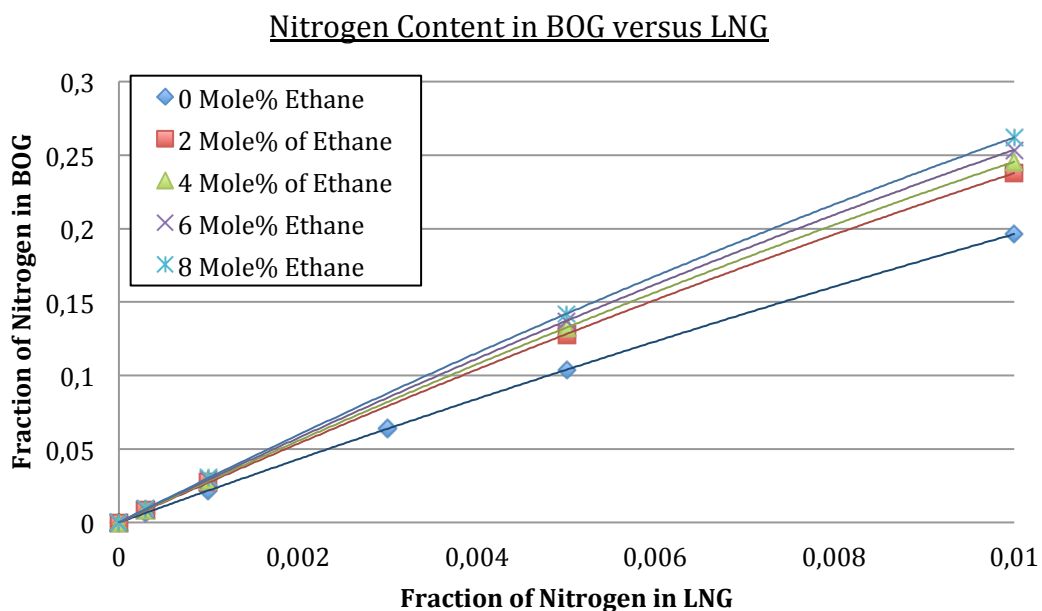


Figure 7: Nitrogen Content in BOG by Fraction of Ethane

The results clearly indicate that an increased fraction of ethane and heavier hydrocarbons in the LNG results in a higher fraction of nitrogen in the gas flashing off. Simply increasing the concentration of ethane from 0 to 2 Mole% in addition to 1 Mole% nitrogen in the LNG will result in 23 Mole % of nitrogen in the BOG. Additionally, further increases in fraction of ethane results in an even higher concentration of nitrogen in the BOG, which is very important for further calculations in the dynamic model.

Polynomial regression fitted for these results as well. Equation 3.1.1 is still valid when the fraction of ethane in the loaded LNG is approximately zero, but the equation had to be updated with new constants to match these new variations in the BOG by ethane content in the LNG. This more general function of the nitrogen content in the BOG is given by Equation 3.1.2, and Table 6 gives the corresponding constants, depending on the ethane content.

$$f_N(x) = ax^2 + bx \quad (3.1.2)$$

Table 6: Constants for Equation 3.1.2

Ethane Content	a	b
0 Mole %	-233.7	22.0
2 Mole %	-375.4	27.5
4 Mole %	-396.2	28.5
6 Mole %	-418.5	29.5
8 Mole %	-442.9	30.6

Having these functions to give the instant concentration of the BOG by a given LNG concentration made it possible to generate a dynamic model adapting to everyday changes of the LNG. The following model is made to choose the most appropriate constants for Equation 3.1.2 according to remaining fraction of all the substances in the LNG at each day. Values between these given fractions of ethane are rounded to the nearest value.

3. Creating Model

The following subsections will show the development of the model, which later will be used in calculating the changing concentration of the BOG and the LNG per day of the voyage, in addition to corresponding change in HHV and reported fuel consumption. The part of the model considering change in concentration of the BOG per day of the voyage by a given LNG concentration is explained first, as it is the fundamental part of the complete dynamic model.

3.2. Model Part 1: Change in Composition of the BOG

This first part of the model explains how the concentration of the BOG is calculated for each day of a complete voyage. The concentration of the LNG and the gas flashing off will change per day of the voyage, as some parts of the containing substances are removed from the tanks and used as fuel. To calculate these daily changes, the model is recalculated for each day of the voyage, making a new initial state of the LNG per day. All these changes were calculated by looping the whole model in a numerical computation software, in this case MATLAB. Before explaining all the equations to calculate the changes of the BOG, some assumptions are needed.

3.2.1. Assumption for the Model of the BOG

The first assumption is that the BOG only contained methane and nitrogen, as it was indicated theoretically and by simulations in the Design II software (See Chapter 3.1). The second assumption is no significant change in concentration of the BOG by increased volume flashing off per day, i.e. Equation 3.1.2 is used regardless the amount of BOG per day. The last assumption is that the density of the LNG is kept constant for a whole voyage. The reason for this last assumption is that nitrogen represents a very low fraction of the LNG, and thereby does not cause any significant changes to the LNG when boiling off. The methane is always the main part, and will still be the main part at the destination port. This is also supported by the studies of Dimopoulos and Frangopoulos (2008).

3.2.2. Model to Calculate Composition of the BOG

To make a mathematical model for the concentration of the BOG compared to the LNG, and how it changes during a voyage, some conversions were needed. This model is handling both gas phase and liquid phase, which has different chemical properties. The gas phase can be modelled by assuming ideal gas behaviour, and thereby look at all the substances separately (Moran and Shapiro, 2010). However, the liquid phase is more complicated as all the substances are mixed together. In addition, a normal cargo report provided by the terminal often gives the fraction of all substances in the loaded LNG, which is in liquid phase, meaning a more complicated liquid phase must be taken into account. Still, these two phases have something in common: the number of moles. The exact number of moles of each substance extracted from the liquid by vaporization will be the same when changing into gas

3. Creating Model

phase, even though the required volume is different (Zumdahl, 2009). This is used as a cornerstone for all calculations in this model.

In order to make the results of the model unique for each voyage and vessel, the model is designed so the user has to specify some input parameters. The mole fraction of each substance in the LNG (X_i) and its density (ρ_{LNG}) are often specified in the loading papers for the vessel, while ship specific parameters as cargo tank volume (V) and average boil-off rate (BOR) is known by the technical department in the company operating the vessel. In addition, days of the voyage (D) have to be entered in order to get correct results. All these required input parameters are listed below:

X_i	Mole fraction of substance i in the LNG	[Mole fraction]
ρ_{LNG}	Density of loaded LNG	[kg/m ³]
V	Vessel's Cargo Tank Volume	[m ³]
BOR	Boil-off rate	[Volume (%)/Day]
D	Number of days at sea	[Days]

In addition, all other variables and parameters used in the model to calculate for each day of the voyage are given below:

X_{LNG}^i	Mole fraction of substance i in the LNG	[Mole fraction]
X_{BOG}^i	Mole fraction of substance i in the BOG	[Mole fraction]
X_i	Mole fraction of substance i in liquid form	[Mole fraction]
N_i	Number of moles of substance i	[Moles]
N_{BOG}^i	Number of moles of substance i in the BOG	[Moles]
N_{BOG}^{tot}	Total number of moles in the BOG	[Moles]
N_{LNG}^i	Number of moles of substance i in liquid form	[Moles]
M_i	Molar mass of substance i	[kg/mole]
$f_N(X)$	Regression from Design II	[Mole fraction]
BOG_{VOL}	Boiled off gas per day (given as liquid volume)	[m ³ /day]
w_{tot}	Weight total	[kg]
w_i	Weight of substance i	[kg]

Numbers of moles of a substance are a fundamental part in this model. All cargo data reported from the vessel are often represented in mole fractions, which specifies the moles of each substance i (N_i) relative to the total moles of all substances in the cargo

$(\sum_i N_i)$. In this model, a mole fraction of substance i is represented as X_i , given by Equation 3.2.1.

$$\frac{N_i}{\sum_i N_i} = X_i \quad (3.2.1)$$

Even though the mole fraction of each substance is a given parameter, the total moles of the product are still unknown. In general, by knowing the total moles of a substance (N_{tot}), the mole fraction of each containing substance (X_i) and their corresponding molar mass (M_i), the total mass (w_i) in kilograms of each substance can be calculated by Equation 3.2.2:

$$w_i = N_{tot} X_i M_i \quad (3.2.2)$$

Thereby, the total mass (w_{tot}) of the product can be calculated by adding up molar fractions multiplied by molar mass for all the substances, and the multiply it all by the total amount of moles. Given by Equation 3.2.3:

$$w_{tot} = N_{tot} \sum_i (X_i M_i) \quad (3.2.3)$$

When loading the LNG to the vessel, the loading terminal specifies the density (ρ_{LNG}) and the total volume (V) of the loaded product. By multiplying these given parameters, the total mass (w_{tot}) of the LNG can be calculated by Equation 3.2.4:

$$w_{tot} = \rho_{LNG} V \quad (3.2.4)$$

Combining Equation 3.2.3 and Equation 3.2.4 enables solving the total moles (N_{tot}) of the loaded LNG, as it is the only unknown variable in these equations. By restructuring for total moles, Equation 3.2.5 is given:

$$N_{tot} = \frac{\rho_{LNG} V}{\sum_i (X_i M_i)} \quad (3.2.5)$$

3. Creating Model

When knowing the total moles in the LNG, the corresponding moles of each substance (N_i) can be calculated by multiplying total moles in the LNG (N_{tot}) by the mole fraction (X_i) of each substance, given by Equation 3.2.6:

$$N_i = N_{tot}X_i \quad (3.2.6)$$

All the necessary parameters of the loaded LNG are then known, but the composition of the gas boiling off will be slightly different from the loaded LNG (See Chapter 3.1), which makes it necessary to perform additional calculations of the BOG. The corresponding concentration, hereby mole fraction, of nitrogen in the BOG (X_{BOG}^{nit}) can be calculated by use of the regression formula $f_N(X)$ in Chapter 3.1.1, showed by Equation 3.2.7:

$$X_{BOG}^{nit} = f_N(X) \quad (3.2.7)$$

Since the BOG only contains nitrogen and methane (See Chapter 3.1), the corresponding mole fraction of methane (X_{BOG}^{met}) can be calculated by Equation 3.2.8:

$$X_{BOG}^{met} = 1 - X_{BOG}^{nit} \quad (3.2.8)$$

To calculate the number of moles in the BOG, the volume of the BOG needs to be known. A typical boil-off rate (BOR) for a vessel will vary, often by how well the cargo tanks are insulated, but it is a known value for a ship owner. By knowing this rate of vaporization the total volume of the gas flashing off per day (BOG_{VOL}) is given by multiplying the BOR with the cargo tank volume (V), as given by Equation 3.2.9. Note that this volume corresponds to liquid volume of the LNG, not the volume of the gas phase.

$$BOG_{VOL} = VBOR \quad (3.2.9)$$

By knowing the total volume of the gas flashing off per day (BOG_{VOL}), the corresponding moles of each substance in the gas can be calculated. The moles of each substance evaporating from the LNG will be equal the number of moles in the BOG (N_{BOG}^{tot}). Thereby, the total moles of the gas can be calculated in liquid phase,

enabling use of the density of the loaded LNG (ρ_{LNG}). The constant density is a simplified assumption, as it will change by changes in the concentration of the LNG. However, the changes in the LNG are nearly negligible during a whole voyage, which makes the assumption reasonable for this model. The equation is very similar to Equation 3.1.6, but the volume and mole fractions are replaced by values for the gas, (BOG_{VOL} and X_{BOG}^i). Equation 3.2.10 gives the modified version.

$$N_{BOG}^{tot} = \frac{\rho_{LNG} BOG_{VOL}}{\sum_i (X_{BOG}^i M_i)} \quad (3.2.10)$$

Then the moles of nitrogen (N_{BOG}^{nit}) and methane (N_{BOG}^{met}) in the BOG corresponding to the mole fractions in Equation 3.2.7 and 3.2.8 are calculated by multiplying total moles (N_{BOG}^{tot}) by the mole fraction of each substance (X_{BOG}^i), given by Equation 3.2.11 and Equation 3.2.12 respectively.

$$N_{BOG}^{nit} = N_{BOG}^{tot} X_{BOG}^{nit} \quad (3.2.11)$$

$$N_{BOG}^{met} = N_{BOG}^{tot} X_{BOG}^{met} \quad (3.2.12)$$

The last step is to calculate the remaining moles of nitrogen (N_{LNG}^{nit}) and methane (N_{LNG}^{met}) in liquid form (LNG), which corresponds to the previous amount in liquid phase (N_i) minus the amount evaporated as BOG (N_{BOG}^i). Equation 3.2.13 gives moles in total (N_{LNG}^{tot}), while Equation 3.2.14 and Equation 3.2.15 give nitrogen (N_{LNG}^{nit}) and methane (N_{LNG}^{met}) respectively.

$$N_{LNG}^{tot} = N_{tot} - N_{BOG}^{tot} \quad (3.2.13)$$

$$N_{LNG}^{nit} = N_N - N_{BOG}^{nit} \quad (3.2.14)$$

$$N_{LNG}^{met} = N_M - N_{BOG}^{met} \quad (3.2.15)$$

3. Creating Model

These new values of methane (N_{LNG}^{met}) and nitrogen (N_{LNG}^{nit}) gives the new mole fractions of the LNG (X_{LNG}^i) by dividing on total remaining moles in the LNG (N_{LNG}^{tot}), given by Equation 3.2.16 and Equation 3.2.17:

$$X_{LNG}^{nit} = \frac{N_{LNG}^{nit}}{N_{LNG}^{tot}} \quad (3.2.16)$$

$$X_{LNG}^{met} = \frac{N_{LNG}^{met}}{N_{LNG}^{tot}} \quad (3.2.17)$$

All the equations given above have to be recalculated for each day of the voyage for an LNG/C. The new fractions of nitrogen (X_{LNG}^{nit}) and methane (X_{LNG}^{met}) are used to calculate the remaining moles of LNG by the next day of the voyage, representing a new initial state for the remaining LNG.

Even though the mole fraction of the loaded LNG is reported from the terminal and used as inputs for the model above, the values may not be completely correct. Some of the LNG will be flashing off and sent back to the terminal during the loading process (Haugbraaten). This may cause the finally loaded LNG to differ in concentration from the reported loading papers, which will influence the results in the model above by giving a different initial state. Thereby this flashing of gas has to be included in the final model, which will be described in the next section.

3.3. Model Part 2: Flashing of Gas During Loading

During loading of the vessel some of the LNG will be flashing off and sent back to the terminal (Haugbraaten). This amount of gas may have significant influence on the concentration of the finally loaded LNG, and thereby deviate from the values specified in the loading papers. The concentrations specified in the loading papers, provided by the terminal, are often based on the product delivered from the terminal without considering change in concentration of the product by gas flashing off. Nitrogen and methane, especially nitrogen, are highly volatile substances at the loading temperature (-162°C), which causes both substances to flash off during the loading process. The amount of gas flashing off is sent back to the terminal, and compensated when specifying the total loaded volume. Even if the volume is compensated and thereby correct, the concentration and the corresponding mole fraction might change from the original loading papers. This difference in concentrations will have influence on the modelling of the BOG, as the initial state of the finally loaded LNG may contain a different fraction of nitrogen and methane.

Therefore, to be able to model the change in concentration of both the BOG and the LNG per day of the voyage, it is important to obtain the correct initial values of the first day of the voyage. This new initial state was obtained by including the model given below. Note that this change in concentration might not be the case for all loading terminals. However, even if this sub-model is included in the main model, whether to run it or not is up to the user by input arguments.

3.3.1. Assumption for the Model of Flashing of Gas

The terminal is specifying the amount of gas sent back to the terminal, but the amount is often specified in kilograms and not as volume. However, the density of the loaded LNG will be specified as well, enabling an easy conversion to corresponding volume. The density will change as the mole fraction of each substance changes, but the difference will be so small that it was ignored in this part of the model. In addition, the whole loading process of gas flashing off per hour is considered as one total amount. Small changes from hour to hour were ignored, as it was assumed to only cause small changes to the overall result.

3. Creating Model

3.3.2. Model to Calculate Flashing of Gas when Loading

This model will eventually be a part of the model developed in Chapter 3.2, but it requires some additional input parameters, which are given below. The parameter t represents the loading time to fill all the cargo tanks in the LNG/C, while the parameter m_{flash} represents the amount of gas flashing off per time of loading. This amount is measured in kilograms, and sent back to the terminal.

t	Loading time	[hours]
m_{flash}	Mass of Gas Flashing Off per loading hour	[kg/hour]

In addition, several parameters and variables equal to the model in Chapter 3.2 are given below. The parameter X_N represents the mole fraction of nitrogen in the loaded LNG, reported from the terminal, while X_{FLASH}^i gives the mole fraction of substance i in the gas flashing off during loading. N_{FLASH}^i and N_{FLASH}^{tot} are the corresponding moles of each substance i and in total, respectively. The regression formula from Chapter 3.1, $f_N(X)$, is used to estimate the mole fraction of nitrogen in the gas flashing off relative to the loaded LNG, while V_{Flash} and ρ_{LNG} are the total volume of the gas flashing off and the density of the loaded LNG, respectively.

X_N	Mole fraction of Nitrogen in loaded LNG	[Mole fraction]
X_{FLASH}^i	Mole fraction of substance i in the flashing gas	[Mole fraction]
$f_N(X)$	Regression from Design II	[kg/hour]
N_{FLASH}^{tot}	Moles Flashing off in total	[Moles]
N_{FLASH}^i	Moles of substance i flashing off in total	[Moles]
V_{Flash}	Total Volume of gas flashing off	[m ³]
ρ_{LNG}	Density of loaded LNG	[kg/m ³]

Equation 3.3.1 gives the mole fraction of nitrogen in the gas flashing off during loading, which is based on the regression formulas in Chapter 3.1. In addition, the corresponding mole fraction of methane in the gas is given by Equation 3.3.2.

$$X_{FLASH}^{nit} = f_N(X) \quad (3.3.1)$$

$$X_{FLASH}^{met} = 1 - X_{FLASH}^{nit} \quad (3.3.2)$$

Equation 3.3.3 gives the corresponding moles in total, as the mole fraction of each substance is known (X_{FLASH}^i). This equation are based on the same principles of mass calculations for liquid used in Chapter 3.2, but the volume and density are replaced by mass per hour (m_{flash}) multiplied by total hours of loading (t).

$$N_{FLASH}^{tot} = \frac{m_{flash}t}{\sum_i (X_{FLASH}^i M_i)} \quad (3.3.3)$$

Equation 3.3.4 and 3.3.5 gives the corresponding moles of nitrogen and methane flashing off when loading.

$$N_{FLASH}^{nit} = N_{FLASH}^{tot} X_{FLASH}^{nit} \quad (3.3.4)$$

$$N_{FLASH}^{met} = N_{FLASH}^{tot} X_{FLASH}^{met} \quad (3.3.5)$$

The initial state of the finally loaded LNG in the cargo tanks can then be calculated by extracting the moles of nitrogen and methane in Equation 3.3.4 and 3.3.5 from the total amount of moles based on the loading papers.

Since all reported data on the gas sent back to the terminal are given in kilograms, it is interesting to calculate the corresponding volume, as all other data of gas boiling off are given by volume. One of the assumptions for this model was constant density of the loaded LNG, which makes volume calculation relatively simple. Equation 3.3.6 thereby gives the corresponding liquid volume of the gas flashing off during loading at the terminal.

$$V_{Flash} = \frac{M_{flash}t}{\rho_{LNG}} \quad (3.3.6)$$

3. Creating Model

3.4. Model Part 3: Change in Heating Value by Gas Quality

The heating value of the BOG is very important in order to compare the amount of gas needed to propel the vessel. It specifies the amount of energy transferred by kilogram of gas used as fuel, and will indicate necessary changes in fuel consumption for the vessel. In addition, the Higher Heating Value (HHV) will change by concentration of the BOG, indicating how the changes in fractions of nitrogen and methane in the BOG will influence the fuel consumption of the vessel. However, to create a suitable model to calculate the HHV some assumptions were needed.

3.4.1. Assumptions for the Model

It is common to specify the transferred energy of the fuel as higher or lower heating values, depending on how well the energy in the fuel is utilized (See Chapter 2.5). HHV is assumed for this model, as many of the vessels in GWM's fleet are using steam engines. Those engines can normally utilize more of the energy in the exhaust gas, making the higher heating values most appropriate (Egeberg). In addition, today's energy calculations done by GWM are based on these HHVs, which made it most appropriate to do the same in this model in order to get comparable results. The HHV of all the substances in the LNG are varying by pressure and temperature. Thereby, identical values used by GWM are used in this thesis in order to compare the results. The last assumption is that all calculations below are based on the same technique used by GWM to calculate the total heating value of the product, which is theoretically correct, to enable comparison.

3.4.2. Model to Calculate Change in Heating Value

To calculate the total HHV of the BOG, some input parameters had to be specified, which are given below. Those are the higher heating value of each substance (HHV_i), the molar mass of each substance (M_i) and the corresponding mole fraction (X_i). All these parameters will be implemented in the main model, as this part is just a sub-model. Thereby, the user does not have to specify these values when calculating changes for a voyage.

HHV_i	Higher heating value of substance i	[MJ/kg]
M_i	Molar mass of substance i	[kg/mole]
X_i	Mole fraction of substance i	[Mole fraction]

In addition, all other parameters and variables for the model are given below:

MR_i	Molar mass ratio of each substance i	[kg/mole]
$Mfrac_i$	Molar mass fraction of each substance i	[-]
$HHVfrac_i$	Energy fraction of each substance	[MJ/kg]
HHV_{tot}	Total higher heating value of the product	[MJ/kg]

Firstly, a ratio considering both the mole fraction (X_i) and the molar mass of each substance (M_i) have to be calculated, given by Equation 3.4.1. The reason is that the HHV is specifying energy per kilogram, while the fractions specified in this case are dealing with moles. The ratio can be calculated by multiplying the values, as both parameters handles number of moles.

$$MR_i = M_i X_i \quad (3.4.1)$$

When knowing the ratio of each substance (MR_i), their relative fractions ($Mfrac_i$) can be calculated by dividing each ratio on the sum of all substances, given by Equation 3.4.2.

$$Mfrac_i = \frac{MR_i}{\sum_i MR_i} \quad (3.4.2)$$

By knowing these fractions, each part of the total HHV of the BOG or LNG ($HHVfrac_i$) can be calculated by multiplying the fraction of each substance ($Mfrac_i$) by their corresponding higher heating value (HHV_i), given by Equation 3.4.3

$$HHVfrac_i = HHV_i Mfrac_i \quad (3.4.3)$$

Then the total higher heating value of the product (HHV_{tot}) can be calculated by summing up all the fractionated parts, as given by Equation 3.4.4

3. Creating Model

$$HHV_{tot} = \sum_i HHVfrac_i \quad (3.4.4)$$

By performing these calculations for every day of the voyage, the energy delivered per kilogram of BOG is known. Yet, a ship owner is very interested in the resulting amount of fuel used per day of the voyage. Since the vessels are using both HFO and BOG as fuel, some equivalents have to be calculated in order to compare days of the trial. Therefore, the next section will specify how to calculate the FOE by a given concentration of the BOG.

3.5. Model Part 4: Change in Fuel Oil Equivalent by Gas Quality

An LNG/C are utilizing both HFO and LNG as fuel, in addition to other fuel types (Küver et al., 2002). However, only HFO and LNG will be considered in this thesis, as those are the main fuel types. Sometimes the daily amount of gas boiling off is not sufficient for the power requirements aboard, which causes the vessel to choose whether to force more gas to boil off or to supplement with HFO. Since the LNG is transported for the reason of delivering gas at the destination terminal, HFO is often used in addition to the natural BOG, preventing losing too much cargo during transport. For these reasons a Fuel Oil Equivalent (FOE) is calculated to measure the total amount of fuel used for power supply. By using this FOE the amount of LNG can be converted to corresponding amount of HFO in order to compare consumption per days of voyage. Normally LNG is given as cubic metres, while HFO is given as metric tons. Thereby, the FOE gives metric tons of HFO per cubic metres LNG.

3.5.1. Assumptions for the Model

The density of the loaded LNG is assumed to be constant for the whole voyage, ignoring small daily fluctuations due to gas flashing off. The calculation of the FOE is based on the same procedures as used by GWM in order to make results suitable for comparison. Note that the heating values are given as energy per metric tons, not by kilograms. The reason is that metric tons are more frequently used for the amount HFO loaded.

3.5.2. Model to Calculate Change in Fuel Oil Equivalent

The model to calculate the FOE is relatively simple, but it requires some input arguments that are given below. HHVs of LNG (HHV_{LNG}) and HFO (HHV_{HFO}) have to be known, in addition to the density of the loaded LNG (ρ_{LNG}).

HHV_{LNG}	Higher Heating Value of LNG	[MJ/MT]
HHV_{HFO}	Higher Heating Value of HFO	[MJ/MT]
ρ_{LNG}	Density of the Loaded LNG	[MT/m ³]

All other variables and parameters used for calculations are given below.

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$Conv_{LNG}$	Conversion from energy per kilogram to energy per volume	[MJ/m ³]
FOE	Molar mass fraction of each substance i	[MT/m ³]

Since LNG is often measured by volume, the HHV has to be converted from energy per metric tons into energy per cubic metres ($Conv_{LNG}$). This conversion is done by multiplying the density of the loaded LNG (ρ_{LNG}) by the HHV of the LNG (HHV_{LNG}), given by Equation 3.5.1.

$$Conv_{LNG} = HHV_{LNG}\rho_{LNG} \quad (3.5.1)$$

Then the FOE is calculated by dividing the energy per cubic metres for the LNG ($Conv_{LNG}$) by the energy per metric tons for the HFO (HHV_{HFO}), given by Equation 3.5.2.

$$FOE = \frac{Conv_{LNG}}{HHV_{HFO}} \quad (3.5.2)$$

By knowing this FOE and its changing value per day of the voyage, the total amount of fuel used by the vessel per day can be calculated very accurately. Thereby, it is interesting to see how the concentration of the loaded LNG, especially the nitrogen content, affects the HHV of the BOG and the corresponding FOE.

The next chapter contains the results by testing the model with different concentrations of the loaded LNG, all to look for changing trends by days of a complete voyage. The cases highlight the difference in concentration of the BOG compared to the LNG per day, in addition to changes in HHV and FOE. The cases will also look into deviations in today's practice of calculating the FOE, and compare it to values given by this theoretical model.

4. Results from Model by Assumed LNG Quality

In general, this part of the thesis is meant for displaying the results of the model in Chapter 3 by different concentrations of the loaded LNG. The aim is to see how the quality and concentration of the BOG is affected by assumed concentration of nitrogen and ethane in the LNG loaded at the terminal. The model will display corresponding changes in higher heating value (HHV) and fuel oil equivalent (FOE) per day of the voyage, in addition to changing concentrations of all the substances in the BOG per day. It is important to know how the assumed concentration of the BOG affects the calculated HHV and FOE, as it will affect the reported fuel consumption of the vessel. Since it has been a common technique to assume the concentration of the BOG to be equal the values given by the loading papers, any deviating results by use of this technique compared to the actual concentration of the BOG will be highlighted.

In total, three cases of different nitrogen content in the loaded LNG have been evaluated. Each case has two subcases of changing ethane content to highlight all aspects of the BOG. The first case contains a very small fraction of nitrogen, nearly zero. However, it is important to evaluate a case of low nitrogen content, as it might be a real case for some of the vessels. The nitrogen content is gradually increased, until it finally constitutes a high fraction of the LNG in the last case. The main goal is to highlight overall trends by a given LNG quality, and not focus too much on actual values given by the model. However, in some cases a large numbers of decimals are included, where the purpose is to highlight the trends, not to give specific results.

All results from the sub-models in Chapter 3 is considered, and structured in order to represent changes during a whole voyage between the terminals. Sub-model 2 is represented first, as changes by loading of the vessel is the first part of the voyage. This part is important in order to have a correct initial state of the LNG. Further on, the changing concentration of the gas will be evaluated, before corresponding change

4. Model Results

in HHV and FOE will be displayed. However, in order to evaluate the results of the model, some assumptions were needed.

4.1. General Assumptions for the Cases

These cases were meant to be as identical as possible to a complete voyage, which means many of the general assumptions in these cases are based on known values from a typical voyage for an LNG/C. The boil-off rate will normally change from day to day, and vary by vessel type, weather conditions and whether the vessel are supplementing with HFO or not. Still, a steady rate of boil-off per day was assumed to be 0.12% of the total loading capacity (normally 98.5% of total tank volume), as it was recommended to be a suitable mean value by GWM. Additionally, the total tank volume of the vessel was assumed to be 144,000 m³, which corresponds to some vessels in GWM's fleet.

It is assumed only methane and nitrogen in the BOG, as the fraction of heavier hydrocarbons in the BOG tends to be negligible. Thereby, the nitrogen concentration in the BOG versus the LNG is based on the Design II regression formulas from Chapter 3.1. Additionally, the density of the loaded LNG reflects a given loading paper for one of the vessels (see Appendix A3 and A4), and was assumed to be 465 [kg/m³]. In reality this value will change by composition of the LNG, but it was assumed to not have a significant influence on the result as it only influences the amount of the LNG boiling off per day (See Equation 3.2.10). There were made several attempts to calculate the exact density by a given LNG concentration. However, this proved to be rather complicated, as the percentage value of each substance is given by mole fractions, while the density is given as kilogram per cubic meter. The intention of this section is to highlight overall trends, and not give specific results. Therefore using an assumed value was considered sufficient.

Another important aspect to include is the loading process. Some gas will normally flash off during the loading, which was assumed to be 24,000 [kg/hour] kilograms of LNG per hour of loading. The total amount of hours estimated for loading the vessel was 15 hours, given by the loading papers for one of the vessels (Appendix A5). Note that this amount of time will depend on many factors, which resulted in an assumed

mean value of 15 hours. Additionally, the HHV of the loaded HFO had to be known to enable calculation of the corresponding FOE. This value of energy per kilogram of HFO will vary by quality, which made an assumed mean value necessary. This value was approximately 43 [MJ/kg] for many reported cases. Some deviations existed, but they were all fairly equal. Thereby, the HHV of the HFO was assumed to be 43 [MJ/kg] for all the cases.

The total number of days for a complete voyage will vary by voyage, but the important part of these cases was not to calculate changes of concentrations for a fixed period of time, rather highlight the changing trend of the product per days of the voyage. A high value of 60 days was chosen to see the overall trend of the product as most of the voyages will be covered by this value, although they normally require fewer days at sea. Table 7 below summarizes all the chosen general parameters for the cases.

Table 7: General Assumptions for Cases

Boil-Off Rate (BOR)	= 0.12	[% of Total Cargo Volume]
Density LNG (ρ_{LNG})	= 465	[kg/m ³]
Cargo Tank Volume (V)	= 144,000	[m ³]
Flashing of Gas During Loading	= 24,000	[kg/hour]
Estimated Loading hours	= 15	[Hours]
Higher Heating Value HFO	= 43	[MJ/kg]
Days at Sea	= 60	[Days]

By having all the required assumptions for the model, the three different cases could be evaluated. The nitrogen content will gradually be increased, starting at a low level.

4.2. Case 1: Low Concentration of Nitrogen in the LNG

4.2.1. Case Specific Assumptions

In this first case it is assumed a very low content of nitrogen in the loaded LNG. The concentration is not assumed to be zero, as it is normal for the LNG to contain some nitrogen, but the value is set to 0.003 [Mole %] of the loaded product. It was initiated theoretically in Chapter 3 that the concentration of nitrogen in the gas flashing off will depend on concentration of ethane in the LNG. Thereby, two different subcases are analysed regarding additional changes in ethane content to highlight all aspects of the BOG. Table 8 gives all the concentrations that are tested in this specific case. Both subcases represent typical values specified in the loading papers provided by the terminal, meaning flashing of gas during the loading process is not yet included.

Table 8: Subcases for Case 1

Subcase 1.1		Subcase 1.2	
Nitrogen	= 0.003 %	Nitrogen	= 0.003 %
Methane	= 97.5 %	Methane	= 89.5 %
Ethane	= 0.0 %	Ethane	= 8.0 %
Propane	= 2.0 %	Propane	= 2.0 %
Iso-Butane	= 0.25 %	Iso-Butane	= 0.25 %
n-Butane	= 0.25 %	n-Butane	= 0.25 %

4.2.2. Change in Concentration of LNG by Flashing of Gas During Loading

When the vessel starts loading LNG at the terminal, some of the product will be flashing off and sent back to the terminal. This might cause deviations in concentration of the finally loaded LNG compared to the product delivered by the terminal. The reason is that some substances in the LNG are more volatile than others, i.e. nitrogen and methane, and will be flashing off from the product, which causes a lower fraction of these substances in the finally loaded LNG. This deviating value has to be known in order to obtain a correct initial state for the first day of the voyage. Normally, the terminal specifies amount of gas sent back to the terminal, but does not specify how this affects the concentration of the LNG (Haugbraaten). The changes in composition regarding the LNG delivered from the terminal and its final values when finished loading are given below for both subcases.

Table 9: LNG Containing No Ethane and 0.003 Mole% Nitrogen

Loading Papers from Terminal			Finally loaded LNG		
Nitrogen	=	0.003 %	Nitrogen	=	0.003 % →
Methane	=	97.5 %	Methane	=	97.5 % →
Other	=	2.5 %	Other	=	2.5 % →

Table 10: LNG Containing 8 Mole% Ethane and 0.003 Mole% Nitrogen

Loading Papers from Terminal			Finally loaded LNG		
Nitrogen	=	0.003 %	Nitrogen	=	0.002 % →
Methane	=	89.5 %	Methane	=	89.4 % ↓
Other	=	10.5 %	Other	=	10.6 % ↑

This specific case with almost no nitrogen in the LNG delivered by the terminal was expected to have nearly no significant differences in the finally loaded product, but some trend lines appeared. The fraction of nitrogen and methane tended to decrease in the finally loaded LNG, which was reasonable as mostly methane and nitrogen are flashing off during loading. However, many decimals had to be included to see these changes for both the subcases. As the cases are based on several assumptions, these results are insignificant. It was decided to include only one decimal in the concentrations, as changes in that specific decimal will influence the concentration of the BOG. On the other hand, the fraction of nitrogen includes more decimals for this case, not because it is significant, but to illustrate that the LNG still contains a very small fraction of the substance when finally loaded.

For the case of low nitrogen content, the changing trends in nitrogen content are negligible, as indicated by blue neutral arrows. This is reasonable, as the LNG only contains a small fraction of nitrogen to evaporate, and because the methane is such a dominant part of the product. However, methane constitutes a lower fraction of the LNG when ethane is present, and thereby the flashing of gas during loading results in a lower fraction of methane when finally loaded, as indicated by a red arrow. The result in this subcase is also heavier hydrocarbons constituting a larger share of the LNG, as those substances tend to remain in liquid form. This is indicated by a green arrow.

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4.2.3. Change in Concentration of BOG and its Influence on HHV and FOE

The concentration of the BOG will change per day of the voyage, as the LNG will contain less of the substances boiling off per day. The main parts of the BOG are theoretically proven to be methane and nitrogen, while the mole fraction of these two substances will vary by concentration of the LNG in the cargo tanks. In general, more nitrogen in the LNG means more nitrogen flashing off per day, resulting in a higher concentration of nitrogen in the BOG.

Figure 8 represents this specific case of low nitrogen content in the LNG. The blue line indicates the mole percentage of nitrogen in the BOG by having no ethane in the LNG, while the dashed red line gives the corresponding fraction by having 8 Mole% of ethane in the LNG. The results are plotted for a period of 60 days in total, even though not many transport routes require that many days.

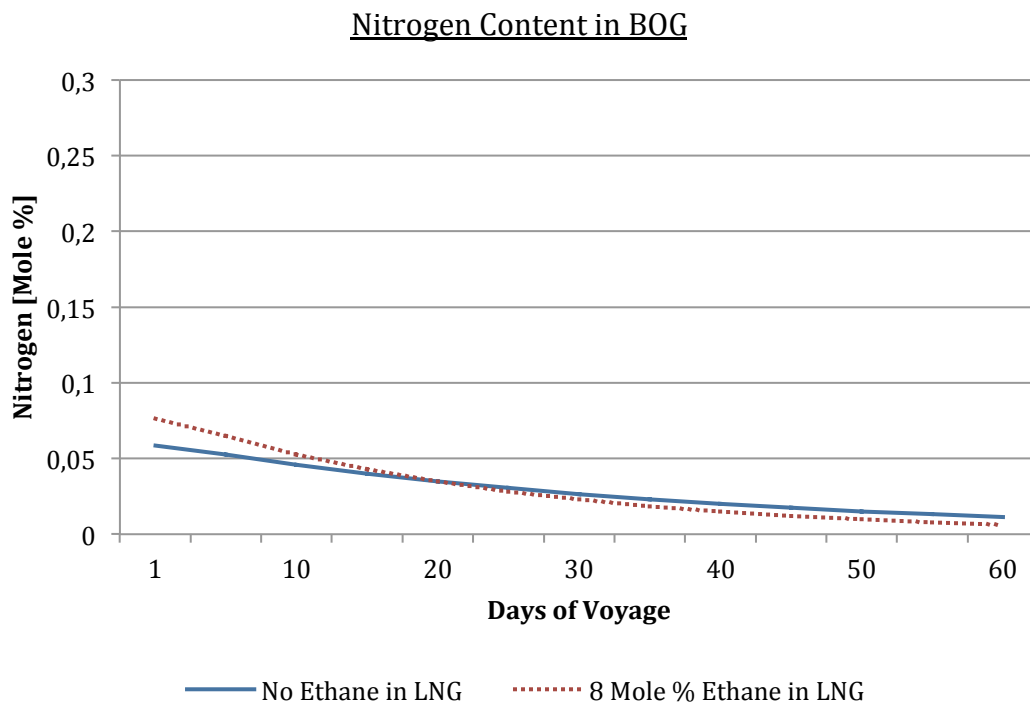


Figure 8: Change in N₂ Content of the BOG During Voyage – Low N₂ Content

The figure clearly illustrates that the fraction of nitrogen in the BOG is higher at an early stage of the voyage, and then decreases by days at sea. Additionally, there is a small difference in nitrogen content by fraction of ethane in the LNG. At the first day of the voyage, the BOG contains 0.058% nitrogen if the LNG does not contain any

ethane, while the value increases to 0.076% if ethane is present. It is also interesting to see that, even if the values are not very significant themselves, the trend is a higher fraction of nitrogen in the BOG than in the LNG itself. At the first day of the voyage the LNG only contains 0.002% nitrogen, which is significantly lower than its fraction of the BOG. This shows that nitrogen is a highly volatile product, which easily evaporates from its liquid form at the given conditions. This also results in nearly no nitrogen present after 60 days at sea. However, note that these values are too accurate to be based on all the given assumptions for the cases. Still, the figure is scaled up to provide an overall picture of the trend of the gas per day of the voyage.

The dashed line indicates that a higher fraction of ethane in the LNG results in more nitrogen flashing off from the cargo. This higher rate of nitrogen evaporation causes a lower fraction of nitrogen in the LNG by time, which results in a steeper decreasing trend of the nitrogen content in the BOG. Thereby, after 60 days the BOG contains 0.006 Mole% of nitrogen if ethane is present, while the remaining part is 0.011% by no ethane at all. The reason is a significant reduction in fraction of nitrogen in the LNG at the end of the voyage, as much of the nitrogen has evaporated from the liquid.

Any change in composition of the BOG will have influence on the HHV of the gas, which is important as the gas is used as fuel for the vessel. Having a lower HHV results in a lower amount of energy released when burning the product. Thereby, more gas has to be supplied to the engine in order to deliver the same amount of propulsive power. It is a common procedure to calculate the HHV of the BOG by assuming a concentration identical to values of the LNG specified in the loading papers, and then use this value to estimate the fuel consumption of the vessel. However, the BOG tends to have a different concentration than the LNG itself, which means that deviations in the calculated HHV might appear. Thereby, it is interesting to see how significant the differences are per day of the voyage.

Figure 9 illustrates the corresponding HHVs for this specific case per day at sea. The dark and light blue lines gives respectively the resulting HHVs of the actual BOG and the concentration assumed identical to the loading papers, containing no ethane. Additionally, the dark and the light red lines gives the HHVs on the same basis, but with 8 Mole% of ethane in the LNG.

these changes in FOE by days of the voyage. The colours and styles of the lines are kept identical to the previous figure, and illustrates the same cases of ethane content, and if the values are based on the BOG or the loading papers. Since the FOE is the conversion factor to be used in order to report the total fuel consumption of the vessel in amount HFO, it is very important to know any deviations by assuming concentrations of the BOG.

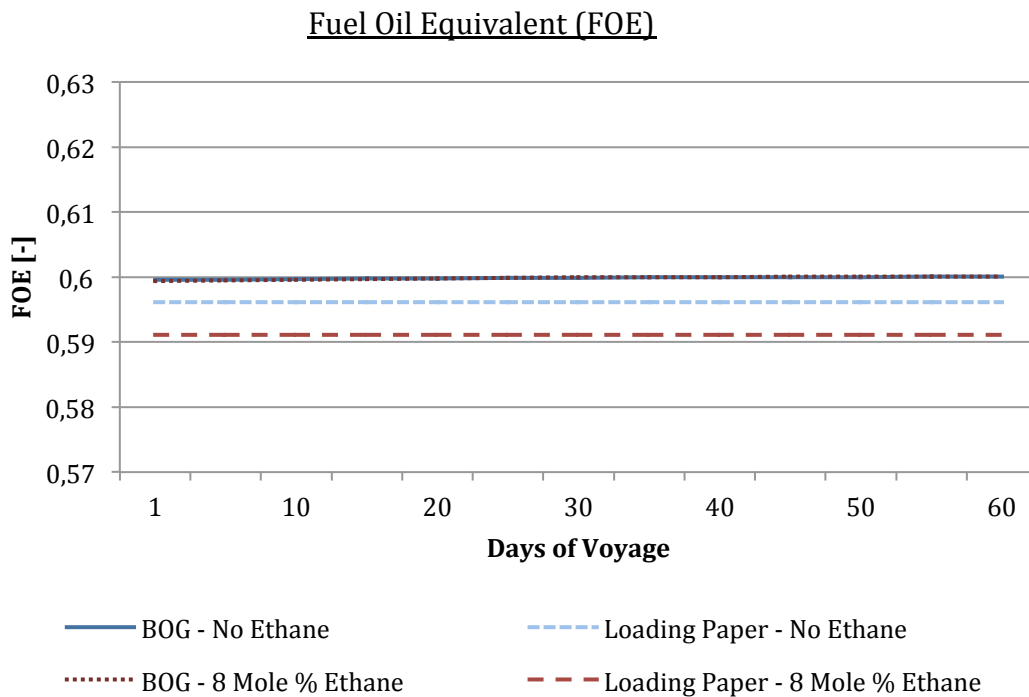


Figure 10: Corresponding Change in FOE During Voyage - Low N₂ Content

The figure clearly illustrates that FOE based on the BOG is nearly independent of ethane content for this specific case, which was expected by the almost identical HHVs. At the first day of the voyage the FOE is approximately 0.60, and remains unchanged for the complete voyage for both ethane concentrations. However, the deviating values of the HHV by assuming concentrations of the BOG identical to the loading paper affect the FOE as well. Making this assumption results in a lower FOE of 0.60 and 0.59 for no ethane and 8 Mole% of ethane, respectively. This means the vessel is underreporting its fuel consumption by making this assumption, but the deviations are not very significant for this specific case. The next section will handle a higher fraction of nitrogen in the LNG to see if it affects the results differently.

4.3. Case 2: Medium Concentration of Nitrogen in the LNG

4.3.1. Case Specific Assumptions

This specific case will have identical scenarios to the previous case, but the fraction of nitrogen, as an input to the model, is increased to 0.5 Mole%. This is assumed to be the middle value of nitrogen content in a typical LNG cargo for transport on an LNG/C. Since the fraction of ethane in the LNG tends to have influence on the results as well, both an LNG containing no ethane and an LNG with 8 Mole% of ethane will be analysed to look for changing trends.

Table 11 gives the assumed concentrations of all the substances in the loaded LNG for both the subcases. In addition to the previous case, all the subcases in this part represent plausible values for the loading papers for an LNG/C.

Table 11: Subcases for Case 2

Subcase 2.1		Subcase 2.2	
Nitrogen	= 0.5 %	Nitrogen	= 0.5 %
Methane	= 97.0 %	Methane	= 89.0 %
Ethane	= 0.0 %	Ethane	= 8.0 %
Propane	= 2.0 %	Propane	= 2.0 %
Iso-Butane	= 0.25 %	Iso-Butane	= 0.25 %
n-Butane	= 0.25 %	n-Butane	= 0.25 %

4.3.2. Change in Concentration of LNG by Flashing of Gas During Loading

This specific case has a more significant amount of nitrogen in the loaded cargo than the previous case, which causes more nitrogen to flash off from the LNG during the loading process. The tables below represents the change in composition of the LNG when finally loaded onto the vessel.

Table 12: LNG Containing No Ethane and 0.5 Mole% Nitrogen

Loading Papers from Terminal			Finally loaded LNG		
Nitrogen	=	0.5 %	Nitrogen	=	0.5 % →
Methane	=	97.0 %	Methane	=	97.0 % →
Other	=	2.5 %	Other	=	2.5 % →

Table 13: LNG Containing 8 Mole% Ethane and 0.5 Mole% Nitrogen

Loading Papers from Terminal			Finally loaded LNG		
Nitrogen	=	0.5 %	Nitrogen	=	0.4 % ↓
Methane	=	89.0 %	Methane	=	89.0 % →
Other	=	10.5 %	Other	=	10.6 % ↑

The fraction of nitrogen is decreasing for both these subcases compared to the previous case, which would have been visible if more decimals were included, but the change is still very small and thereby negligible for the subcase of no ethane in the LNG. Additionally, the fraction of methane stays relatively unchanged, while the remaining heavier hydrocarbons constitute a higher fraction of the LNG in the last subcase. This is caused by methane and nitrogen being the substances flashing off during loading, while the remaining substances remains in liquid form. By knowing these new initial states of the LNG, it is interesting to see how the larger fraction of nitrogen affects the changes of the BOG per days of the voyage, as represented in the next section.

4.3.3. Change in Concentration of BOG and its Influence on HHV and FOE

As for the previous case of low nitrogen content, the resulting concentrations of the BOG have been calculated for both the case of no ethane and 8 Mole% of ethane in the LNG. Figure 11 gives the resulted concentration of the BOG over a period of 60 days, with 0.5 Mole% of nitrogen in the LNG delivered by the terminal.

4. Model Results

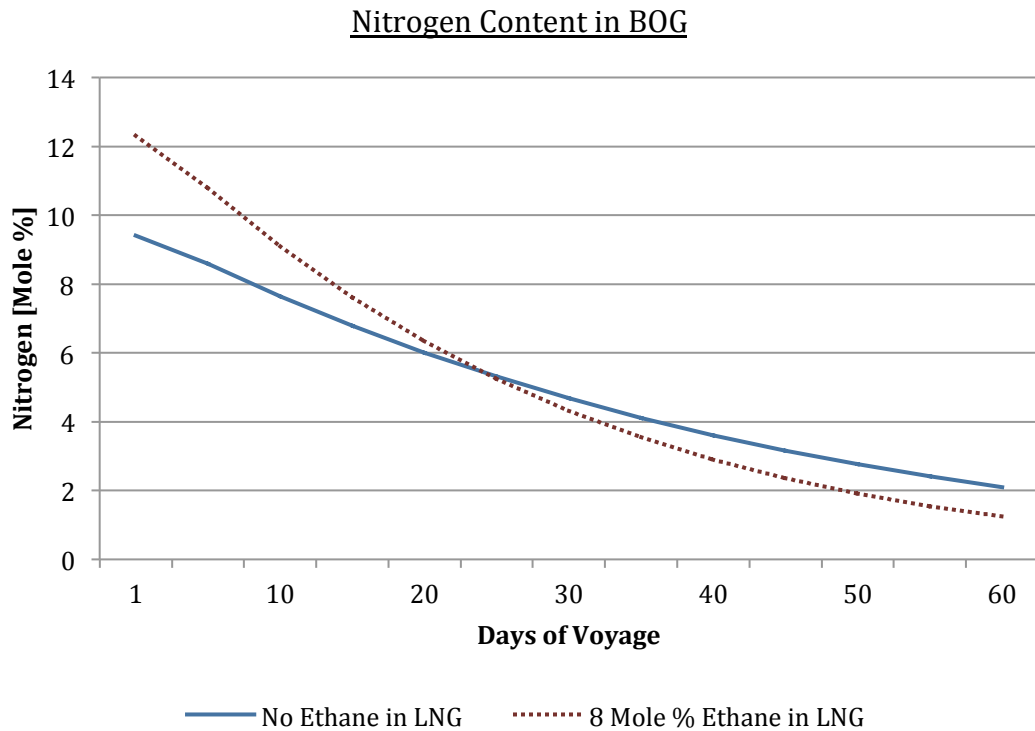


Figure 11: Change in N₂ Content of the BOG During Voyage – Med. N₂ Content

The higher fraction of nitrogen in the LNG results in a higher content of nitrogen in the BOG, in addition to a steeper change in concentration per day. The most significant change happens when the LNG contains 8 Mole% of ethane. Then the fraction of nitrogen in the BOG is 12.3 Mole% at the first day of the voyage, while the LNG with no ethane results in a BOG containing 9.4 Mole% of nitrogen. This is a significant difference, as both the subcases only have 0.4 and 0.5 Mole% of nitrogen in the LNG at the first day, respectively.

It is interesting to notice that there is an intersection in nitrogen content in the BOG after approximately 25 days at sea. The reason is a higher rate of nitrogen evaporating from the liquid when ethane is present, resulting in a lower remaining fraction of nitrogen in the LNG. Actually, after 25 days at sea there is only 0.17 Mole% nitrogen left in the LNG containing ethane, while the other subcase of no ethane has 0.24 Mole% nitrogen left. The overall trend is that the LNG hardly contains any nitrogen after a long period at sea.

This significant change in concentration of the BOG has great influence on the HHVs, especially deviations by assuming concentrations of the BOG based on the loading papers. Figure 12 gives the resulting HHVs.

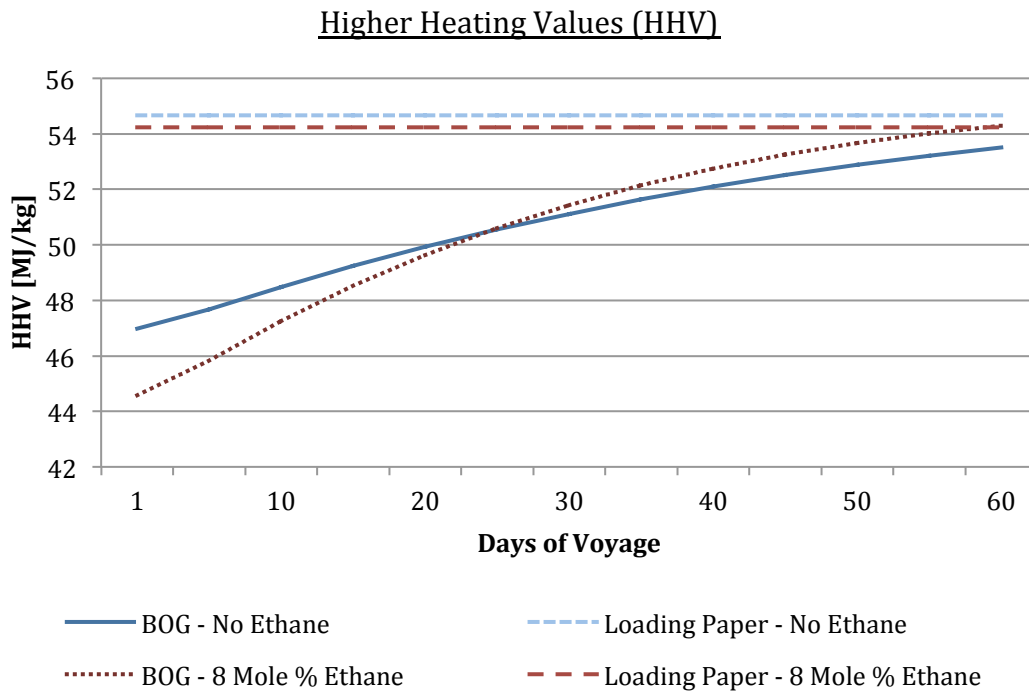


Figure 12: Corresponding Change in HHV During Voyage - Medium N₂ Content

The higher fraction of nitrogen in the BOG results in a significant difference in calculated HHV compared to calculations based on the loading papers, especially at an early stage of the voyage. At the first day the BOG have HHVs of 44.6 [MJ/kg] and 47.0 [MJ/kg], with and without ethane respectively. At the same time, using the concentration given by the loading papers will result in HHVs of 54.2 [MJ/kg] and 54.7 [MJ/kg], with and without ethane respectively, which is a significant difference compared to the actual values.

The increasing trend of the HHVs based on the BOG results in a smaller difference between the assumed values and the real values by days at sea. After approximately 60 days the HHVs of both techniques tend to be equal when the LNG contains 8 Mole% of ethane, while there still exists a difference of 1.2 [MJ/kg] for the two techniques when no ethane is present. However, a voyage of 60 days is very unusual, which means the differences will be significant for a normal shipping route.

4. Model Results

These deviating HHVs caused by assuming the concentration of the BOG to be equal the loading papers will have influence on the reported fuel consumption, as the BOG used as fuel might seem to have more energy per kilograms than it actually does. This can clearly be seen by the corresponding FOE in Figure 13.

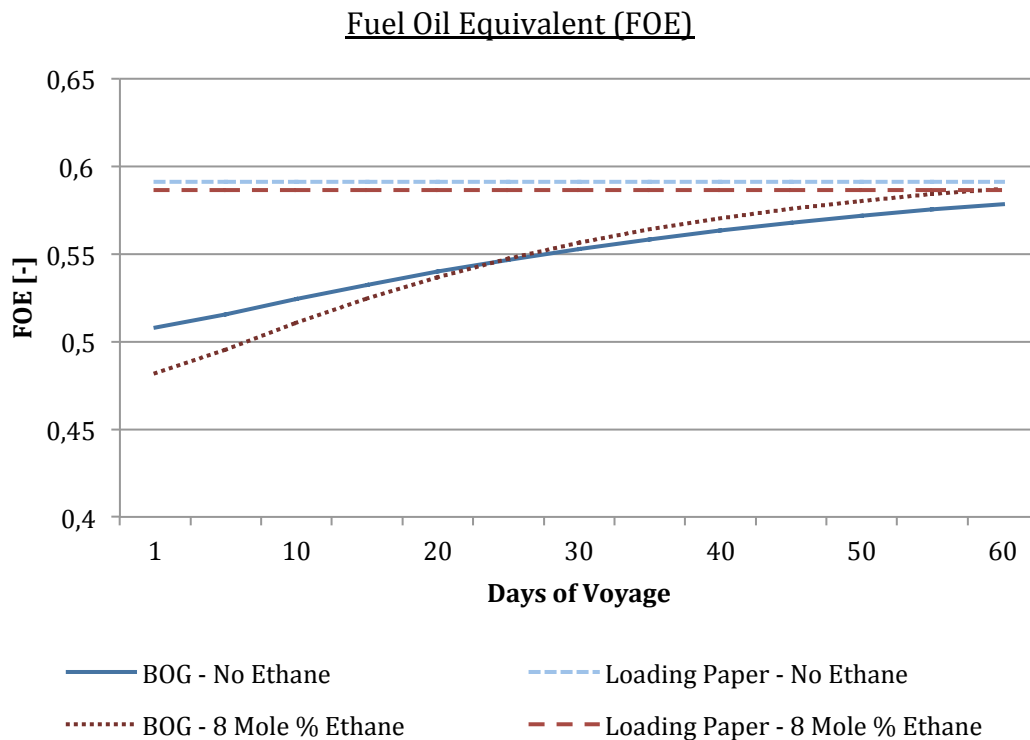


Figure 13: Corresponding Change in FOE During Voyage – Medium N₂ Content

The FOE changes more significantly for this specific case of higher nitrogen content, as expected by the differences in HHVs. At the first day of the voyage the FOE of the BOG is 0.48 and 0.51, with and without ethane respectively. However, using the common technique of basing the calculations on the loading papers will result in much higher FOEs, approximately 0.59 for both subcases. This means the vessel will overreport its fuel consumption for a complete voyage when basing the calculations on the loading papers, although the differences become smaller by days at sea. Before looking into what this means in both contractual and economical terms for a ship owner, a last case of high nitrogen content will be evaluated. The next section will look into the upper range of possible nitrogen content and its influence on the BOG.

4.4. Case 3: High Concentration of Nitrogen in the LNG

4.4.1. Case Specific Assumptions

In this third case, the fraction of nitrogen in the loaded LNG, specified by the loading papers, is 1 Mole% in total. That is actually in the upper range of possible nitrogen content in the LNG at the given pressure and temperature (Haugbraaten). Yet some vessels are transporting LNG with such a high concentration of nitrogen. Since the evaporation rate of nitrogen is highly significant by such a high content of nitrogen in the LNG, it was interesting to evaluate the results for this specific concentration. The same fractions of ethane as in the previous cases will be investigated, and Table 14 specifies the corresponding concentrations of the LNG in both subcases.

Table 14: Subcases for Case 3

Subcase 3.1		Subcase 3.2	
Nitrogen	= 1.0 %	Nitrogen	= 1.0 %
Methane	= 96.5 %	Methane	= 88.5 %
Ethane	= 0.0 %	Ethane	= 8.0 %
Propane	= 2.0 %	Propane	= 2.0 %
Iso-Butane	= 0.25 %	Iso-Butane	= 0.25 %
n-Butane	= 0.25 %	n-Butane	= 0.25 %

4.4.2. Change in Concentration of LNG by Flashing of Gas During Loading

This case had the most significant amount of nitrogen in the LNG with its 1 Mole% in total, which resulted in a higher fraction of nitrogen in the gas flashing off during the loading process. As for the previous cases, the difference between the values specified by the loading papers and the finally loaded LNG is given with and without ethane.

Table 15: LNG Containing No Ethane and 1.0 Mole% Nitrogen

Loading Papers from Terminal		Finally loaded LNG	
Nitrogen	= 1.0 %	Nitrogen	= 0.9 % ↓
Methane	= 96.5 %	Methane	= 96.6 % ↑
Other	= 2.5 %	Other	= 2.5 % →

Table 16: LNG Containing 8 Mole% Ethane and 1.0 Mole% Nitrogen

Loading Papers from Terminal		Finally loaded LNG	
Nitrogen	= 1.0 %	Nitrogen	= 0.9 % ↓
Methane	= 88.5 %	Methane	= 88.6 % ↑
Other	= 10.5 %	Other	= 10.6 % ↑

4. Model Results

The deviations in concentrations of the nitrogen are the most prominent part for both the subcases. In general, the trend is more nitrogen flashing off when ethane is present, but it does not show as the differences between the subcases are too small to be significant. The important aspect is that the finally loaded product has a better quality (i.e. less nitrogen) than the LNG originally sent from the terminal. Still, there is a large remaining fraction of nitrogen in the LNG when it is finally loaded, which makes it interesting to look at corresponding concentrations of the BOG.

4.4.3. Change in Concentration of BOG and its Influence on HHV and FOE

Given the initial state of the finally loaded LNG from the last section, the change in concentration of the BOG during voyage can be calculated. This case generally has a higher content of nitrogen than the previous cases, which causes the BOG to contain even more nitrogen. Thereby the difference in concentration of the BOG compared to the LNG itself will be even more significant. Figure 14 represents the changing nitrogen content of the BOG at the given conditions.

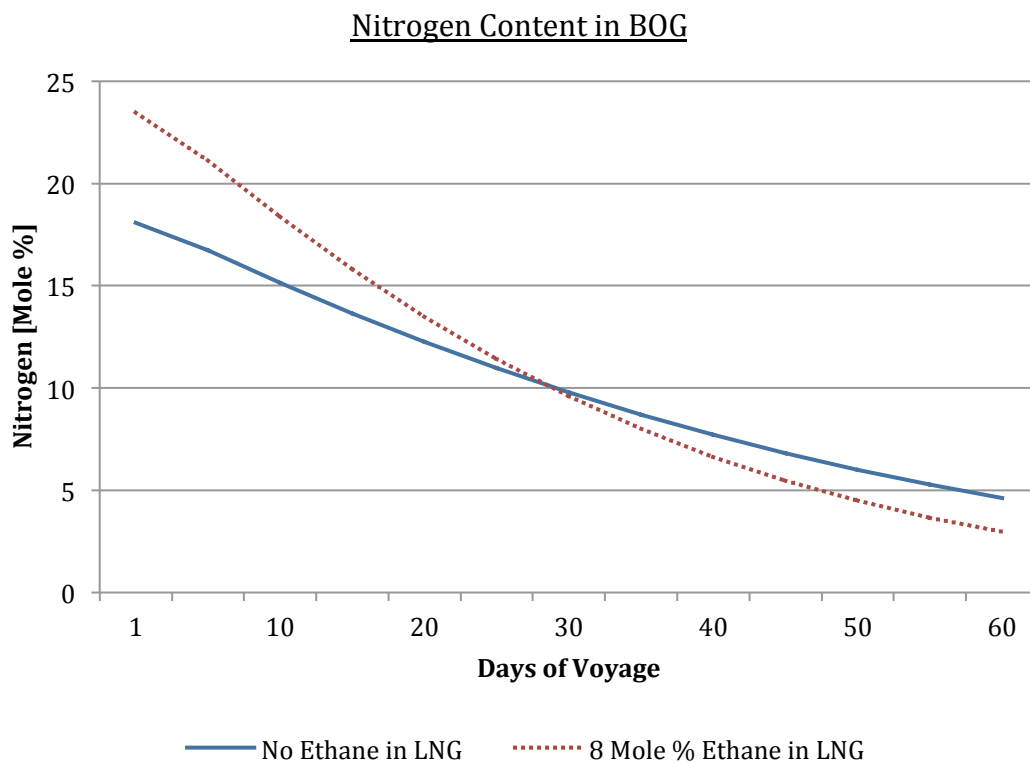


Figure 14: Change in N₂ Content of the BOG During Voyage – High N₂ Content

This specific case of a very high nitrogen content results in a highly significant fraction of nitrogen in the BOG. At the first day of the voyage 23.5 Mole% of the BOG is nitrogen when the LNG contains 8 Mole% of ethane, while it contains 18.1 Mole% if no ethane is present. However, the high rate of nitrogen evaporation results in a very steep decreasing trend of the BOG concentration, due to a reduced fraction of nitrogen in the LNG per day.

Additional to the previous case, the same type of intersection between the results happens, but this time at day number 30. At this point the LNG only contains 0.32 Mole% and 0.46 Mole% of nitrogen, with and without ethane respectively. After this point the fraction of nitrogen in the BOG decreases and becomes 3.0 Mole% and 4.6 Mole% after 60 days at sea. Overall, these large differences in concentrations of the BOG compared to the LNG are very interesting, and will cause large deviations in calculated HHVs. The corresponding HHVs representing both the actual value of the BOG and the assumed value by loading papers are given by Figure 15.

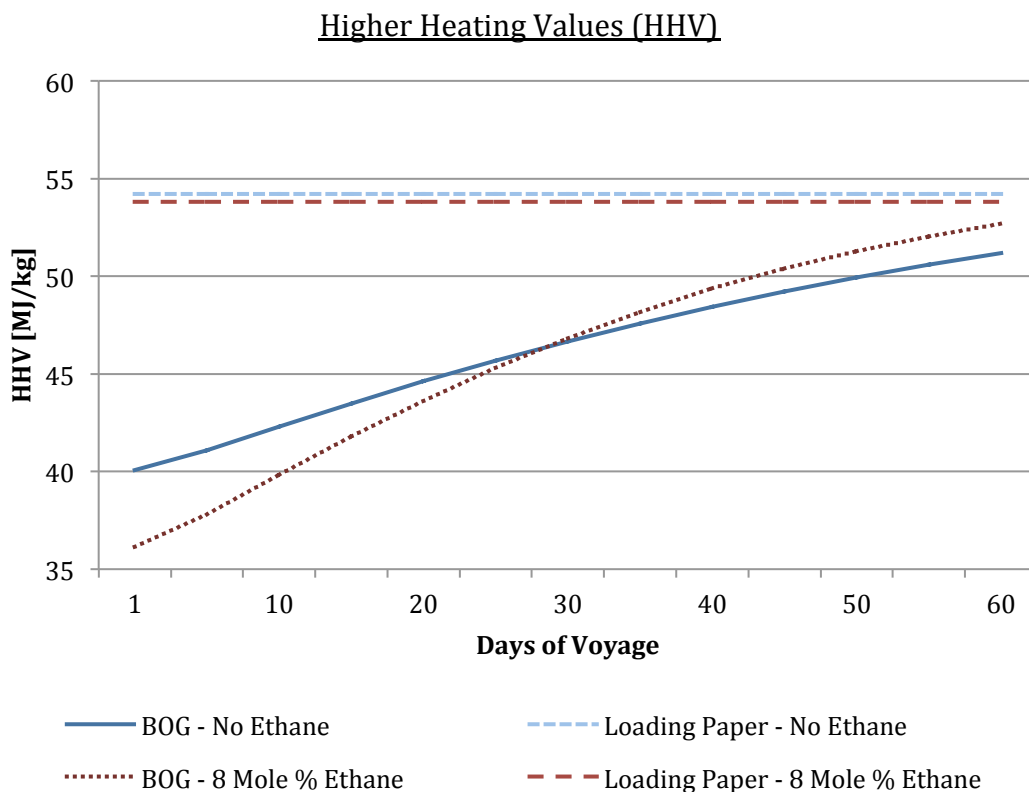


Figure 15: Corresponding Change in HHV During Voyage - High N₂ Content

4. Model Results

The corresponding HHVs in the figure clearly illustrate that performing calculations based on the loading papers will result in too high values of the energy content in the BOG, and thereby cause significant deviations in reported fuel consumption. The large fraction of nitrogen in the BOG at the first day results in HHVs of 36.2 [MJ/kg] and 40.1 [MJ/kg], with and without ethane respectively. However, basing the calculations on the loading papers will result in HHVs of 53.8 [MJ/kg] and 54.2 [MJ/kg], for the same ethane differences respectively.

The vessel has to sail many days at sea for the values to be closing in on each other. Even after 60 days at sea the values are not yet equal. The BOG containing ethane has a steeper increasing trend, which results in a HHV of 52.7 [MJ/kg] at day 60. Still, there is a gap to the HHV of 53.8 [MJ/kg], based on the loading papers. Additionally, it has to be remembered that a sea voyage does not normally last for that many days, which makes the deviations even more significant. The big difference in calculated HHVs reflects in the corresponding FOEs, which is given by Figure 16.

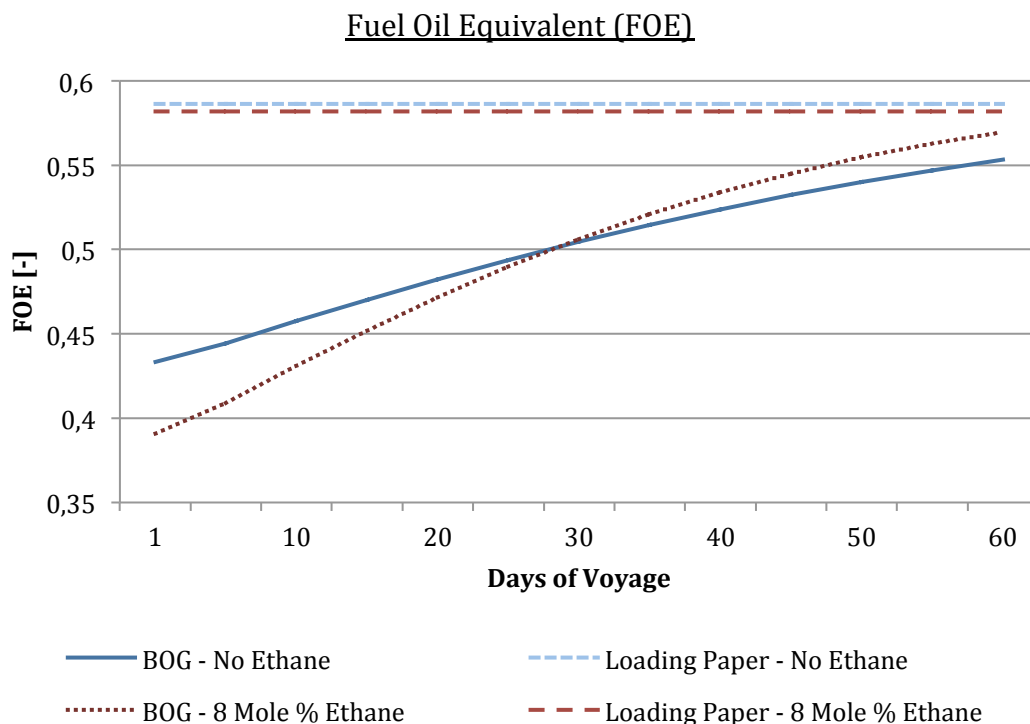


Figure 16: Corresponding Change in FOE During Voyage – High N₂ Content

The trends of the corresponding FOEs are identical to the trend lines in the previous figure, as the values are related by difference in HHV of the LNG and HFO used as fuel. The figure clearly illustrates that wrong assumptions for the concentration of the BOG will cause large deviations in reported fuel consumption, especially at an early stage of the voyage. At the first day the large difference in HHVs results in FOEs equal to 0.39 and 0.43 for actual concentration of the BOG, while the assumed concentration results in values increased to 0.58 and 0.59. This concerns LNG with and without ethane content respectively. The values become more equal after several days at sea, but the gap is still highly significant. This means the vessel gets significant overreported fuel consumption by the given LNG concentration if calculations are based on assumed concentrations of the BOG.

4. Model Results

4.5. General Trend in All the Given Cases

The overall trend in the results from the model was a significant increase in fraction of nitrogen in the BOG by only a small increase of nitrogen in the transported LNG. The concentration of the LNG will change during the loading process, which might influence the initial state of the cargo for the first day of the voyage. Especially LNG with a high content of nitrogen experienced a noticeable loss in fraction of nitrogen in the finally loaded product.

The difference in concentration of the BOG compared to the transported LNG did affect the calculated HHVs. It has been a common technique to assume the concentration of the BOG to be equal the values of the LNG given by the terminal. However, this resulted in large differences in calculated HHVs, especially in cases of high nitrogen content, where the BOG tended to have a much lower HHV than the calculations based on assumed concentrations. Additionally, this change in HHVs resulted in deviations in the calculated FOEs, which as a consequence will result in highly significant overreported fuel consumption for the vessel.

However, all these results are based on theoretical assumptions, which made it necessary to compare the results by real measurements from LNG Carriers. Thereby, the following chapter will compare the concentration of the BOG calculated by the model with real measurements from two GWM vessels on equal basis.

5. Validation of Model by Real Measurements

The model developed in the last section was only based on theoretical assumptions, which makes it interesting to compare its results with real values reported from some of the vessels in GWM's fleet. The focus on the characteristics of the BOG is relatively new, and therefore not many vessels in the fleet had equipment to sample data of the gas boiling off per day of the voyage. However, gas chromatographs were newly installed on two of the vessels making it possible to validate the results of the theoretical model by real values for a voyage.

5.1. Assumptions for the Validations

The overall aim of the validation was to look for changes in the in the BOG by quality of the loaded LNG. Thereby, it was desirable to compare two identical vessels, called sister vessels, transporting LNG of different quality. The two sister vessels, here called Vessel 1 and Vessel 2, was chosen for this purpose as they were identical vessels, but mainly transported gas of different quality. Vessel 1 had LNG with a high content of nitrogen, while Vessel 2 had nearly no nitrogen in the loaded LNG.

Both the vessels were built in 2006, and have an International Gross Tonnage of 97491 metric tons. Their cargo capacity are approximately 146,000 m³ fully loaded, but its normal procedure to only utilize 98.5% of the overall cargo volume at normal fillings. However, the loaded quantity given as input to the theoretical model was set equal to the loading papers for the vessels, and not their theoretical capacity, in order to get comparable results. Additionally, it was only focused on the laden condition for the vessels, as that is the condition were the concentration of the LNG in the cargo tanks are given by the loading papers provided by the terminal. Reported values of the voyage were distinguished by weather conditions to look for changes in concentration of the BOG. Only measurements for calm weather condition were considered valid for comparison.¹²

¹² Calm weather conditions means a wave height and wind speed less than 5 on Beaufort scale.

5.2. Reported Values From LNG/C – Vessel 1

Vessel 1 experienced some problems with the installed gas chromatograph during the validation period, causing only a small amount of days to be reported. Of a complete voyage of 28 days in laden condition, only 8 days were reported. This was too few days to establish a good validation of the model. Still, it was included as it was the only reported values on a voyage containing a high content of nitrogen in the loaded LNG. These reported values were plotted in the same figure showing the results of the theoretical model to look for correlations in concentration of the BOG.

5.2.1. Data for the Voyage

Vessel 1 experienced calm weather conditions for all the reported days at sea. The BOR varied from 0.16% to 0.09%, which caused an assumption of the average value as input for the theoretical model, which was 0.12% per day. Additionally, all reported days had a steaming time of more than 23 hours per day and no forced boil off, making the reported values suitable for validation.

5.2.2. Loading Papers for the Loaded LNG and Input Requirements

The same concentrations of the LNG, as specified in the loading papers, were used as input for the theoretical model to enable comparison. This specific voyage for Vessel 1 had a great amount of nitrogen in the LNG with its approximately 1 Mole%. All the values of the loaded LNG are specified in Table 17.

Table 17: Loading Paper - Vessel 1

Loading Paper	
Nitrogen	1.0 %
Methane	87.7 %
Ethane	8.4 %
Propane	2.2 %
isoButane	0.3 %
nButane	0.5 %
Density	465.6 [kg/m³]

It was shown in Chapter 4 that the concentration of the finally loaded LNG could deviate from the values specified by the loading papers, especially at high nitrogen

content. However, the specific time of the loading and the amount of gas sent back to the terminal was not available in this case, which resulted in assumed values for the loading time and the amount of gas returned. On the basis of data from other loading procedures, an approximate value of 15 hours of loading and 24,000 kilograms sent back to the terminal per hour were assumed. Additionally, the density of the LNG was assumed the same as given by the loading papers, which in this case was 465.6 [kg/m³]. At last the HHV of the HFO was assumed to be 43.0 [MJ/kg], which is a normal average value of the loaded product. By using all these input requirements it was possible to validate the theoretical model by real values from the vessel.

5.2.3. Validation - Concentration of BOG

The results from the theoretical model established in Chapter 3 were plotted in a graph along with values reported from the vessel. Unfortunately, only values from day 15 to day 22 of the complete voyage of 28 days were reported, due to technical problems with the measuring equipment. Still, the values reported from the vessel were implemented in the same graph at the corresponding days of the trial. Figure 17 gives the compared nitrogen content of the BOG, while Figure 18 gives the corresponding methane content.

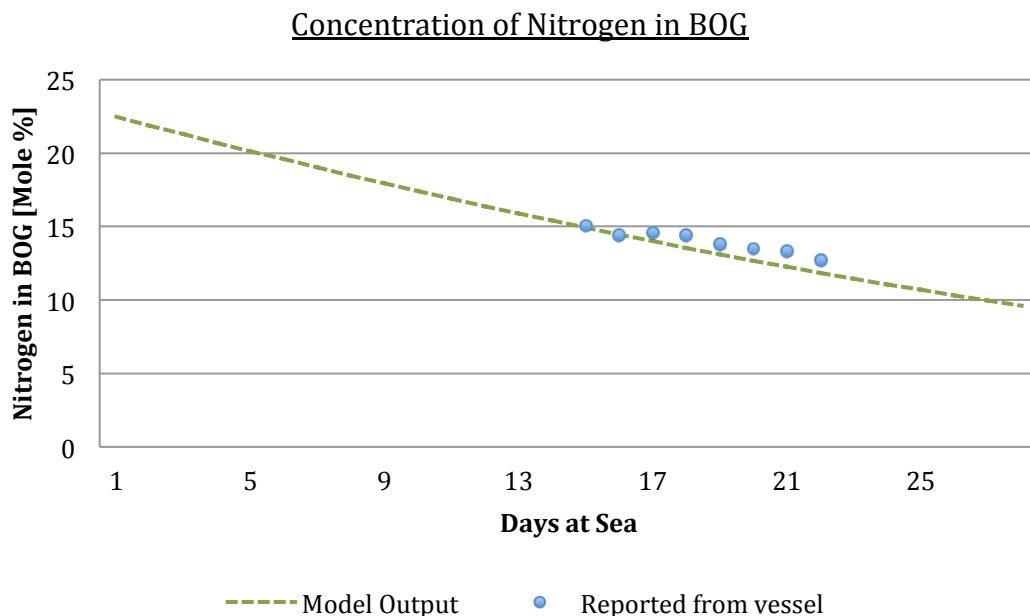


Figure 17: Nitrogen Content BOG - Vessel 1

5. Validating Model

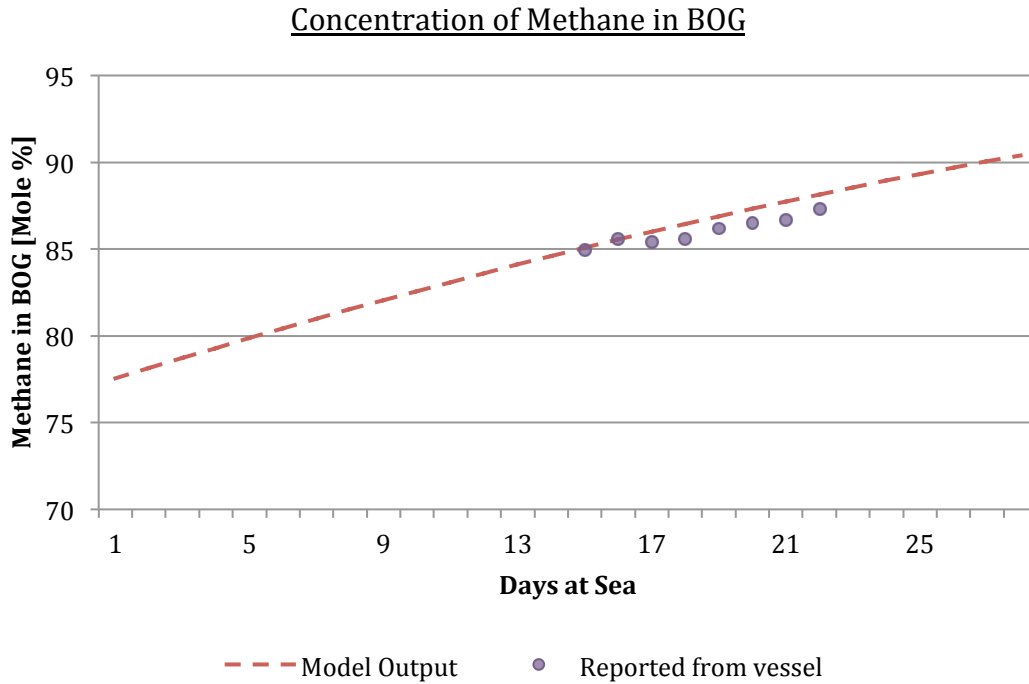


Figure 18: Methane Content BOG - Vessel 1

This specific case had a very high content of nitrogen in the LNG, causing the concentration of nitrogen in the BOG to be highly significant. It is interesting to notice that the reported values from the vessel matches very well with the results from the theoretical model. There are some variations in the reported values, which were anticipated, but the overall trend of decreasing amount of nitrogen in the BOG per days is similar. Additionally, the significant amount of nitrogen as well as the methane, representing the rest of the BOG, corresponds very well with the reported values. The correlation coefficient¹³ of the reported values compared to the theoretical values indicated a very well fit by a value of 0.96 for both methane and nitrogen.

¹³ Correlation Coefficient is equal 1 in case of perfect direct (increasing) linear relationship, called correlation. Its value can vary from -1 to 1, where -1 indicates anticorrelation.

5.3. Reported Values From LNG/C – Vessel 2

Vessel 2 had the gas chromatograph running for a complete voyage of 16 days, making it possible to validate the theoretical model. However, some of the reported values were given by intervals of only some minutes, and the corresponding fluctuations made it difficult to set an average value of the concentration of the BOG per day. These values were finally assumed to be the average of all the reported values for a day.

5.3.1. Data for the Voyage

Vessel 2 experienced calm weather conditions for the complete voyage of 16 days. However, the vessel had a more significant BOR than Vessel 1, varying from 0.11% to 0.24%. The average value of 0.16% was chosen as input for the theoretical model. Additionally, all the days of the voyage had a steaming time of more than 23 hours per day, and no forced boil off.

5.3.2. Loading Papers for the Loaded LNG and Input Requirements

As for the previous vessel, Vessel 1, the same concentration as specified by the loading papers were used as input for the theoretical model. For this specific case, Vessel 2 had a very low fraction of nitrogen in the loaded LNG, containing only 0.03% in total. This voyage was chosen to validate the theoretical model for LNG containing a small fraction of nitrogen. All the values of the loaded LNG are specified in Table 18.

Table 18: Loading Paper - Vessel 2

Loading Paper	
Nitrogen	0.03 %
Methane	97.7 %
Ethane	2.0 %
Propane	0.3 %
isoButane	0.03 %
nButane	0.02 %
isoPentane	0.01 %
Density	427.5 [kg/m3]

5. Validating Model

It was assumed the same loading time of 15 hours for this case, and 24,000 kilograms of gas sent back to the terminal per hour, as both vessels are identical. However, in this case the density of the loaded LNG was 427.5 [kg/m³], given by the loading papers for this specific voyage. Similar to Vessel 1, the HHV of the HFO was set to be 43.0 [MJ/kg]. By use of all these input requirements the theoretical model was validated on an equal basis as the real voyage.

5.3.3. Validation – Concentration of BOG

As for the previous case the results from the theoretical model were plotted along with reported values from the vessel over the same period of time. This voyage was a bit shorter in time with its 16 days in total, and the fraction of nitrogen in the LNG was significantly lower. Figure 19 and Figure 20 give the compared values of the nitrogen and the methane content in the BOG, respectively. There were some deviations in the reported values, as some days were reported by minute intervals. However, by assuming an average value for every day these values were plotted for comparison.

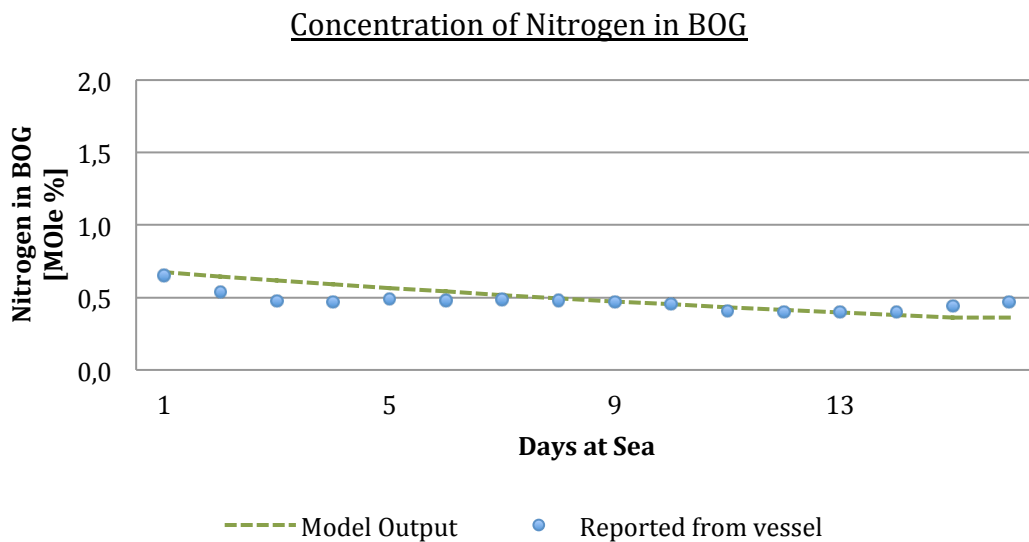


Figure 19: Nitrogen Content BOG – Vessel 2

This specific case had a very low content of nitrogen in the loaded LNG, which theoretically should give a small fraction of nitrogen in the BOG as well. Figure 19 clearly illustrates that this statement corresponded with the real measures from the vessel, as the overall trend is a small fraction of nitrogen in the BOG. Some

deviations between real measures and the theoretically calculated values are noticeable, but the error is not very significant. The important aspect is that both lines, model output and reported values, lies within the small range.

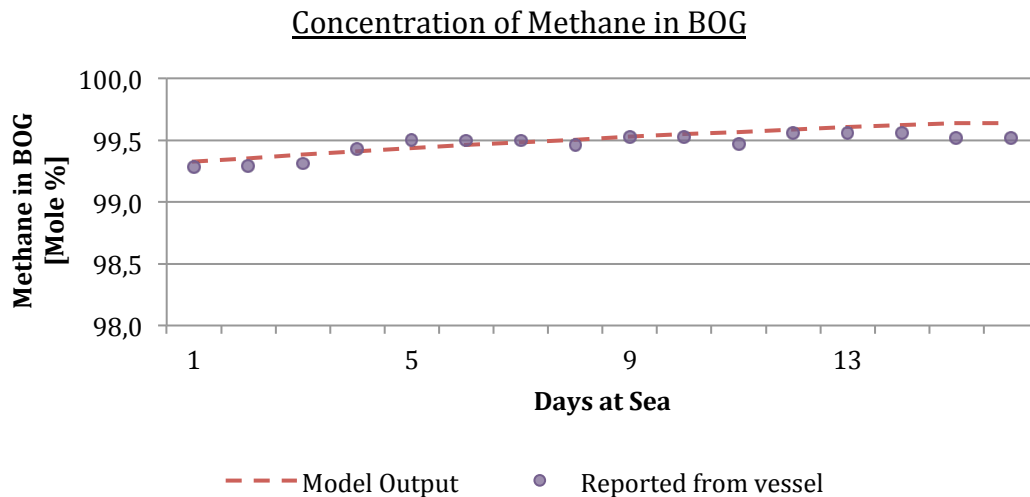


Figure 20: Methane Content BOG - Vessel 2

Figure 20 clearly illustrates that the assumption of methane being the remaining part of the BOG corresponds very well with the real measures from the vessel, even with such a low fraction of nitrogen in the LNG. The theoretical results, which are based on this assumption of only methane and nitrogen in the BOG, are indicated with the dashed line. The correlation coefficient was a bit weaker for this case of low nitrogen content, but values of 0.79 and 0.85 indicated a well fit for both nitrogen and methane respectively.

When knowing that the results from the model correspond well with real measurements from LNG Carriers, it is time to move on to the deriving consequences of the findings in this thesis. Therefore, the next chapter will look into deviations in reported fuel consumption for the vessel by assuming a concentration of the BOG, and corresponding contractual and economical consequences by not utilizing the model given in Chapter 3.

6. Contractual and Economical Consequences

Up to now, it has been illustrated that the BOG contains a much higher fraction of nitrogen than the loaded LNG, which further will have a significant influence on the HHV and the corresponding FOE of the BOG. These important aspects have also been proven to correspond very well with real measurements from two LNG Carriers. However, two important aspects have not yet been considered, namely how these findings can cause economical and contractual consequences for a ship owner. Therefore, this chapter will illustrate important consequences of not using the model to calculate the correct concentration of the BOG.

Normally, every LNG/C in a shipping company has a given chartering contract specifying the upper limit of allowed fuel consumption for the vessel per day. These upper limits depend on given speed ranges, and are specified by tons of fuel oil equivalent per day. The FOE converts all fuel types to a corresponding amount of HFO, in order to easily measure the overall fuel consumption of the vessel. However, there is no contractually committed way to calculate the FOE. Since the concentration of the BOG has been previously out of focus, the ship owner has normally assumed this conversion factor. Two commonly used ways to assume the FOE have been: Assuming a fixed value calculated on the basis of experience, or by assuming a concentration of the BOG identical to the loaded LNG.

The latter assumption method might result in deviations, as the concentration of the BOG used as fuel is normally different from the loaded LNG, while a fixed FOE might be wrong as the concentration of the BOG tends to change per day. This might result in inaccurate values of the total reported fuel consumption for the vessel, and cause economical consequences for the ship owner by breach of chartering contract. The following section will compare deviations in reported fuel consumption by making such assumptions, and how significant they are regarding loaded LNG quality. Furthermore, a last section illustrates corresponding economical consequences of making these assumptions. In both sections, the methods of

assuming the FOE will be compared with values given by the model in Chapter 3. This is because the model is taking into account the changing concentration of the BOG during voyage, and thereby gives correct reported fuel consumption per day.

6.1. Influence of Assumed FOE on Reported Fuel Consumption

To make it as realistic as possible two real loading conditions are considered, having a low and a high fraction of nitrogen in the loaded LNG. The vessels used to validate the model in Chapter 5, Vessel 1 and Vessel 2, are transporting LNG of different quality, and will be used in the comparison. It turned out that these vessels have been utilizing different techniques to assume the FOE before gas chromatographs were installed. Vessel 2 was assuming a FOE based on the concentration of the LNG in the loading papers, while Vessel 1 was assuming a fixed FOE of 0.475. The latter vessel considered changing into a FOE based on the loading papers, which made it interesting to see how this affects the reported fuel consumption as well. To cover all aspects of both high and low nitrogen content, a fixed FOE and a FOE based on the loading papers will be considered for both cases.

6.1.1. Deviation in Reported Fuel Consumption - Low Nitrogen Content

Vessel 2 is normally transporting LNG with a low content of nitrogen. Thereby, this vessel can illustrate any deviation in reported fuel consumption by using assumed FOEs for an LNG with a low nitrogen level. The vessel has been utilizing a FOE based on the loading papers, which will be analysed. However, it is interesting to see changes caused by using a fixed FOE as well. This value was set to be 0.547 by running several iterations and look for the constant that gave the best result for a sea voyage of 16 days, as that is the case for this specific vessel.

Table 19 gives the loading paper used in this analysis. This is an actual voyage for the vessel. The BOR varied from day to day of the voyage, but it was considered appropriate to use an average value of 0.162% of the cargo volume per day. This is identical to the rate used in Chapter 4.

6. Consequences

Table 19: Loading Paper - Vessel 2

Loading Paper	
Nitrogen	0.03 %
Methane	97.7 %
Ethane	1.9 %
Propane	0.3 %
isoButane	0.03 %
nButane	0.02 %
isoPentane	0.01 %
Density	427.5 [kg/m3]

The resulted deviation in reported fuel consumption per day, both for a constant FOE and a FOE based on the loading paper, are given in Figure 21. The dashed line represents the FOE based on the loading paper, while the continuous line represents a constant FOE of 0.547.

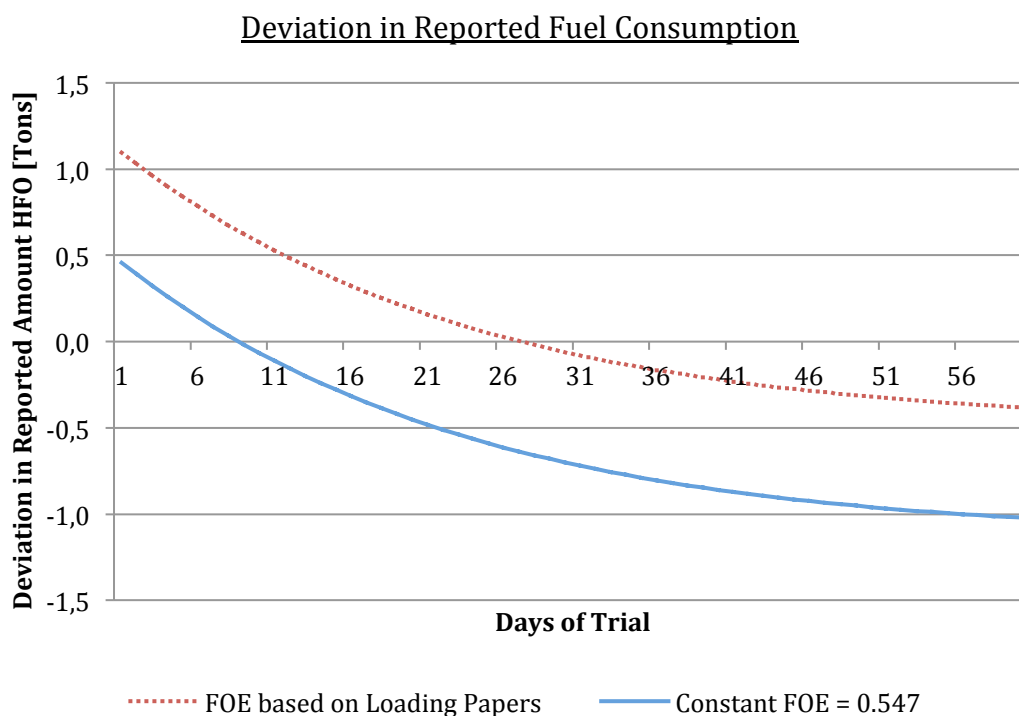


Figure 21: Deviation in Reported Consumption - Low Nitrogen Content

This case of low nitrogen content has nearly no significant deviations in reported fuel consumption per day by assuming values of the FOE. Using a FOE based on the

loading paper results in an overreported value of 1.1 tons of HFO at the first day of the voyage. The value decreases per day of the voyage and becomes zero after 27 days at sea. The fixed FOE of 0.547 is not very interesting for this specific case, as it is adapted to even out any deviations in reported consumption for a voyage of 16 days. Still, it is included to illustrate the trend of an overreported consumption at an early stage, while the value becomes negative after 6 days to even out the deviations. This is better illustrated by accumulating the deviations for a long period of time, as given by Figure 22.

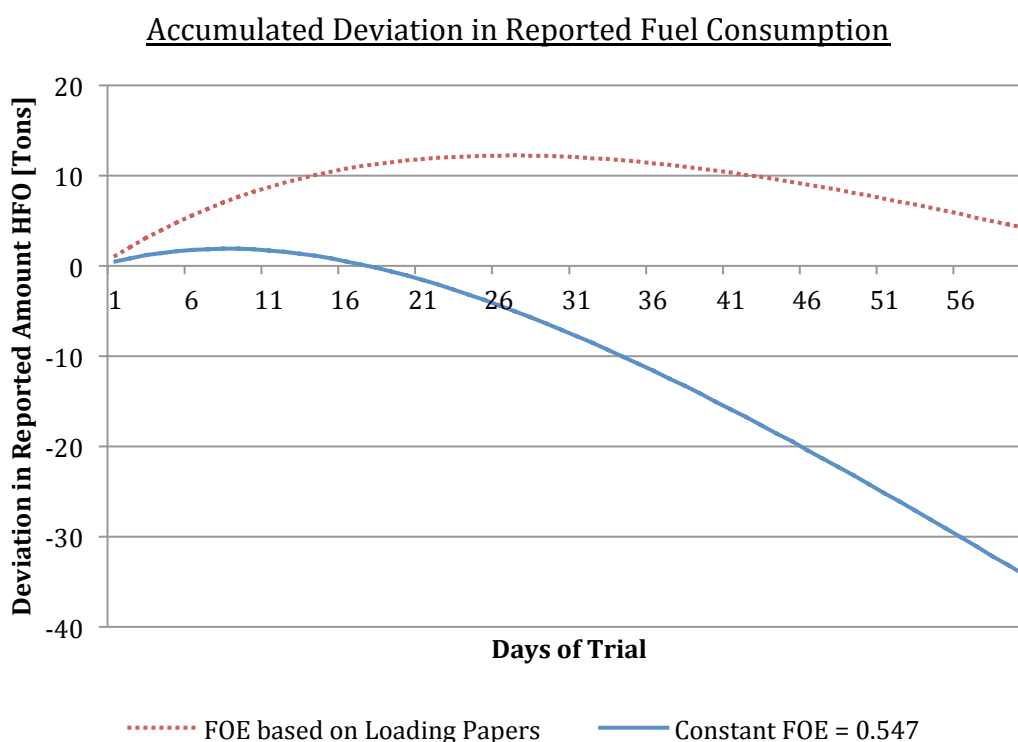


Figure 22: Accumulated Deviation - Low Nitrogen Content

Vessel 2 used 16 days on a complete voyage between the terminals. According to the accumulated values this gives an overreported fuel consumption of 10.75 tons in total by using a FOE based on the loading paper, which is not a very significant value compared to the total fuel consumption for an LNG/C.

By using a constant FOE the deviations will even out for the complete voyage and become zero after 16 days. For this specific case this means that it would have been better for the vessel to assume a fixed FOE of 0.547 than a FOE based on the loading

6. Consequences

paper, but this will depend on the duration of the voyage and the composition of the LNG. However, it is important to be aware that the accumulated value of the fixed FOE decreases rapidly after its maximum value is reached, which means an incorrect assumed value will cause large deviations in overall reported fuel consumption by time at sea.

Overall, the deviations are not very significant by using the two techniques to assume the FOE, when the fraction of nitrogen in the LNG is very low. On the other hand, it will be interesting to see how a more significant fraction of nitrogen will affect the results.

6.1.2. Deviation in Reported Fuel Consumption - High Nitrogen Content

Since Vessel 1 was mainly transporting LNG with a high content of nitrogen, it was interesting to see if a fixed value of the FOE and a value based on the loading paper would result in deviations in reported fuel consumption per day. Similar to the case of low nitrogen content, it was assumed a real loading condition, but with high nitrogen content in this case. Table 19 gives the loading paper for this specific voyage. The BOR was assumed to be the average value of all the days at sea, and was set to be 0.12% of the cargo volume.

Table 20: Loading Paper - Vessel 1

Loading Paper	
Nitrogen	1.0 %
Methane	87.7 %
Ethane	8.4 %
Propane	2.2 %
isoButane	0.3 %
nButane	0.4 %
Density	465.6 [kg/m ³]

Figure 23 gives the corresponding deviations in reported fuel consumption per day. The dashed line indicates the deviation in reported values when using a FOE based on the loading paper, while the continuous line gives the deviation by using a constant FOE of 0.475. This fixed value is actually the value chosen for this vessel, which

makes it interesting to see how well it corresponds with the actual values given by the model.

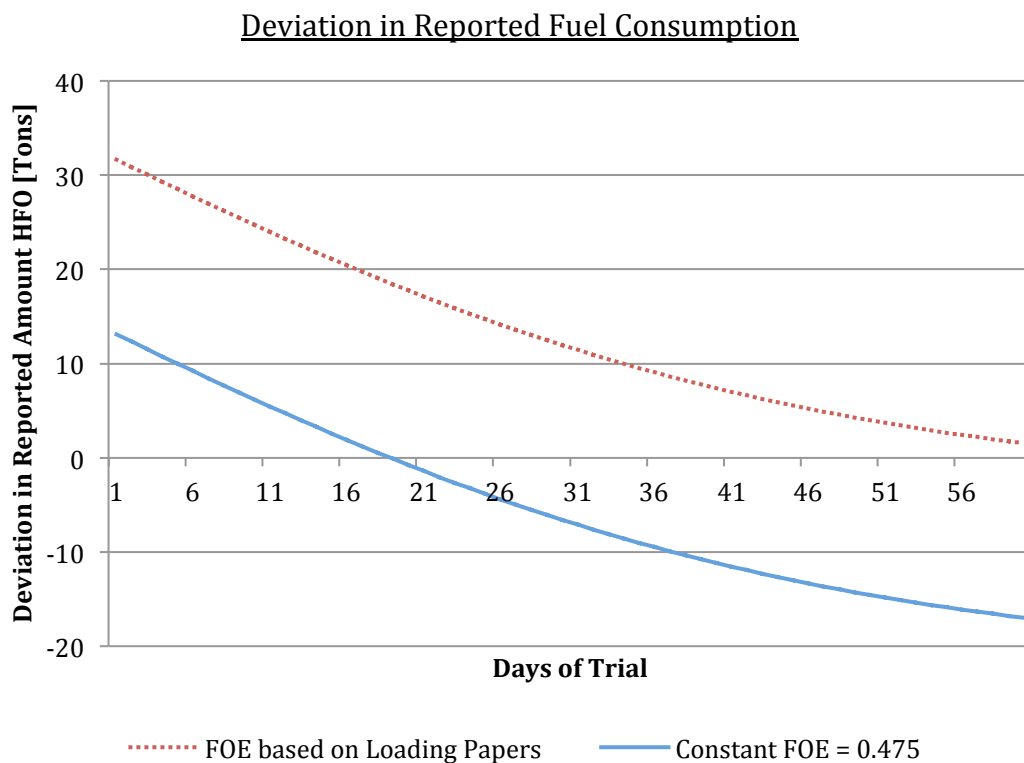


Figure 23: Deviation in Reported Consumption - High Nitrogen Content

The graph clearly illustrates a big gap in reported values in an early phase of the voyage. At the first day, using a FOE based on the loading paper will result in 31.6 tons of HFO overreported. The amount decreases by days of the voyage, but still, at day 20, 17.7 tons HFO is overreported. This means the vessel seems to be using more fuel in total than its actual consumption. Additionally, using a constant FOE of 0.475 gives 13.11 tons of overreported HFO at the first day, while the deviating values decreases and become negative after 18 days at sea. This means the vessel tends to report more fuel than its actual usage at an early phase, while it actually tends to report less fuel after 19 days or more at sea. This negative value at the end of the voyage affects the overall reported consumption positively, which is easier illustrated by accumulating over a long period of time. Figure 24 gives the accumulated value of both the FOE based on the loading paper, which is given by the dashed line, and the constant FOE, given by the continuous line.

6. Consequences

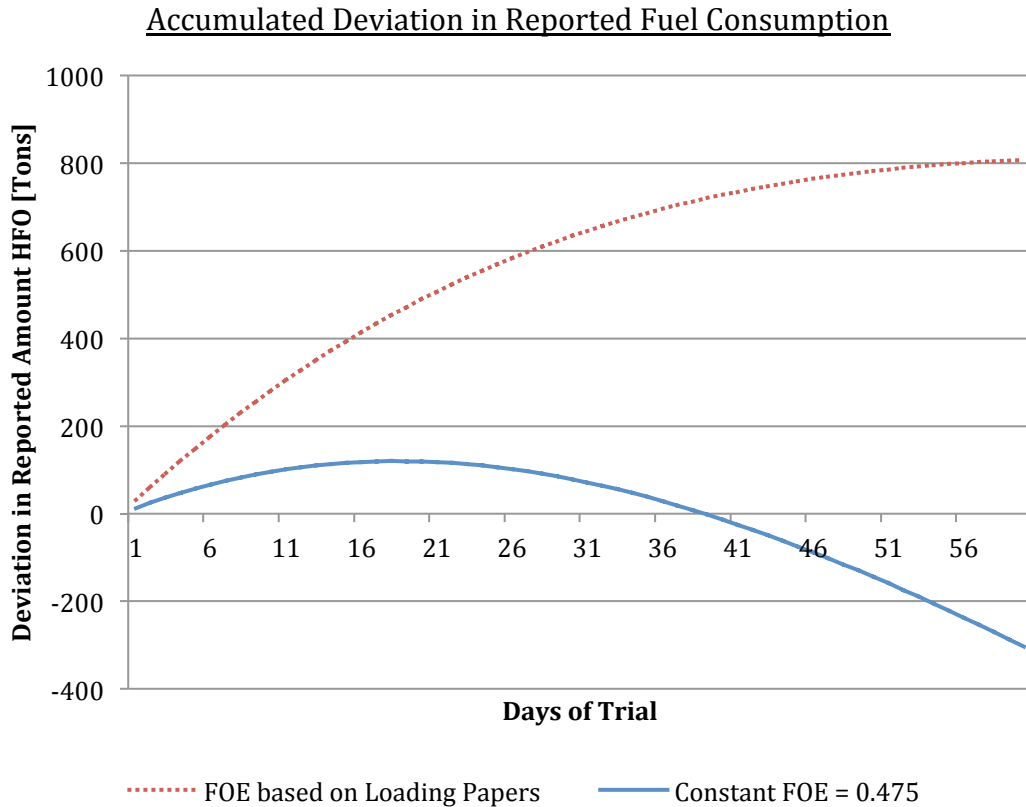


Figure 24: Accumulated Deviation - High Nitrogen Content

For this specific case, Vessel 1 used 28 days to transport the LNG between the terminals. According to the accumulated value, when using a FOE based on the loading paper, the vessel is over-reporting its fuel consumption by 610 tons of HFO for this period of time, which is highly significant. On the other hand, using a constant FOE of 0.475, which the vessel is using today, results in a total overreported consumption of 91 tons of HFO for a voyage of 28 days. On this basis, using a constant FOE gives less deviation than by using a FOE based on the loading papers. Nevertheless, the value is still high, and the deviations caused by this constant FOE will not even out before the voyage lasts for 39 days.

It is interesting to see that knowing the exact concentration of the BOG, as given by the model, becomes more and more important by an increased fraction of nitrogen in the transported LNG. Both techniques of assuming a FOE will cause deviations in reported values. The constant FOE will result in the least deviating values when estimated correctly, but is likely to end up with significant deviations if using the wrong constant. These resulted deviations will have influence on the chartering

contract and its upper limit of allowed fuel consumption per day. Therefore, it is interesting to see how significant these findings are in economical terms.

6.2. Influence on Contract and Economical Consequences

The total reported fuel consumption per day for an LNG/C is very important regarding the vessel's chartering contract. If the vessel exceeds the upper limit of maximum allowed fuel consumption per day there might be a financial settlement including fines, and the ship owner may have to cover the overconsumption. This can be very expensive, depending on the given fuel price.

To stay within the range of allowed fuel consumption, it is important that all the reported values are correct. A FOE being too low will benefit the ship owner, as their vessel seems to be using less fuel than it actually does, but that will probably be rejected by the charterer of the vessel. On the other hand, a chosen FOE being too high will benefit the charterer of the vessel, as they can claim payments for the overconsumption, but then the ship owner will lose money. Additionally, an overreported fuel consumption might not be durable in the long run as it can weaken the reputation of the company by having incorrect values of the vessel's fuel consumption.

The best solution, that satisfies both parties, is to use the correct FOE calculated on basis of the current concentration of the BOG, which is given by the theoretical model in Chapter 3. However, the necessity of these calculations will depend on the concentration of the loaded LNG. To highlight this and its corresponding costs, it is assumed that the overreported fuel consumption has to be covered by the ship owner, as this is the amount that exceeds the upper contractual limit per day.

6.2.1. Cost of Deviations

The cost of the deviations in total reported fuel consumption for an LNG/C will depend on the given price of the HFO. This price will fluctuate per day, which caused a conservative price assumption of 600 USD per ton HFO (Bunkerworld) for the calculations. Figure 25 illustrates the corresponding costs of deviations per days of the voyage in the case of low nitrogen content.

6. Consequences

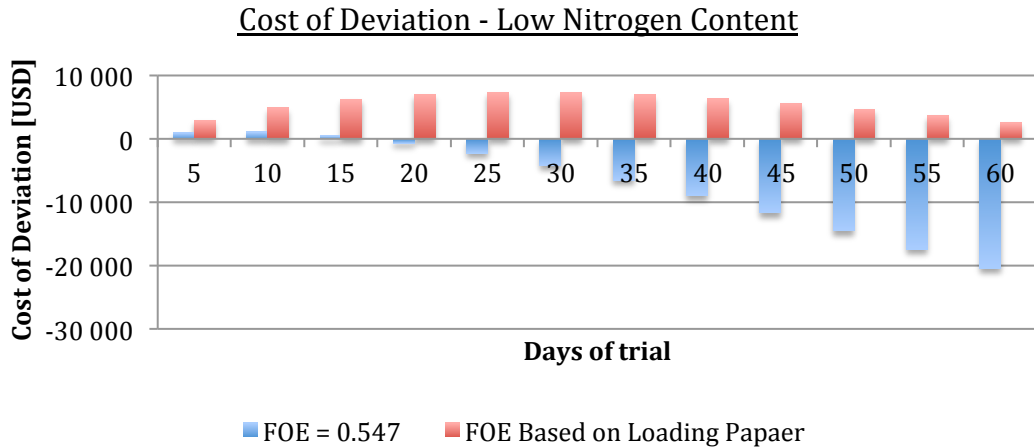


Figure 25: Cost of Deviation - Low Nitrogen Content

Transporting LNG with a low fraction of nitrogen and a FOE based on the loading paper, as represented by Vessel 2 in this case, would result in an unnecessary cost of around 6,500 USD for a voyage of 16 days, although this is insignificant related to operational expenses for the vessel. On the other hand, by using a constant FOE of 0.547 the total cost is almost negligible for this voyage, as shown in the figure. However, it is interesting to notice that the cost by using a constant FOE increases relatively rapidly in a negative direction after several days at sea. This illustrates unexpected costs that can occur when using a FOE that is not adapted to the exact number of days at sea. After 60 days at sea it would reach a negative cost of around 20,000 USD.

Even though these small deviations results in some unnecessary costs for the overreported fuel consumption, they become relatively insignificant compared to the transport of LNG that contains a higher fraction of nitrogen. Figure 26 illustrates the corresponding cost of deviation per days of the voyage for Vessel 1, when transporting LNG with a high fraction of nitrogen. Both a constant FOE, as used on this vessel, and a FOE based on the loading paper is displayed in the figure.

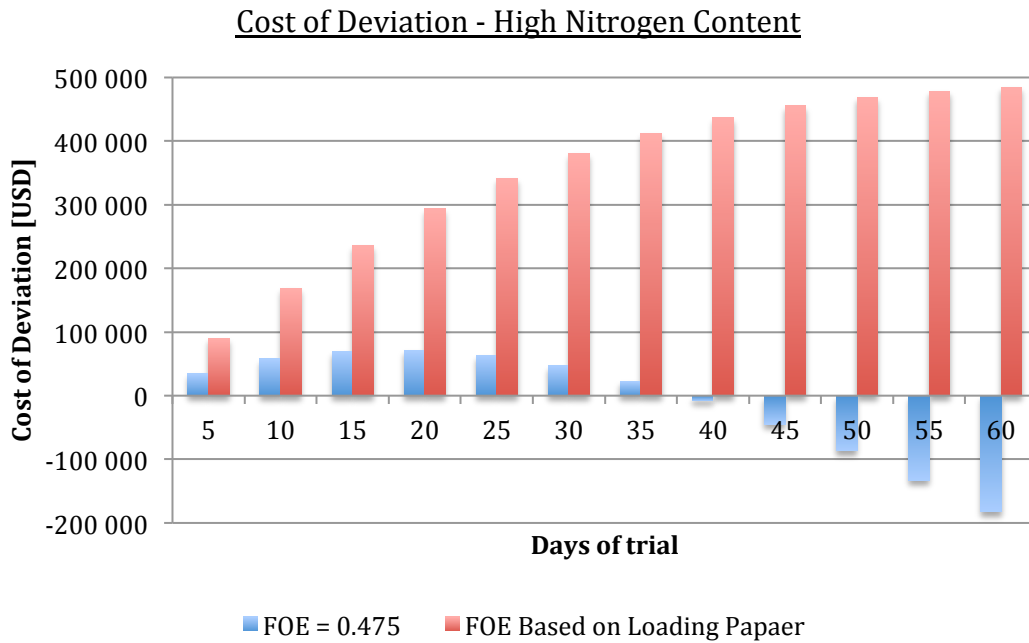


Figure 26: Cost of Deviation - High Nitrogen Content

There is a big difference in cost by choosing a constant FOE compared to a FOE based on the loading paper for the voyage. The high fraction of nitrogen in the loaded LNG results in a large amount of nitrogen in the BOG, which gives a significant deviation in reported fuel consumption. The cost increases constantly with a FOE based on the loading paper, which causes an overreported fuel usage with a cost of 485,000 USD in total after 60 days at sea. Vessel 1 used 28 days to complete the voyage, which would result in an overreported fuel consumption having a cost of approximately 366,000 USD in total, which is highly significant. Today, the vessel is using a constant FOE of 0.475. This gives a better result, but still leads to an unnecessary cost of approximately 55,000 USD for a complete voyage of 28 days.

These examples illustrate the importance of knowing the exact concentration of the BOG per day of the voyage, as assumptions of the FOE will much likely result in significant deviations and unnecessary costs. The changing value of the FOE per day can easily be calculated by use of the theoretical model represented in this thesis, and its importance increases by nitrogen content in the LNG. When transporting LNG with a very low fraction of nitrogen, as illustrated by Vessel 2, the deviations were insignificant. In this case the ship owner can assume the value of the FOE, although it will most likely result in some unnecessary costs of deviations. However, when the

6. Consequences

fraction of nitrogen in the LNG increases, the model becomes highly relevant. When transporting LNG with a very high concentration of nitrogen, as Vessel 1 does with its 1 Mole%, making assumptions will be very costly for the ship owner. This only considers the cost of covering the overreported fuel usage. In reality, this overreported fuel consumption might result in breach of contract and additional fines for the ship owner.

7. Conclusion

This thesis has been looking into the chemical and thermodynamic properties of LNG transported on an LNG Carrier. The main focus has been the change in concentration of the Boil-off gas (BOG) per day of the voyage compared to the loaded LNG. As BOG is used as fuel for the vessel, it was desirable to get a better understanding of its change in concentration. Further, it was investigated how this difference influenced the reported fuel consumption for the vessel, and deviations caused by assuming a concentration of the BOG.

The general trend was a significant increase in the amount of nitrogen in the BOG by a small increase in fraction of nitrogen in the loaded LNG. Additionally, the amount of ethane in the LNG influenced the evaporation rate of nitrogen, where the most significant difference appeared in case of a high fraction of both ethane and nitrogen in the LNG. By having 1 Mole% of nitrogen and 8 Mole% of ethane in the loaded cargo, the BOG theoretically contained 23.5 Mole% of nitrogen at the first day of the voyage, while methane represented the rest of the BOG. On the other hand, transporting LNG with a very small fraction of nitrogen resulted in a BOG containing nearly solely methane.

The fraction of nitrogen in the BOG tended to decrease per day of the voyage, as nitrogen is a volatile substance at the given cargo temperature of -162°C . This resulted in a delivered LNG with a better quality than what was originally loaded. Additionally, some of the substances in the LNG were flashing off during the loading process. Nitrogen and methane both have boiling points below the liquefaction temperature, which resulted in an LNG with lower nitrogen content when it was finally loaded onto the vessel. The results from two cases of both high and low nitrogen content in the loaded LNG were tested by real measurements from two of the LNG Carriers in the fleet of Golar Wilhelmsen Management (GWM).

The total reported fuel consumption for an LNG Carrier is estimated by use of a fuel oil equivalent (FOE), which depends on higher heating value (HHV) of both the BOG

7. Conclusion

and the HFO. This constant is very important as it affects the reported fuel consumption for the vessel when converting the amount of LNG to corresponding HFO. It has been a common technique to assume the concentration of the BOG to be equal the concentration of the loaded LNG, or to assume a constant value for all the voyages. However, using these assumptions to calculate the total fuel consumption of the vessel caused significant deviations in reported fuel consumption, as differences in concentrations of the BOG affects its HHVs. In cases of having a low fraction of nitrogen in the loaded LNG, the deviations were not that significant. However, by increasing the fraction of nitrogen and ethane it resulted in significant deviations when assuming concentrations of the BOG. The worst case resulted in an unnecessary cost of 366,000 USD for a voyage of 28 days.

Overall all, it is more important to know the exact concentration of the BOG when a vessel is transporting LNG with a high fraction of nitrogen, while the deviations in reported consumption are not that significant with a low fraction of nitrogen. In order to report correct fuel consumption the best solution is always to know the exact concentration of the BOG to calculate the FOE and corresponding fuel consumption. This value can be estimated by use of the theoretical model, or measured every day of the voyage by use of a gas chromatograph. This is very important in cases of high nitrogen content in the LNG, while cases of nearly no nitrogen can utilize assumed values.

8. Further Work

As the scope of a master thesis does not permit including the limitations mentioned in the introduction, this chapter will suggest possible issues for further work. The model developed in this thesis corresponded well with measurements from two vessels. However, due to few validations in this thesis, the theoretical model might not always perfectly reflect the reality. It is desirable for the model to predict exact changes in concentration of the BOG per day of the voyage, and reflect real measurements from an LNG Carrier. A ship owner wants to be sure that the model can give accurate results on deviations caused by making different assumptions of the BOG. Some of the factors that can prevent the theoretical model from perfectly reflecting reality are hereby stated: There will not be a steady boil-off rate per day, due to different sea conditions and outside temperature. Movements on the vessel might also affect the composition of the BOG. Furthermore, significant movements during transport might stir the LNG in the cargo tanks and affect the evaporation rate of the substances in the LNG. Including these factors by further developing the existing model would ensure more accurate and reliable results.

By use of several measurements the model can be adapted to reflect each vessel individually. Plotting several measurements enable creating corresponding functions by use of mathematical regression. Using these formulas in the model will result in a more customized model for each vessel and its transport routes. Then it will be possible to take into account weather conditions and speed during voyage. As the chartering contract specifies different limits of allowed fuel consumption regarding vessel speed, different regression formulas can be made in order to reflect all aspects of the voyage.

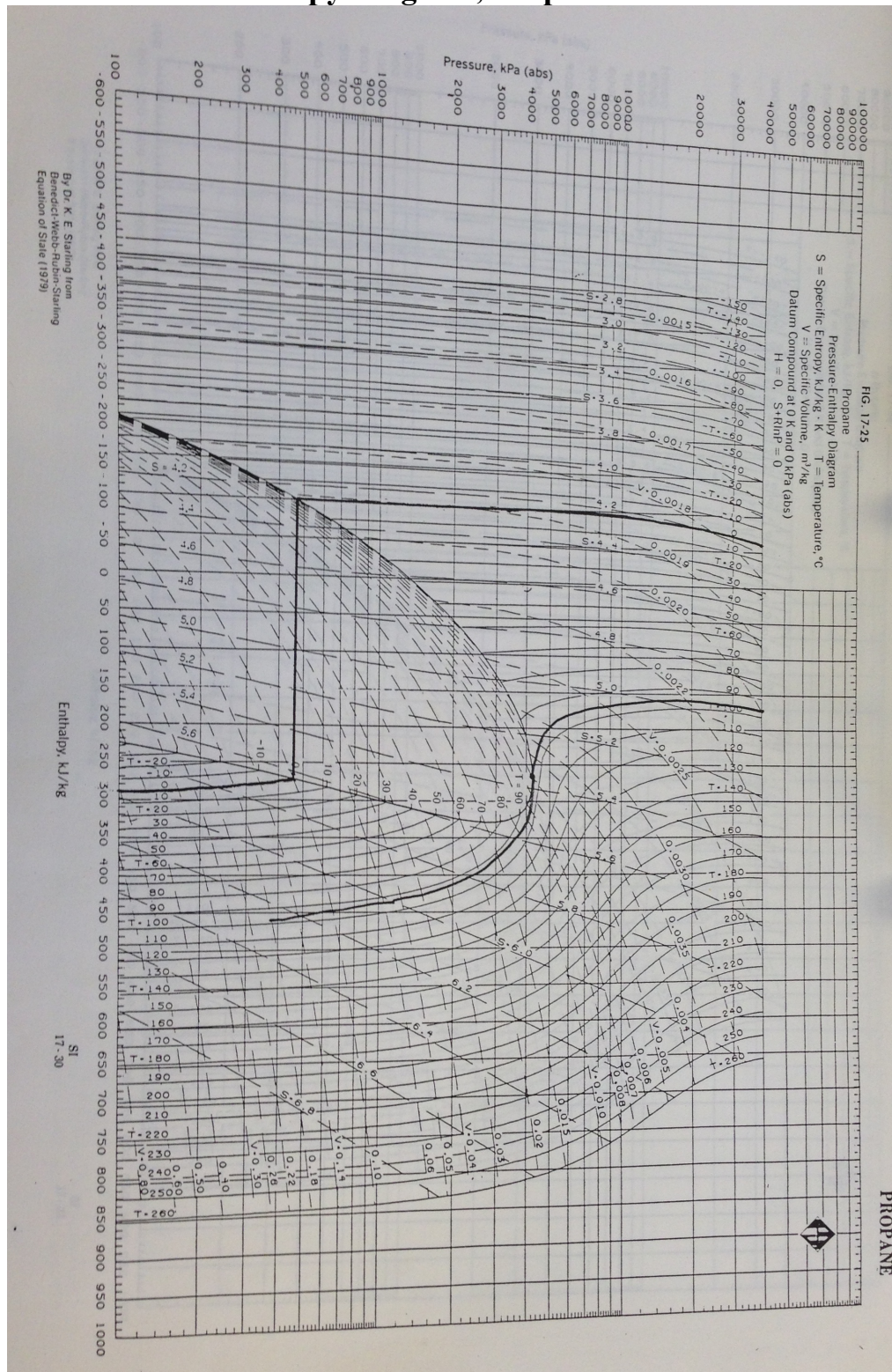
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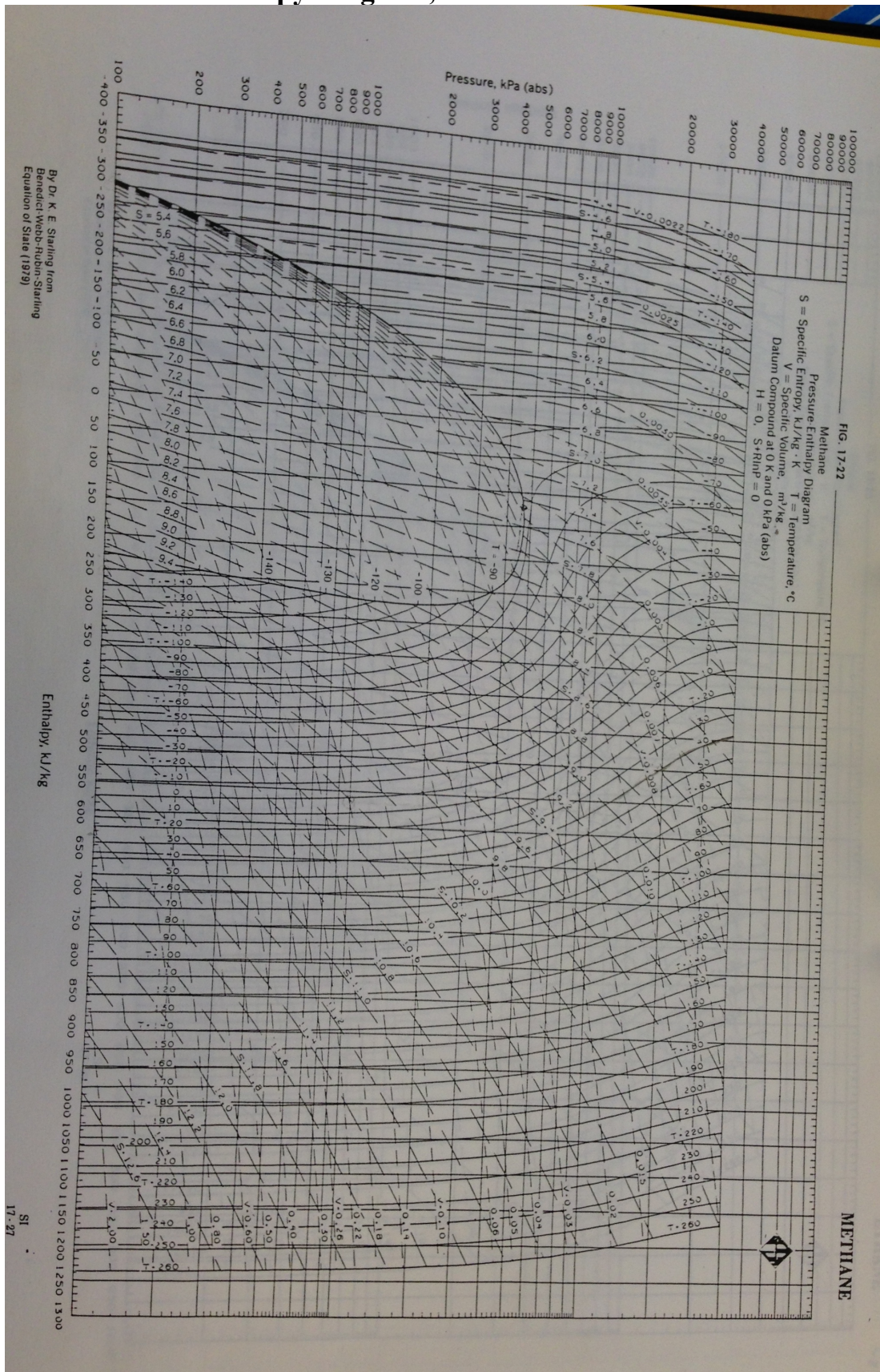
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Appendix

A1 – Pressure-Enthalpy Diagram, Propane



A2 – Pressure Enthalpy Diagram, Methane



A3 – Loading Paper – Vessel 1



CERTIFICAT DE QUALITE GNL

Complexe: GL1Z
Département Technique
Service Laboratoire

Intentionally Hidden Info

Température du GNL (°K) : 111,45 Densité du GNL (Kg/m3) : 465,617
Valeur du PCS (Th/nm3) : 10,527 Valeur du PCS (Th/Kg) : 12.8816

COMPOSITION DU GNL :

CI	C2	C3	IC4	NC4	IC5	NC5	N2	C6+
0.87702	0.08407	0.02186	0.00299	0.00447	0.00000	0.00000	0.00959	0.00000

CALCUL DE LA MASSE MOLAIRE :

FRCT	M MOL	M MOLFR	MV T1	MV T2	DIFMV	DIFMVFR	MOLT	MOLTFR
0.87702	16.043030	14.070058	0.037995	0.037735	0.000260	0.000072	0.037923	0.033259
0.08407	30.070120	2.527995	0.047845	0.047678	0.000167	0.000046	0.047799	0.004018
0.02186	44.097210	0.963965	0.062392	0.062212	0.000180	0.000050	0.062342	0.001363
0.00299	58.124300	0.173792	0.078236	0.078035	0.000201	0.000055	0.078181	0.000234
0.00447	58.124300	0.259816	0.076765	0.076574	0.000191	0.000053	0.076712	0.000343
0.00000	72.151000	0.000000	0.091596	0.091379	0.000217	0.000060	0.091536	0.000000
0.00000	72.151000	0.000000	0.091462	0.091252	0.000210	0.000058	0.091404	0.000000
0.00959	28.013400	0.268649	0.046231	0.045031	0.001200	0.000330	0.045901	0.000440
0.00000	86.172000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

18.264275

0.039657

FACTEURS D'INTERPOLATION :

Fact. Temp.: 0.710000
Fact.d'interp. Temp: 0.275000

Fact. Poids. Mol : 0.735725
Vol. Mol. Corrigé : 0.039226

PARAMETRES DE CALCUL :

K1 : 0.000437
K2 : 0.000679

CALCUL DU PCS MASSIQUE :

FRCT	M MOL	MFR	PCSM	FRPCSM
0.87702	16,04	14,067	13,297	10,2425
0.08407	30,07	2,528	12,431	1,7208
0.02186	44,09	0,964	12,062	0,6367
0.00299	58,12	0,174	11,831	0,1127
0.00447	58,12	0,260	11,860	0,1689
0.00000	72,15	0,000	11,703	0,0000
0.00000	72,15	0,000	11,738	0,0000
0.00959	28,01	0,269	0,000	0,0000
		18,262		12,8816

CALCUL DU PCS GAZ :

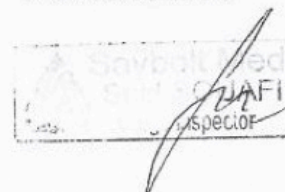
FRCT	V MOL	FRCTVMOI	PCSG	FRPCSG
0.87702	22.38	19.628	9.53	187.055
0.08407	22.17	1.864	16.86	31.427
0.02186	21.84	0.477	24.35	11.615
0.00299	21.78	0.065	31.57	2.052
0.00447	21.50	0.096	32.06	3.078
0.00000	21.03	0.000	40.15	0.000
0.00000	20.86	0.000	40.60	0.000
0.00959	22.40	0.215	0.00	0.000
		22,345		235,227

VISA DU SERVICE LABORATOIRE :

SISPRO/LABO V1.2
Code: GDF

Chef de Service
Laboratoire GL 1 / Z
M. BOURENANE

VISA DU CLIENT :



A4 – Loading Paper – Vessel 2

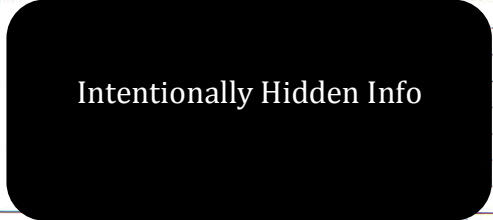
ATLANTIC LNG 2/3 COMPANY OF TRINIDAD AND TOBAGO UNLIMITED

11 Maraval Road, Port of Spain, Trinidad W.I.
Tel. (868) 628 2916 / Fax (868) 628 5641

CERTIFICATE OF QUALITY

Atlantic LNG Co., Port of Point Fortin, LNG Berth 2, Trinidad.

Train:
LNG Vessel:
Cargo No.:
Loading for:
Destination:
Consignee:
Product Type:
Date Loaded:



UNIT

Test	Unit	Method	Results
Component Analysis:			
C ₁	% mol	GPA 2261	97.7008
C ₂	% mol	GPA 2261	1.9461
C ₃	% mol	GPA 2261	0.2635
i-C ₄	% mol	GPA 2261	0.0314
n-C ₄	% mol	GPA 2261	0.0215
C ₅ ⁺	% mol	GPA 2261	0.0062
N ₂	% mol	GPA 2261	0.0305
O ₂	%mol	GPA 2261	0.0000
CO ₂	%mol	GPA 2261	0.0000
Density @ - 159.6 deg C	kg / m3	Modified K.M. Calculation	427.522
Gross Heating Value	Btu/kg	Calculation Conversion	52,475.4
	Btu/SCF		1,034.4
Wobbe Index	Btu/scf	GPA 2172 @14.73psia & 60 deg F.	1372.28
Mercaptan Sulphur	mg/Nm3	GPA 2265	Nil
Hydrogen Sulphide	% mol	GPA 2377	Nil
Total Sulphur	mg/Nm3	GPA 2265	0.6621

Signed:
Atlantic LNG

ATLANTIC LNG COMPANY
OF TRINIDAD AND TOBAGO

Terminal Representative: _____ Date 03/03/14

Surveyor:

[Handwritten signature]
[Handwritten signature]

SGS

Master:

Port:



Date



Hour	Loading Rate (m3)	Fuel (NG) to boilers (kg)	BOG sent to terminal (kg)	Manifold temp	Remarks
10:05	N/A	2051900	0	-88	CTS
10:16	N/A	2051900	2400	-88	Comm. cooling down
11:10	N/A	2051900	19800	-88	Comp. cooling down
12:35	4 666	2051900	40600	-89	Full rate
13:00	10 308	2051900	61200	-91	
14:00	9 276	2051900	96000	-91	
15:00	9 320	2051900	119400	-90	
16:00	9 190	2051900	141100	-91	
17:00	9 428	2051900	160100	-91	
18:00	9 221	2051900	179400	-91	
19:00	9 282	2051900	201400	-90	
20:00	9 363	2051900	223400	-90	
21:00	9 245	2051900	245800	-91	
22:00	9 220	2051900	265500	-92	
23:00	9 423	2051900	287400	-93	
00:00	9 260	2051900	306600	-95	
01:00	9 356	2051900	330800	-99	
02:00	9 173	2051900	356700	-104	
03:00	4 646	2051900	364100	-98	Stop loading
04:00	N/A	2051900	369700	-80	
04:31	N/A	2051900	373900	-78	CTS / Closed Vapor to shore
TOTAL	135 711	0	373900		

A5 – Loading Process

A6 – MATLAB script – Main Model, Change in Concentration

```
clc
format shorteng
format long

% %%%%%%%%%% INPUT %%%%%%%%%% %

% Concentration when loading [%] %
Methane = 88.5;
Ethane = 8;
Propane = 2;
isoButane = 0.25;
nButane = 0.25;
Nitrogen = 1.0;

% Boil-off rate [Volume fraction per day]
BOR = 0.0012;

% Number of days at sea
D = 60;
%Interval for calculation of BOG
int = 1; % Should always be equal 1 when using the model.
%Tank Volume
V = 144000; %m3 %Check amount much after loading
%Loading hours
t = 15;
%Amount [kg/hour] flashing off when loading
m_flash = 24000; %Set as zero if no flashing
%Density loaded LNG
Rho_LNG = 465; % [kg/m3]
% Higher Heating Value of Loaded HFO
HHV_HFO = 43.0; %MJ/kg

% %%%%%%%%%% %%%%%%%%%% %%%%%%%%%% %

% Checking correct total
LNG_met = Methane/100;
LNG_eta = Ethane/100;
LNG_pro = Propane/100;
LNG_isobut = isoButane/100;
LNG_nbut = nButane/100;
LNG_nit = Nitrogen/100;

xLNGisum = LNG_met + LNG_eta + LNG_pro + LNG_isobut + LNG_nbut + LNG_nit;

if round(xLNGisum*1000000) == 1000000;

% %%%%%%%%%% Parameters %%%%%%%%%% %

%Mass Gross Calorific Value [MJ/kg]
HHV_m = 55.5;
HHV_e = 51.878;
HHV_p = 50.350;
HHV_ib = 49.5;
HHV_nb = 49.5;
```

```

HHV_n = 0;

% Molar mass
Mm = 0.016043; %kg/mol
Me = 0.03007; % kg/mol
Mp = 0.044097; % kg/mol
Mib = 0.058123; % kg/mol
Mnb = 0.058123; % kg/mol
Mn = 0.02802; % kg/mol

% Seconds per day:
spd = 86400; %sec/day

% %%%%%%%%%%% %

% Calculation of specific energy for the LNG %
HHV_LNG = HHV_load(LNG_met, LNG_eta, LNG_pro, ...
    LNG_isobut, LNG_nbut, LNG_nit);

% Calculation of FOE When Loading
FOE_loading = FOE_caculation(HHV_HFO, HHV_LNG, Rho_LNG);

% Calculating number of moles in LNG loaded included flashing
Nlng_total = (Rho_LNG/(LNG_met*Mm + LNG_eta*Me + ...
    LNG_pro*Mp + LNG_isobut*Mib + LNG_nbut*Mnb + ...
    LNG_nit*Mn))*(V+(m_flash*t)/Rho_LNG));
Nlng_nit = Nlng_total*LNG_nit;
Nlng_met = Nlng_total*LNG_met;
N_rest = Nlng_total - Nlng_nit - Nlng_met;

Results = zeros([D,3]);
VOL = zeros([D,1]);
Percentage = zeros([D,5]);
HeatingValue = zeros([D,2]);
FOE_calc = zeros([D,2]);
FUEL = zeros([D,3]);

Heading1 = {'Day' 'xg_m' 'xg_n' 'xl_m' 'xl_n'};
Heading2 = {'Nlng' 'Ngtot' 'Nltot'};
Heading3 = { 'HHV_BOG [MJ/kg]' 'HHV_LNG [MJ/kg]'};
Heading4 = { 'BOG_Volume' };
Heading5 = { 'FOE_BOG' 'FOE_load'};
Heading6 = { 'Fuel by BOG' 'Fuel by Load' 'Difference'};

% %%%%%%%%%%% Flashing when loading %%%%%%%%%%% %

flash = flash_load(LNG_nit, LNG_eta, m_flash, t, Rho_LNG);
Nlng_total_flash = flash(1,1);
Nlng_nit_flash = flash(2,1);
Nlng_met_flash = flash(3,1);
Volume_flash = flash(4,1);

% %%%%%%%%%%% %

% %%% Amount after flashing when loading %%% %

```

```

Nlng_tot = Nlng_total - Nlng_total_flash;
Nlng_m = Nlng_met - Nlng_met_flash;
Nlng_n = Nlng_nit - Nlng_nit_flash;

xLNG_nit = Nlng_n/Nlng_tot;
xLNG_met = Nlng_m/Nlng_tot;

%Only for testing
x_rest = N_rest/Nlng_tot;
test = xLNG_nit + xLNG_met + x_rest;

% %%%%%%%%%%% %

% %%%%%%%%%%% Amount BOG per interval %%%%%%%%%%% %
Volume = V; %Afetr including new volume by flashing
BOG_volume = Volume*BOR;

% %%%%%%%%%%% %

for i = int:int:D

%Regression
if LNG_eta <= 0.005
    a = -232.04;
    b = 21.937;
    c = 0;
elseif LNG_eta <= 0.03
    a = -375.37;
    b = 27.521;
    c = 0;
elseif LNG_eta <= 0.05
    a = -396.24;
    b = 28.511;
    c = 0;
elseif LNG_eta <= 0.07
    a = -418.52;
    b = 29.541;
    c = 0;
else
    a = -442.87;
    b = 30.622;
    c = 0;
end

% Mole [%] of BOG
xgn = a*xLNG_nit^2 + b*xLNG_nit + c;
xgm = 1 - xgn;

%Calculation of BOG [Moles]
BOG_total = (Rho_LNG/(xgm*Mm + xgn*Mn))*BOG_volume;
BOG_n = BOG_total*xgn;
BOG_m = BOG_total*xgm;

% For testing
vekt_n = BOG_n*Mn;
vekt_m = BOG_m*Mm;
volum_m = vekt_m/Rho_met;

```



```

%          volum_n = vekt_n/Rho_nit;
%          volumtotal = volum_n + volum_m

% Amount liquid equal amount LNG minus BOG
Nltot = Nlng_tot - BOG_total;

Nlm = Nlng_m - BOG_m;
Nln = Nlng_n - BOG_n;

xlm = Nlm/(Nltot);
xln = Nln/(Nltot);

%Calculating HHV for BOG:
% Mass weight
Mass_met = Mm*xgm;
Mass_nit = Mn*xgn;
Total_mass = Mass_met + Mass_nit;
% Mass fraction
frac_met = Mass_met/Total_mass;
frac_nit = Mass_nit/Total_mass;

HHV_BOG = frac_met*HHV_m + frac_nit*HHV_n;

FOE_BOG= FOE_claculation(HHV_HFO, HHV_BOG, Rho_LNG);
FOE_calc(round(i/int),1) = FOE_BOG;
FOE_calc(round(i/int),2) = FOE_loading;

FUEL(round(i/int),1) = FOE_BOG*BOG_volume;
FUEL(round(i/int),2) = FOE_loading*BOG_volume;
FUEL(round(i/int),3) = FOE_loading*BOG_volume - FOE_BOG*BOG_volume;

% If constnat FOE:
%          FUEL(round(i/int),2) = 0.547*BOG_volume;
%          FUEL(round(i/int),3) = 0.547*BOG_volume - FOE_BOG*BOG_volume;

VOL(round(i/int),1) = BOG_volume;
Results(round(i/int),1) = Nlng_tot;
Results(round(i/int),2) = BOG_total;
Results(round(i/int),3) = Nltot;
Percentage(round(i/int),1) = i;
Percentage(round(i/int),2) = xgm;
Percentage(round(i/int),3) = xgn;
Percentage(round(i/int),4) = xlm;
Percentage(round(i/int),5) = xln;
HeatingValue(round(i/int),1) = HHV_BOG;
HeatingValue(round(i/int),2) = HHV_LNG;
FOE_calc(round(i/int),1) = FOE_BOG;
FOE_calc(round(i/int),2) = FOE_loading;

Nlng_tot = Nltot;
Nlng_m = Nlm;
Nlng_n = Nln;

Volume_new = (Nlng_tot*(xlm*Mm + xln*Mn))/Rho_LNG;

%Not included because of constant BOR
%          BOG_volume = Volume_new*BOR;

```

```

    if Nlng_n >= 0
        xLNG_nit = Nlng_n/Nlng_tot; %Mole%
        xLNG_met = Nlng_m/Nlng_tot;
    else
        xLNG_nit = 0; %Mole%
        xLNG_met = Nlng_m/Nlng_tot;
    end
end

disp(Heading1)
disp(Percentage)
disp(Heading2)
disp(Results)
disp(Heading3)
disp(HeatingValue)
disp(Heading4)
disp(VOL)
disp(Heading5)
disp(FOE_calc)
disp(Heading6)
disp(FUEL)

X = Percentage(:,1); % Days of trial
Y = HeatingValue(:,1) % HHV of BOG
G = HeatingValue(:,2) %Heating Value LNG when loading
Z = Percentage(:,2); %xgm
T = Percentage(:,3); %xgn
U = Percentage(:,4); %xlm
V = Percentage(:,5); %xln
F1 = FOE_calc(:,1); %FOE_BOG
F2 = FOE_calc(:,2); %FOE_load
Diff = FUEL(:,3);

figure(1)
plot(X,Z,X,T,'LineWidth',2)
grid on
title('Concentration of BOG', 'FontSize', 18, 'fontWeight','bold')
xlabel('Days of trial [days]', 'FontSize', 14, 'fontWeight','bold')
ylabel('Concentration [Fraction]', 'FontSize', 14, 'fontWeight','bold')
legend('Methane','Nitrogen')
axis([0 D+(D/2) -0.1 1.1])
set(gca, 'fontsize',14)

figure(2)
plot(X,Y,X,G,'LineWidth',2)
grid on
title('Changing in HHV During Voyage', 'FontSize', 18, 'fontWeight','bold')
xlabel('Days of trial [days]', 'FontSize', 14, 'fontWeight','bold')
ylabel('Lower Heating Value [MJ/kg]', 'FontSize', 14, 'fontWeight','bold')
legend('Calculated HHV BOG', 'HHV LNG Loading')
axis([0 D 30 65])
set(gca, 'fontsize',14)

figure(3)

```

```
plot(X,F1,X,F2,'LineWidth',2)
grid on
title('Changing in FOE During Voyage', 'FontSize', 18, 'fontWeight','bold')
xlabel('Days of trial [days]', 'FontSize', 14, 'fontWeight','bold')
ylabel('Fuel Oil Equivalent', 'FontSize', 14, 'fontWeight','bold')
legend('FOE of BOG','FOE by Loading')
axis([0 D 0.3 0.65])
set(gca,'fontsize',14)

else
    disp('konsentrasjonene stemmer ikke (ikke totalt 100%), rett opp og kjør igjen')
    disp('Total sum skal vaere 100, men er naa:')
    disp(xLNGisum*100)
end
```

A7 – MATLAB script – Sub-Model, Flashing During Loading

```
function flash = flash_load(xLNG_nit, xLNG_eta, m_flash, t, Rho_LNG)

%% Flashing when loading the LNG

% Molar mass
Mm = 0.016043; %kg/mol
Mn = 0.02802; % kg/mol

%Regression
if xLNG_eta <= 0.005
    a = -232.04;
    b = 21.937;
    c = 0;
elseif xLNG_eta <= 0.03
    a = -375.37;
    b = 27.521;
    c = 0;
elseif xLNG_eta <= 0.05
    a = -396.24;
    b = 28.511;
    c = 0;
elseif xLNG_eta <= 0.07
    a = -418.52;
    b = 29.541;
    c = 0;
else
    a = -442.87;
    b = 30.622;
    c = 0;
end

% Mole [%]
xgn = a*xLNG_nit^2 + b*xLNG_nit + c;
xgm = 1 - xgn;

Ntot_flash = ((m_flash*t)/(xgm*Mm + xgn*Mn));
Nnit_flash = Ntot_flash*xgn;
Nmet_flash = Ntot_flash*xgm;
Volume_flash = (Ntot_flash*(xgm*Mm + xgn*Mn))/Rho_LNG;

flash = zeros(4,1);

flash(1,1) = Ntot_flash;
flash(2,1) = Nnit_flash;
flash(3,1) = Nmet_flash;
flash(4,1) = Volume_flash;

return
```

A8 – MATLAB script – Sub-Model, Change in HHV

```
% Calculation of specific energy for the LNG %  
  
function HHV = HHV_load(xm, xe, xp, xib, xnb, xn)  
  
% Molar mass  
Mm = 0.016043; %kg/mol  
Me = 0.03007; % kg/mol  
Mp = 0.044097; % kg/mol  
Mib = 0.058123; % kg/mol  
Mnb = 0.058123; % kg/mol  
Mn = 0.02802; % kg/mol  
  
%Mass Gross Calorific Value  
HHV_m = 55.5;  
HHV_e = 51.878;  
HHV_p = 50.350;  
HHV_ib = 49.5;  
HHV_nb = 49.5;  
HHV_n = 0;  
  
% Mass weight  
Mass_m = Mm*xm;  
Mass_e = Me*xe;  
Mass_p = Mp*xp;  
Mass_ib = Mib*xib;  
Mass_nb = Mnb*xnb;  
Mass_n = Mn*xn;  
Mass_sum = Mass_m + Mass_e + Mass_p + Mass_ib + Mass_nb + Mass_n;  
%Mass fraction  
fm = Mass_m/Mass_sum;  
fe = Mass_e/Mass_sum;  
fp = Mass_p/Mass_sum;  
fib = Mass_ib/Mass_sum;  
fnb = Mass_nb/Mass_sum;  
fn = Mass_n/Mass_sum;  
%Mass Calorific Value by fraction  
H_m = HHV_m*fm;  
H_e = HHV_e*fe;  
H_p = HHV_p*fp;  
H_ib = HHV_ib*fib;  
H_nb = HHV_nb*fnb;  
H_n = HHV_n*fn;  
  
%HHV for LNG when loading  
HHV = H_m + H_e + H_p + H_ib + H_nb + H_n; %MJ/kg  
  
return
```

A9 – MATLAB script – Sub-Model, Change in FOE

```
function FOE = FOE_calaculation(HHV_HFO_kg, HHV_LNG, Rho_LNG)
    HHV_HFO = HHV_HFO_kg*1000; %Converted to MJ/MT
    Conv_LNG = HHV_LNG*Rho_LNG; %Converted to MJ/m3
    FOE = Conv_LNG/HHV_HFO; %[MT/m3]
return
```