UNIVERSITY OF WEST ATTICA

SCHOOL OF ENGINEERING

DEPARTMENT OF NAVAL ARCHITECTURE

Diploma Thesis

Investigation of BOG management during marine LNG transport focusing on its use for ship propulsion

Author:

Nikolaos K. Panagiotopoulos

Supervisor:

Dimitrios Koubogiannis

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UNIVERSITY OF WEST ATTICA
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Διπλωματική εργασία

Διερεύνηση διαχείρισης BOG κατά τη θαλάσσια μεταφορά LNG εστιάζοντας στη χρήση του για την πρόωση του πλοίου

Συγγραφέας

Νικόλαος Κ. Παναγιωτόπουλος (Α.Μ.: 18393076)

Επιβλέπων

Δημήτριος Κουμπογιάννης,

Αναπληρωτής Καθηγητής ΠΑ.Δ.Α.

Ημερομηνία εξέτασης

14/02/2024

Εξεταστική Επιτροπή

Georgios Livanos
Digitally signed by Georgios Livanos
Date: 2024.02.18 12:49:12 +02'00'

Γεώργιος Λιβανός,

Αναπληρωτής Καθηγητής ΠΑ.Δ.Α.

Antonios Hatziapostolou
Digitally signed by Antonios Hatziapostolou
Date: 2024.02.18 14:29:45 +02'00'

Αντώνης Χατζηαποστόλου,

Αναπληρωτής Καθηγητής ΠΑ.Δ.Α.

Dimitrios Koumpogiannis
Digitally signed by Dimitrios Koumpogiannis
Date: 2024.02.16 18:22:50 +02'00'

Δημήτρης Κουμπογιάννης,

Αναπληρωτής Καθηγητής ΠΑ.Δ.Α.

ΔΗΛΩΣΗ ΣΥΓΓΡΑΦΕΑ ΔΙΠΛΩΜΑΤΙΚΗΣ ΕΡΓΑΣΙΑΣ

Ο κάτωθι υπογεγραμμένος Παναγιωτόπουλος Νικόλαος του Κωνσταντίνου, με αριθμό μητρώου 18393076 φοιτητής του Πανεπιστημίου Δυτικής Αττικής της Σχολής Μηχανικών του Τμήματος Ναυπηγών Μηχανικών, δηλώνω υπεύθυνα ότι:

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Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του διπλώματός μου».

Ο Δηλών

Νικόλαος Κ. Παναγιωτόπουλος

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Abstract

This thesis is aimed firstly at comparing BOG utilization as fuel by different vessel propulsion plants and secondly by proposing a BOG management method for said propulsion plant arrangements. Maritime LNG transport is the way one of the largest quantities of LNG are transported, due to the BOG generated though, quantity of the cargo is wasted. The purpose of this thesis is to analyze the natural gas history, highlight its maritime transport and the BOG problem, examine the different propulsion plants and compare how each one differs and utilizes the BOG. How this is going to be achieved is by setting up a virtual case study vessel and deciding which propulsion plant system arrangements are interesting in comparing to one another. After that, the BOG rate for the case study vessel size will be estimated using at least two different methods. Following BOG supply calculations, the propulsion plant energy and thus BOG supply demands will be calculated. It will be found that the BOG in most cases is more than enough to supply the vessel's fuel needs. Lastly, a way to treat the excess BOG and some calculations evaluating its effectiveness will be conducted. The whole procedure of gathering the information and specific characteristics will result in an easy comparison between the chosen propulsion plants and possible BOG treatment methods. Concluding, key takeaways will be pinpointed and future research ideas will be given.

Key words

LNG fuel on ships, BOG, BOG utilization, BOG management, boil-off gas, DFDE, dual fuel diesel electric, hybrid ships, electric powered ships, steam powered ships, STaGE, Steam turbine and gas engines, efficiency, LNG ships, LNG ships, MEGI, XDF, 2-stroke dual fuel engines, partial reliquefaction.

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Nomenclature

BOG	Boil Off Gas
BSEC	Brake Specific Energy Consumption
CNG	Compressed Natural Gas
CST	Conventional Steam Turbine
DE	Diesel Electric
DFDE	Dual Fuel Diesel Electric
DFE	Dual Fuel Engine
D/G	Diesel Generator
ECAs	Emission Controlled Areas
FGSS	Fuel Gas Supply System
GCU	Gas Combustion Unit
GHG	Greenhouse Gases
GTL	Gas To Liquid
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LHV	Lower Heating Value
LNG	Liquified Natural Gas
LNGC	Liquified Natural Gas Carrier
LPG	Liquified Petroleum Gas
MARPOL	Marine Pollution
MCR	Maximum Continuous Rating
MDO	Medium Diesel Oil
MPEC	Marine Environment Protection Committee
MGO	Medium Gas Oil
MHI	Mitsubishi Heavy Industries
ME	Main Engine
MEGI	M-type Electronically Controlled Gas Injection
OPEX	Operational Expenses
PLNG	Pressurized Liquified Natural Gas
PM	Particulate Matter

- PMS………………………………………………. Power Management System
- RLQ…………………………………………………………. Reliquefaction
- SDGs………………………………………… Sustainable Development Goals
- SECAs……………………………………… Sulfur Emission Control Zones
- SFOC…………………………………….. Specific Fuel Oil Consumption
- SGC……………………………………………….. Specific Gas Consumption
- SOLAS…………………………..……………….. Safety of Life at Sea
- SPOC………………………………………. Specific Pilot Oil Consumption
- ST……………………………………………………………. Steam Turbine
- STaGE……………………………………… Steam Turbine and Gas Engine
- TFDE………………………………………………. Triple Fuel Diesel Electric
- ULSFO……………………………………………… Ultra Low Sulfur Fuel Oil
- UN…………………………………………………………... United Nations
- UST……………………………………………………. Ultra Steam Turbine
- VLE………………………………………………... Vapor-Liquid Equilibrium
- VLSFO……………………….……………….. Very Low Sulfur Fuel Oil
- WHRS……………………………………….. Waste Heat Recovery System
- XDF…………………………………………. Low Pressure 2-stroke Engine

1. Chapter 1: Introduction

1.1. Motivation leading to current thesis

Starting from a young age I was always intrigued by STEM (Science Technology Engineering and Mathematics). The progress of technology and mechanics, huge creations – static and non – planes, ships, power plants, etc. I started by reading STEM books – especially technology ones – and watching videos on the internet. Without being aware of it, I always leaned over towards things that tend to make something more efficient. What setting do I use in my TV to improve image quality? Or my smartphone so it doesn't consume as much battery? What gear should I drive my car in a specific scenario – RPM, load, throttle input etc. – to improve fuel consumption and power generation. During my late high school years and early university years all those puzzle pieces started coming together realizing that what I had going there all those years was a measurable value, energy management, efficiency.

Higher efficiency is what everyone is hardwired to achieve, either they have been taught/learn by themselves and understand the idea of efficiency as a measurable value or not. Our car's fuel consumption – kilometers per liter, electricity consumption – Price / kWh, food consumed in relation to its price, work done in relation to monthly payment, these are just some of the random examples someone can quickly come up with. If one gives a certain amount of attention, will quickly realize that everything revolves around efficiency, how can we take more by giving less? It is an upwards trend, as time passes everything tends to become more efficient or left behind for something that works better – more efficiently.

By understanding that the concept of efficiency is not just thermodynamics we can apply that mentality across different scenarios across our lives you can start seeing the world differently. It is truly simple to understand yet complicated to implement – even impossible sometimes. That is what makes it so intriguing, the fact that few realize its' value but many actually do something to improve efficiency across different science fields, scenarios, everyday life etc. Almost everything we do we do it to improve efficiency, so why not consciously do something that can actually help improve a procedure's efficiency?

Even better if that "something" requires little extra cost relatively to the bigger budget given. Looking at the task at hand – this thesis' point of interest – the tools to improve efficiency on liquid natural gas carrier (LNG ships) are already there, people have worked on this before making clever use of these tools to improve the ships performance across different fields. Why not double down on that and streamline this procedure? Given certain parameters, a course of action can be followed in order to improve the economy of these type of ships. LNG carriers use also happens to be on the rise during the last couple of decades due to the increased market demand for natural gas, a cleaner energy source with less harmful particulates being released in the atmosphere.

1.1. Scope of work

Main aspects of the scope of work of this thesis include the following:

- Historic recap of natural gas use and maritime LNG (Liquid Natural Gas) transport.
- Categorize LNGC (Liquid Natural Gas Carriers) types, propulsion plant types, cargo tanks types.
- Causes of BOG (Boil Off Gas), the problems that accompany that and ways to counter it.
- Calculate a ships' BOG production in relation to factors such as tank and ship size.
- Selection of interesting propulsion plants configurations as well as a case study of a ship using said configurations.
- Analise each propulsion plant with rough estimates of its efficiency, BOG utilization as well as its special characteristics. Propose a BOG management method.
- Compare the propulsion plants pinpoint advantages and disadvantages.

In order though for one to understand all the terminology, concepts and procedures we will need to build upon the principles of each component of this complex system. So, first things first, we will be starting from a historic recap of the basic columns of this thesis' topic. We will build on top of them using today's knowledge, data, methods and practices. Boil off gas (BOG) will be one of the most important columns of the thesis along with understanding how to pick the right treatment methods. Just mentioning these methods, they are the following:

- Using it as fuel (most frequent)
- Reliquefying it and storing it back in the storage tanks (used in bigger ships)
- Buring it and/or venting it in the atmosphere

Following that, attention will be focused particularly in the option of using it as fuel on the vessel's main engines. BOG production rates will be calculated using different formulas and compared to each other. A case study will be picked and compare the propulsion methods that can be equipped on said ship.

We will proceed by analyzing each LNGC propulsion type in use and highlight those with higher expectations for the future of maritime LNG transport.

Having boil off rate calculated, we would be able to pick a case study vessel. Comparing this no – name vessel to exact same ones equipped with different popular propulsion systems will be the ultimate goal of this thesis.

1.2. Questions to be answered

As briefly touched during the last paragraph of the previous page, the ultimate goal of this thesis is to make comparisons between different popular propulsion arrangements among LNG vessels.

Let’s start by stating the fact that BOG generation is inevitable during transport. During the ships’ voyage the LNG stored in the tank (various types of tanks – different pressure, temperature, state) evaporates due to thermal energy leaking into the system from the surrounding environment, causing heating, evaporation and inevitably pressure build-up inside the tanks. Many engineers, naval architects and people with decade old practical experience have proposed ways to deal with the excess gas and many have come ideas that came into fruition becoming practical solutions to the problem. Among the different ways someone can solve that problem there are some that work better under certain conditions or even work better by combining them. There are a few dozen different combinations the management can happen, each one of them with its positive and negative attributes. For example:

- Small sized vessels usually just use the available BOG, as the loss of cargo and its cost outweighs the cost of the energy spent during the reliquefying procedure during a small ship/voyage.
- Medium sized vessels also burn the BOG as fuel as reliquefying it is not economically viable. However, there are cases where small partial reliquefaction (RLQ) plants are installed.
- Big vessels that operate on long routes and with large quantities of LNG always come equipped with reliquefying plants as its more economically viable.

In conclusion before moving into the next chapter including “the chapters to follow”, this thesis aims to invoke the readers interest on which ship propulsion plant and BOG management method seem to be the most promising for the upcoming transitional years while in search for a cleaner energy source other than carbon-based fuels.

1.2. Content and chapters to follow

In the chapters and their respective paragraphs to follow the basic principles, terminology, phenomena will be built upon in order for one to have a coherent view of this paper and the questions arising to be answered and debated upon.

The second chapter of the thesis starts with a historic recap of natural gas. Briefly touching fossil fuels (carbon-based fuels) and later on focusing on natural gas, its characteristics, advantages and disadvantages along with why it was preferred over other types of hydrocarbon fuel over the ages. Moving towards present time we will examine natural gas means of transport, demand, supply chain and problems arising with it.

Entering chapter three, it will be evident that LNG transport is necessary to meet today's societies energy demands and emission restrictions. So, taking that into consideration BOG management methods aboard LNG carriers during voyage will be described in detail. Reliquefaction systems, burners, compressors, vents, piping and every other machinery part/subsystem aiding in the whole process will be named and explained throughout. Evaporation of LNG is something inevitable and ways to counter it are high in the list of priorities with every party associated with its delivery to the end consumer. The factors affecting and/or worsening this effect (BOG) will be pinpointed and thoroughly analyzed. After finding the root cause, one will quickly come to realize that it cannot be eliminated, so ways to counteract the generation of the unwanted BOG or even take advantage of it are highly valued. Various models, formula and data will be used to calculate evaporation of gas during given scenario. These BOG production rates values are the first half or the puzzle. Depending on various external factors (e.g., environmental conditions, ambient temperature, pressure, humidity, sea state and voyage distance and time) BOG rate of production may vary along with its management methods. Necessary simplifications and assumptions will be made in order to calculate BOG in a coherent and compact frame time.

During the fourth chapter, LNG carrier ship types followed by their tank configuration types will be mentioned and briefly described. Different tank configurations have emerged through the years, older designs becoming obsolete due to newer ones being improved in every aspect due to better material science, structural improvements and insulation type and efficiency. Building on top of the LNG ship and its special characteristics IGS regulations code and IMO restrictions applied on LNG carriers will also be an important aspect of this chapter as understanding it and the restrictions it sets is crucial to making the right decisions when optimizing BOG management procedures. During the second half of this chapter, we will focus on the use of natural gas as fuel on LNG carriers. More specifically, the use of BOG originating from the LNG the ship already stored onboard by burning it as fuel. The propulsion methods used, mainly large DF (dual fuel) two – stroke engines, heater and gas turbine arrangements and last but not list electrical motor driven propulsion from energy originating from generators operating on natural gas. At the end of this chapter a case study ship with its particulars dimensions and other key characteristics will be chosen.

During Chapter 5 after having a basic understanding of several different propulsion plants and picked ship particulars and characteristics for the case study we will pick some for a more detailed comparison. The choice of the propulsion plants will be based upon three factors:

1. Futureproofing
2. Efficiency and emissions
3. Boil-off gas utilization

The goal is to compare three propulsion plant configurations, each having one specific special attribute:

1. Experimental yet promising (Steam Turbine and Gas Engine)
2. Hybrid future prof and compact (Dual Fuel Diesel Electric)
3. Long established and reliable (Dual Fuel Two Strokes)

The comparison will occur under three operating conditions:

1. Rough weather and/or high-speed maneuvering (high load)
2. Anchorage/port call (low load)
3. Voyage/seagoing conditions (normal load)

Large two stroke engines are renowned for their individual engine efficiency but lack in versatility when compared to a compact hybrid dual fuel diesel electric plant with advanced power management and reliquefaction options. On the other hand, Steam Turbine and Gas Engine arrangements, debuted in 2018 by Mitsubishi have shown promising results in terms of BOG utilization and overall efficiency by combining positive characteristics from different propulsion plant configurations.

2. Chapter 2: Natural Gas

2.1. Natural gas - historic recap

Throughout mankind's history during the last two centuries our need for energy – in any form that might be – has been increasing exponentially. Being heavily industrialized makes us dependent on anything that can produce energy, either that being superheated gas generated by uranium on a nuclear reactor passing through a gas turbine or just kinetic power harvested by wind turbines. Hydro, solar and wind energy has been used for a while throughout our history and have been the main sources of energy. After the industrial revolution though one of the biggest contributors of energy production has been undoubtably, hydrocarbons, including coal, crude oil, petroleum, natural gas and products of them.

Our first discovery and use of hydrocarbon-based fuels dates back to thousands of years actually. Coal had been used for heating since humans were still occupants of the caves, though hydrocarbon-based fuels use for industrialized purposes didn't start until the 19th century (during industrial revolution, as mentioned above) when humans started using it to heat up water and create steam in order to drive reciprocating engines, turbines and heat up their houses. Natural gas can exist wherever crude oil can, as its just lighter bonds of hydrocarbon molecules and a byproduct of compressed biomass under extreme pressure and temperature, just as crude oil is created. It just happens that is some places the conditions favor the creation of one more over the other, these conditions include reservoirs of porous rock sealed by airtight strata around it (Bakar & Ali, 2010). People had identified natural gas leaking though the ground into the atmosphere as far back as 1626, but a lot of them were afraid of it, due to its volatility and the fact that it was odorless and invisible thinking made it dangerous, but that was about to change.

The first natural gas and oil wells were dug up in 1821 and 1859 respectively, William Hart was the man that successfully extracted and successfully transported natural gas through a pipeline and Edwin Drake managed to extract oil from a 22 meter deep well. Although their presence had been known for years prior – as mentioned in the previous paragraph – they were the first to see their potential (Bakar & Ali, 2010). It took some time for the world to notice through, but once they saw that potential, the onset of a new era was already on. Full on production of the first diesel engines was just around the corner and some basic inventions fueled by natural gas were already on the prototype stages. The public quickly saw the benefits oil and gas offered over coal.

With the First World War starting, oil products – mainly gasoline and diesel – saw extended use in any land vehicle ranging from bikes to battle tanks. Coal continued to be used in larger more ragged, power-hungry uses such as trains, ships and power plants. Little did we know; coal would still be used – albeit to a smaller extent – even to this day. The Second World War pushed this effect of moving away from coal and into crude oil products even more with ships using heavy fuel oil alongside steam power ones by coal. This pattern continued forming a closed feedback loop, as more and more industrialization led to higher energy demands at the same time it pushed research and development, introduced new oil extraction technologies, increased distillation efficiency and quantities making the progress of said industrialization easier.

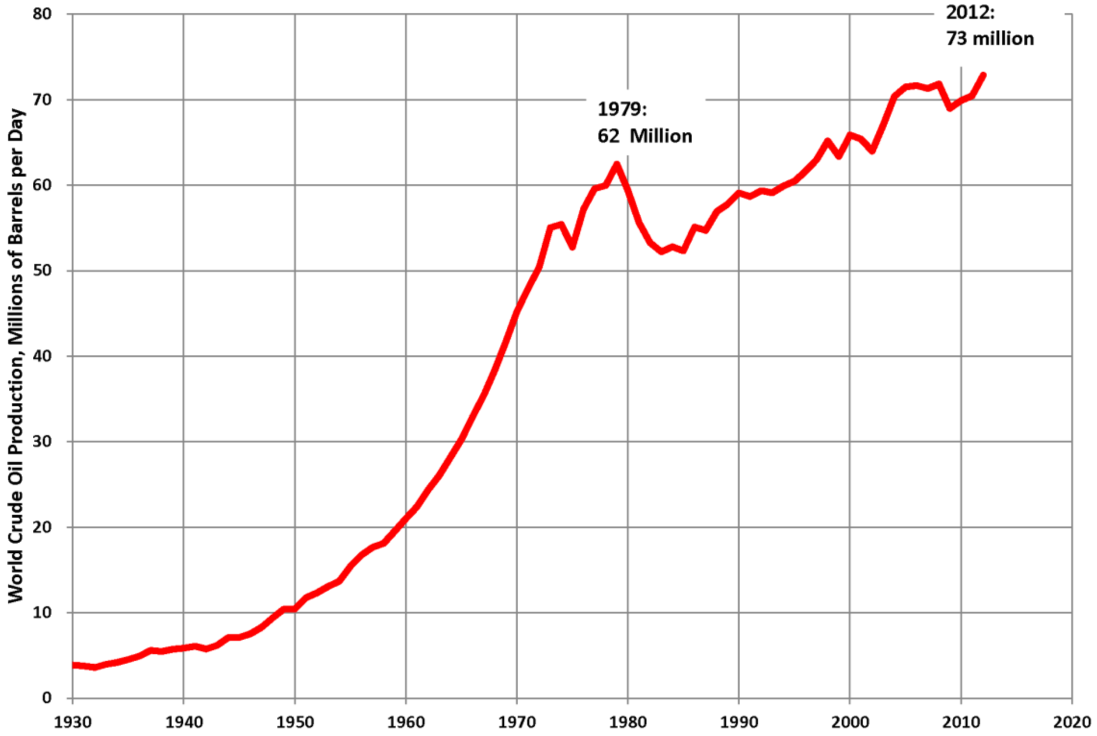
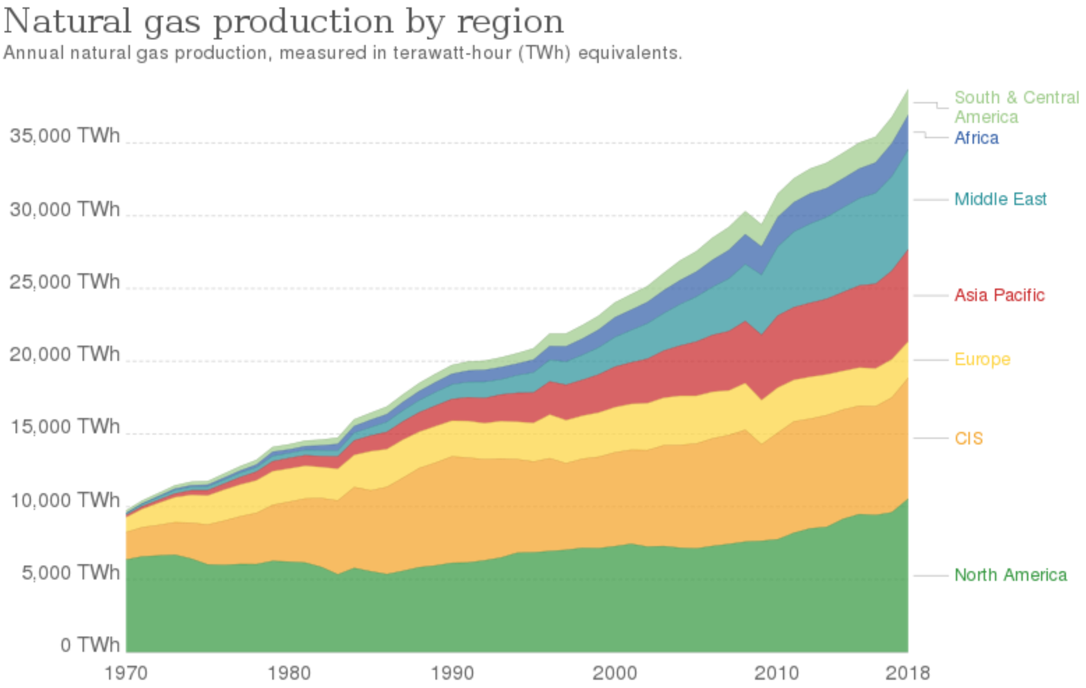


Figure 1.1: Oil production increase over the last century

[https://upload.wikimedia.org/wikipedia/commons/4/4a/World_Oil_Production.png]

There were a few setbacks regarding the power crisis of the 1970s, but for the most part we continued moving more and more into “cleaner” oil products of higher levels of distillation such as gasoline, petroleum gas and natural gas. The energy density of a fuel started becoming a concern too as a plane for example needs kerosene and its compact engines to achieve high weight to trust ratios. Something that was unachievable with coal and a steam powered reciprocating engine. As we can see in the figure below, natural gas production more than tripled over the last 50 years where crude oil saw an increase of about 60% (Figure 1.1), a substantial yet small amount when compared to the 300% increase of natural gas production, confirming the statement mentioned above.


Natural gas production by region

Annual natural gas production, measured in terawatt-hour (TWh) equivalents.

Source: BP Statistical Review of Global Energy (2019)

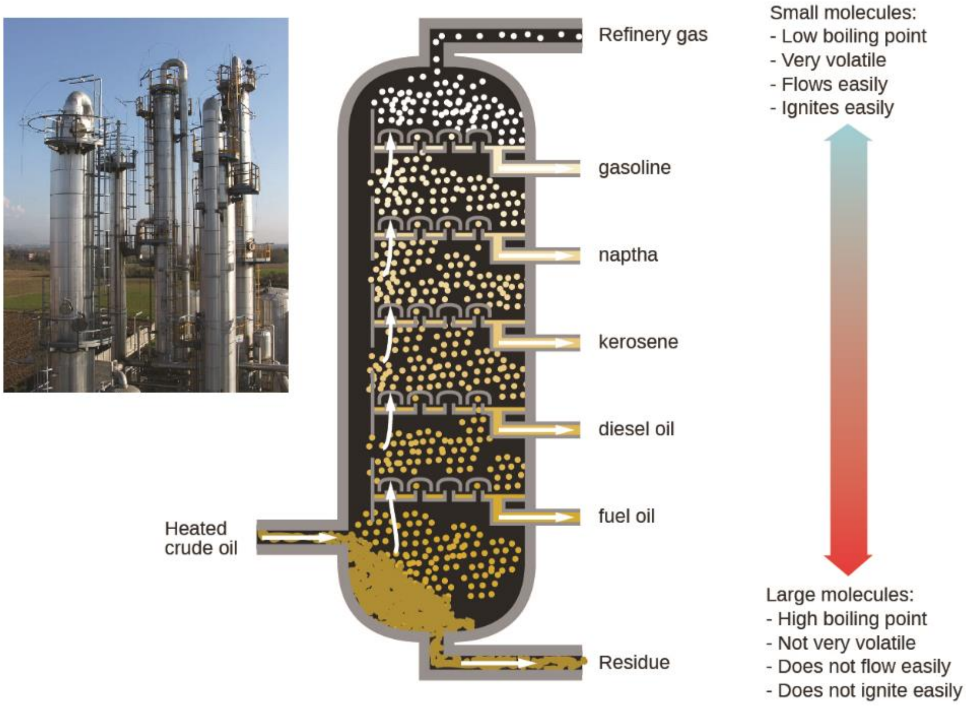
Note: CIS (Commonwealth of Independent States) is an organization of ten post-Soviet republics in Eurasia following break-up of the Soviet Union.

Figure 1.2: Natural gas production

[https://commons.wikimedia.org/wiki/File:Natural_gas_production_by_region,_OWID.svg]

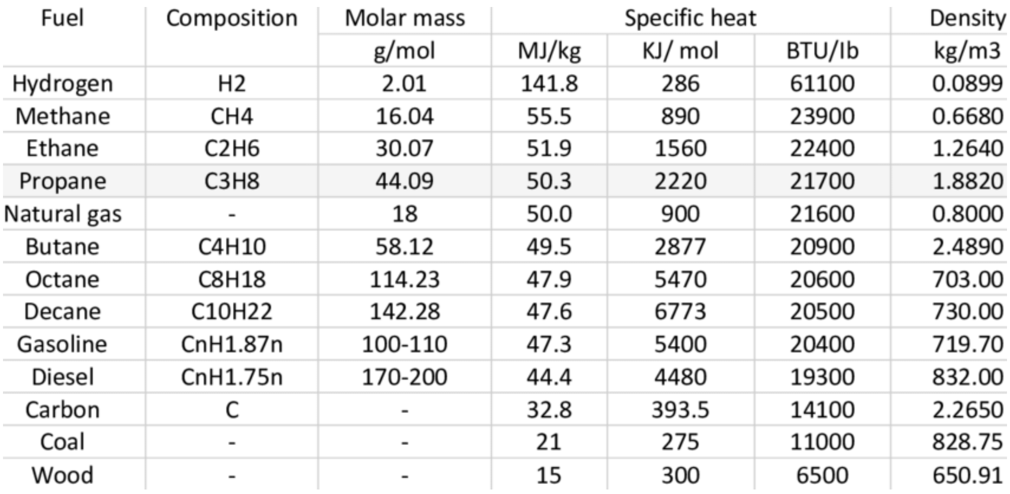
2.2. Natural gas over heavier carbon-based fuel types

We are starting by taking a look at the closest related thing to natural gas, crude oil, which is extracted from the ground and refined into several different byproducts. Depending on the amount of distillation we extract different type of hydrocarbons based on their molecular weight and thus different type of fuels, each with its own characteristics, as it can be seen in the following picture.



Picture 1.1: Crude oil distillation stages

[https://upload.wikimedia.org/wikipedia/commons/8/88/CNX_Chem_11_04_refinery.png]



Fuel	Composition	Molar mass	Specific heat			Density
		g/mol	MJ/kg	KJ/ mol	BTU/Ib	kg/m3
Hydrogen	H2	2.01	141.8	286	61100	0.0899
Methane	CH4	16.04	55.5	890	23900	0.6680
Ethane	C2H6	30.07	51.9	1560	22400	1.2640
Propane	C3H8	44.09	50.3	2220	21700	1.8820
Natural gas	-	18	50.0	900	21600	0.8000
Butane	C4H10	58.12	49.5	2877	20900	2.4890
Octane	C8H18	114.23	47.9	5470	20600	703.00
Decane	C10H22	142.28	47.6	6773	20500	730.00
Gasoline	CnH1.87n	100-110	47.3	5400	20400	719.70
Diesel	CnH1.75n	170-200	44.4	4480	19300	832.00
Carbon	C	-	32.8	393.5	14100	2.2650
Coal	-	-	21	275	11000	828.75
Wood	-	-	15	300	6500	650.91

Figure 1.3 Different fuel characteristics and composition

[https://www.researchgate.net/figure/Fuel-Heating-Value-to-calculate-furnace-power_tbl1_289767242]

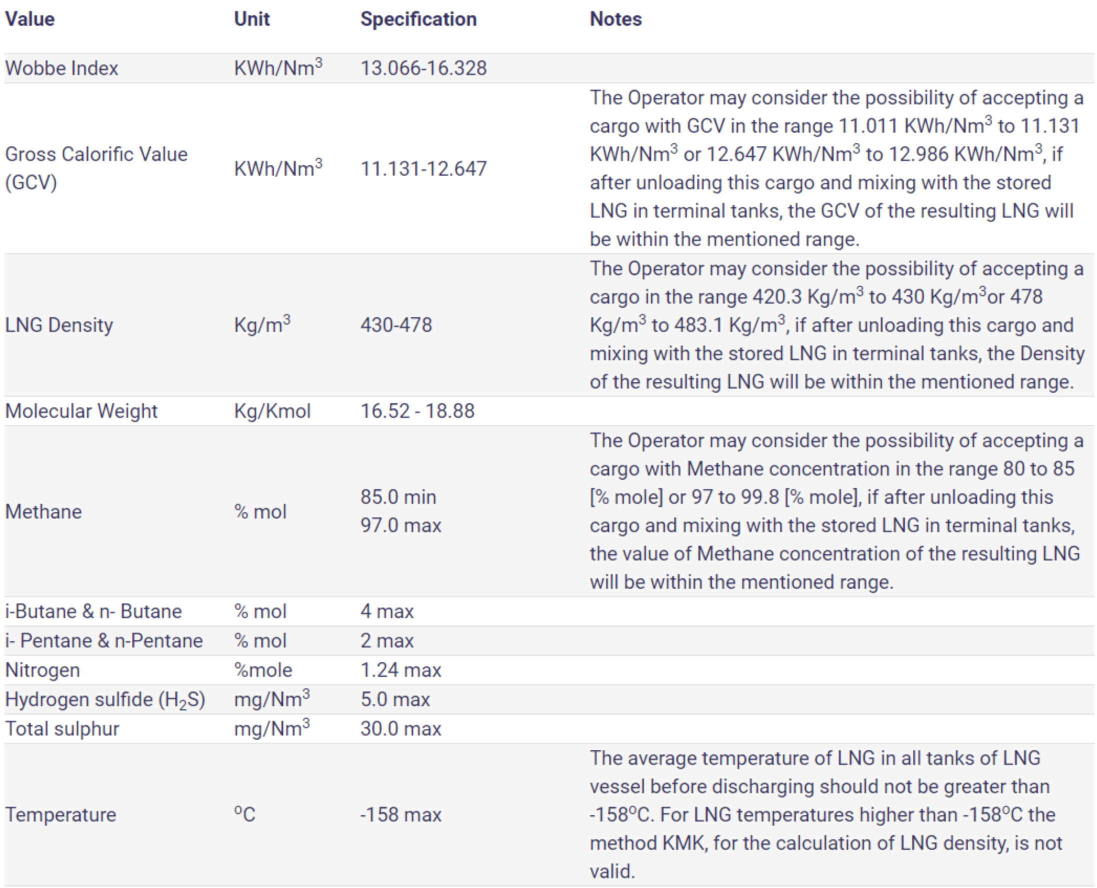
Products of crude oil extracted at the beginning of the refinement procedure include large – and thus heavier – molecular bonds that are part of less volatile mixtures with high viscosity, products like that include fuel oil that is used on large diesel marine engines and are considered dirty or else, non-pure type of fuel. On the other side of the spectrum as the refinement procedure goes on lighter molecular bonds make up most of the mixture resulting in fuels that are of very low viscosity and mainly gas in normal atmospheric temperature and pressure making them highly volatile and easily ignitable, these are considered pure fuels (Seo, Oh, & Lee, 2000).

Heavier fuel types originating from the original stages of distillation have higher concentration of sulfur. Sulfur during combustion reacts with oxygen and creates sulfur dioxide. This substance if exposed to it sort-term causes irritation to the eyes and respiratory tract causing coughing and increasing mucus production and being exposed long-term will harmful for the respiratory system of living organisms making them more susceptible to infections. In addition to that, sulfur dioxide is acidic, making it one of the main contributors of acidic rain which is known to cause a variety of problems (Singh & Agrawal, 2006). Whom of which are ranging from its negative effects of dissolving nutrients needed for the healthy development of flora to damaging human infrastructure by eroding it.

Purer fuels ranging from lighter to heavier are natural gas consisting mostly of hydrocarbons of lighter molecular weight, methane and ethane – CH_4 and C_2H_6 respectively – and petroleum gas consisting from heavier hydrocarbon molecular bonds of propane and butane – C_3H_8 and C_4H_{10} respectively (Foss, Introduction to LNG, 2012). These fuels being byproducts of later stages of distillation means that any heavier particles and molecular bonds are non-existent as they have already been extracted during the earlier stages. This makes them “cleaner” fuels meaning during the combustion process all is generated is carbon dioxide and water vapor. Carbon dioxide (CO_2) although being the main contributor to the greenhouse effect, it isn’t toxic to the living organisms as it is already a byproduct of the natural breathing function, inhaling oxygen and releasing carbon dioxide. There is a caveat to that though, having a rich fuel mixture combined with low combustion temperatures can lead to incomplete combustion creating carbon monoxide which can be toxic for living organisms. This effect though is much more manageable and environmentally friendly making liquid natural and petroleum gas (LNG and LPG respectively) much better choices moving forward.

In today’s world due to the constant push for less emissions and decarbonization we are seeing all the more and more use of lighter fuels of higher distillation, as mentioned above. Especially smaller vehicles, mainly cars, light track and even public transport vehicles are starting to see extensive use of LNG and LPG. Even power plants, which during the past were almost dependent on coal for electricity production have seen their energy source replaced by natural gas or by renewable sources.

It is important to note that we live through a transitional era. In order to decrease GHG (Green House Gases) we use natural gas – a cleaner fuel compared to other carbon-based fuels, while searching other more sustainable energy sources. Sources that are sustainable environmentally, practically and economically. As it will be described in the following chapter, when trying to transport natural gas by tanks, the most efficient way to do it is to cool it down to cryogenic temperatures in order to decrease its density and by extension its volume. When maritime transport is conserved, according to DESFA website (DEFSA website), based on the quality of the LNG its specifications are as shown below:



Value	Unit	Specification	Notes
Wobbe Index	KWh/Nm^3	13.066-16.328	
Gross Calorific Value (GCV)	KWh/Nm^3	11.131-12.647	The Operator may consider the possibility of accepting a cargo with GCV in the range 11.011 KWh/Nm^3 to 11.131 KWh/Nm^3 or 12.647 KWh/Nm^3 to 12.986 KWh/Nm^3, if after unloading this cargo and mixing with the stored LNG in terminal tanks, the GCV of the resulting LNG will be within the mentioned range.
LNG Density	Kg/m^3	430-478	The Operator may consider the possibility of accepting a cargo in the range 420.3 Kg/m^3 to 430 Kg/m^{3}or 478 Kg/m^3 to 483.1 Kg/m^3, if after unloading this cargo and mixing with the stored LNG in terminal tanks, the Density of the resulting LNG will be within the mentioned range.
Molecular Weight	Kg/Kmol	16.52 - 18.88	
Methane	% mol	85.0 min 97.0 max	The Operator may consider the possibility of accepting a cargo with Methane concentration in the range 80 to 85 [% mole] or 97 to 99.8 [% mole], if after unloading this cargo and mixing with the stored LNG in terminal tanks, the value of Methane concentration of the resulting LNG will be within the mentioned range.
i-Butane & n- Butane	% mol	4 max	
i- Pentane & n-Pentane	% mol	2 max	
Nitrogen	%mole	1.24 max	
Hydrogen sulfide (H_2S)	mg/Nm^3	5.0 max	
Total sulphur	mg/Nm^3	30.0 max	
Temperature	°C	-158 max	The average temperature of LNG in all tanks of LNG vessel before discharging should not be greater than -158°C. For LNG temperatures higher than -158°C the method KMK, for the calculation of LNG density, is not valid.

Table 1.1: LNG categorized based on quality

[https://www.desfa.gr/en/regulated-services/lng/users-information-lng/quality-specifications]

For the purpose of this thesis, we will assume LNG density on atmospheric pressure is the average between the two values: 430 to 478 [kg/m^3] meaning its 454 [kg/m^3].

2.3. Natural gas supply chain

LNG chain of supply consists of 4 stages, each one of them revolving around natural gas' state. First on being the search and discovery of gas reserves – natural gas is still unfound. Second stage is natural gas extraction, refinement and liquification, third stage is transportation – liquid in cryogenic temperatures – and fourth and final stage is regasification once the gas is offloaded in the final destination terminal to be delivered to the consumer, power plant etc.

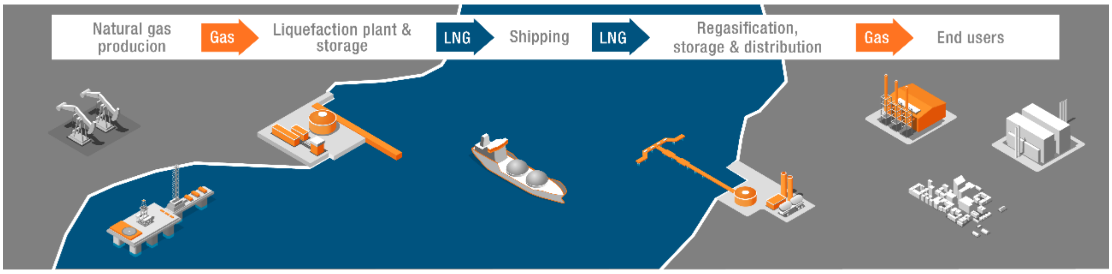
Starting from the search and extraction of natural gas, scientists and petroleum engineers during the last couple of decades have come up with advanced ways when it comes to searching, estimating and pinpointing natural gas reserves.

During the exploration of earth's crust and extraction stage of LNG supply, technologies like seismic imaging are the leading ones in this department. By sending seismic waves we can extract 3D models of earth's crust composition, rock formations and possible void spaces containing natural gas. After the potential finding of a void space containing natural gas, the quality of it is estimated and drilling tests begin. Samples are examined evaluating the gas' composition and by extension, its quality.

In the event the reserve is below the sea's surface and after the drill finishes with opening up the gas reserve's well, the reservoir is sealed with cement and special equipment containing non-return valve installations that prevent leakage into the surrounding environment. Later on, a connection between the well's non returns safety valve and the surface is established. The gas extracted from the reserve goes through a preliminary cleanup when passing through the oil rig located above the well, removing any large contaminants. It is then transported on shore using piping, these pipes lead the natural gas – possibly contaminated with water, dirt, impurities etc. – into the refinery. This is where the largest portion of the refinement and filtration happens, after which the gas passes through a variety of cooling circles in order to be stored and transported through various methods. It is of upmost importance the natural gas is clean of impurities, water, dirt or any other contaminants as cooling it into cryogenic temperatures with such foreign matter in it can cause damage to the equipment and machinery containing the LNG during its different stages of transportation.

After cooling the natural gas into cryogenic temperatures (below -150°C), specifically -160°C, the volume the gas takes up is reduced by 600 times (Placeholder1). Then it can be loaded into LNG ships in liquid form, greatly improving its transfer efficiency as its density is much higher. Through the years LNG carrier sizes have increased as scale economy phenomenon has shown bigger ships have better freight rates – unit of cargo per unit of price has increased. More regarding LNG transport will be analyzed in the following Chapter 2.4.

Following offloading at the destination terminal, the LNG is heated controllably through various heat exchangers using sea water or in some cases heated water. After regasification, natural gas is fed into the system for final transportation to the destination.



Picture 1.2: LNG supply chain

[https://cdn.Wärtsilä.com/images/default-source/twentyfour7/in-detail/lng-value-chain-optimisation-02.png?sfvrsn=9e788f45_0]

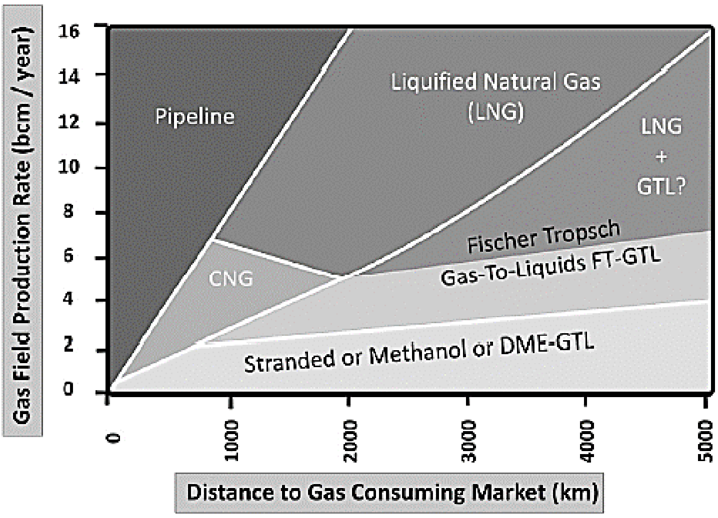


Figure 1.4: Gas transportation based on production and distance to consume

[https://www.researchgate.net/figure/Comparison-of-NG-transportation-methods-depending-on-the-volume-of-produced-gas-and-the_fig2_351911039/actions#reference]

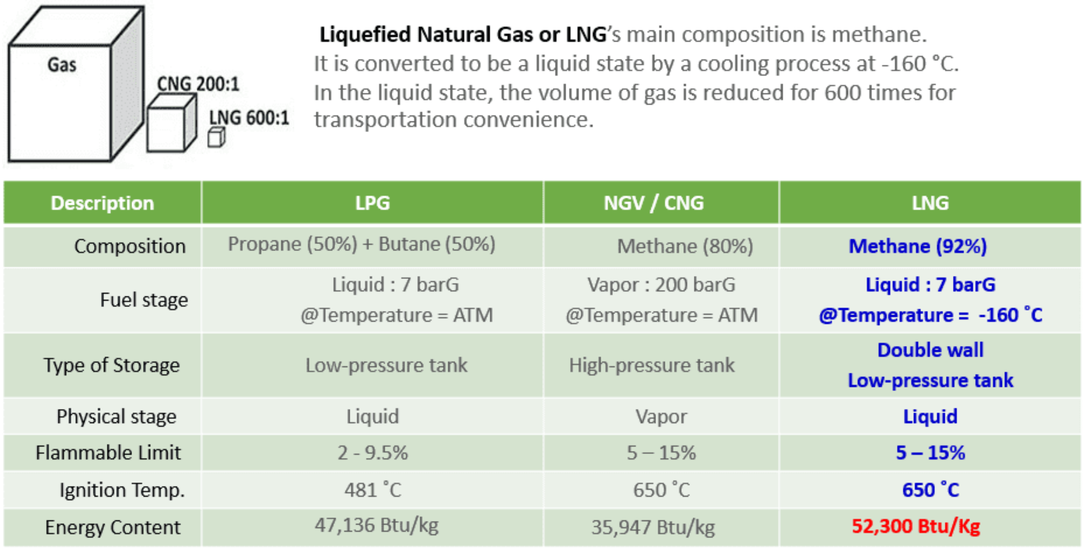
2.4. Transportation of natural gas

Natural gas, like the majority of things meant to be consumed by the general population, is most of the times produced far away from the place in which it will eventually be used. This unavoidably created a need for a network of gathering, transferring then distributing the product across the consumers and just as every other product, this whole process is accompanied with its set of complications.

First of all, the need of natural gas isn't constant in relation to time, neither is its rate of extraction and therefore, production. That makes it necessary to create some kind of storage of natural gas in order to act as a buffer, always having some kind of reserve even when need is high and production is low.

The ways we store natural gas though are limited, yet temperature, pressure and state of the fuel can vary and different methods can be used for different circumstances. Natural gas can be stored in atmospheric pressure and temperature by placing it inside underground sealed spaces such as empty oil and gas wells (Bakar & Ali, 2010, Chapter 2.4., second paragraph) for future use. Alternatively it can be compressed and stored at atmospheric temperature at 200 bar in containers able to withstand that high of a pressure. The natural gas in this state is called CNG (compressed natural gas).

A more space efficient way of storing the natural gas is by making it stop being a gas, according to the equation of state of thermodynamics in order to decrease a gas volume you either compress it or cool it, in our case we do both, by passing the natural gas through different cooling and compression cycles it is cooled into cryogenic temperatures, at -162℃ it converts to liquid natural gas, or else LNG. This method is economically viable when trying to transport large quantities of LNG using ships in ranges exceding 4000km. (Bahgat, 2015)



Liquefied Natural Gas or LNG's main composition is methane.
It is converted to be a liquid state by a cooling process at -160 °C.
In the liquid state, the volume of gas is reduced for 600 times for transportation convenience.

Description	LPG	NGV / CNG	LNG
Composition	Propane (50%) + Butane (50%)	Methane (80%)	**Methane (92%)**
Fuel stage	Liquid : 7 barG @Temperature = ATM	Vapor : 200 barG @Temperature = ATM	**Liquid : 7 barG** **@Temperature = -160 ˚C**
Type of Storage	Low-pressure tank	High-pressure tank	**Double wall** **Low-pressure tank**
Physical stage	Liquid	Vapor	**Liquid**
Flammable Limit	2 - 9.5%	5 – 15%	**5 – 15%**
Ignition Temp.	481 ˚C	650 ˚C	**650 ˚C**
Energy Content	47,136 Btu/kg	35,947 Btu/kg	**52,300 Btu/Kg**

Table 1.2: LPG - CNG - LNG characteristics

[https://www.ngesth.com/knowledge-what-is-lng/]

A combination of the previous two methods of storage (CNG and LNG) leads to PLNG or else pressurised liquid natural gas. By cooling the gas close to – 110℃ the density of it can be reduced enough to be stored at relativelly small volume and pressure of 17 bar, compared to 200 bar of CNG storage. (Bahgat, 2015)

Natural gas is supplied to the gathering part of the pipeline either by offshore linking point to ships or straight from the extraction point. After that, running down the line the gathering parts meet up and pass through proccessing just as crude oil does in a refinery. The natural gas is then passed through compressors in order to force it to move through large diameter pipes which are used to deliver it to key points inland – across cities and countries – straight to areas of high demand and consumption, like power plants and large cities. Then the distributing part of the pipeline comes into play splitting the large pipeline into smaller ones intended to supply each consumer according to their demand. All along the way the pressure inside the pipeline is dropping due to friction with the pipe walls – also known as fluid head loss – so compressors are placed along the way to keep the gas under compression and moving.

An alternative way some countries without the pipeline infrastructure choose to deliver the gas is by trucks. Once the LNG ship unloads the gas into the tanks it can be stored and kept in a liquid state until its loaded – again in liquid state – into trucks to be delivered inland. In exemption to the pipeline transfer, natural gas is always kept in a liquid state so constant cooling needs to occur in order to keep the temperature from rising resulting in higher pressure inside the tanks which could lead to the tank erupting.

In the boundaries of this thesis though, we will focus our attention to the complications the method of liquefying natural gas can arise. As transport of the LNG accounts for a great portion of the expenses included until the final delivery to the consumer and therefore its price, it is essential we try to minimize possible loses as much as possible.

3. Chapter 3: LNG Storage, BOG management and calculation

3.1. Tank structure, characteristics and insulation

Through the years numerous tank designs have emerged, ranging from different type of configuration, shape, supporting structure and materials used for insulation. LNGC are also categorized based on their tank types including (Shafran, 2023):

- Membrane type (prismatic shaped)
- Moss type (spherical shaped)
- Self-Supporting prismatic type
- Semi-membrane type

Moss and self-supporting type of tanks have great carry capacitates but they are not as safe and leak prof as membrane type tanks. The membrane type is the prevailing tank type due to its insulation efficiency, durability, ease of maintenance and safety regarding cargo leaks.

Semi-membrane tanks are on the rise the last few years as they combine the benefits of all tank types mentioned above, notable benefits being that they are safe and take advantage of the ships internal structure in the most efficient way. Tanks designs included in the aforementioned tank types include (Omholt-Jensen, 2020):

- TGZ Mk III (membrane type – LNG)
- GT96 (membrane type – LNG)
- CS1 (combination of TGZ Mk III and GT96 tanks – LNG)
- IHI (Self-supporting prismatic type – LNG)
- LTN A-BOX (Self-supporting prismatic type – LNG)
- Cylindrical (natural gas is stored in compressed gas state – CNG)
- C type (Also called bilobed – CNG)

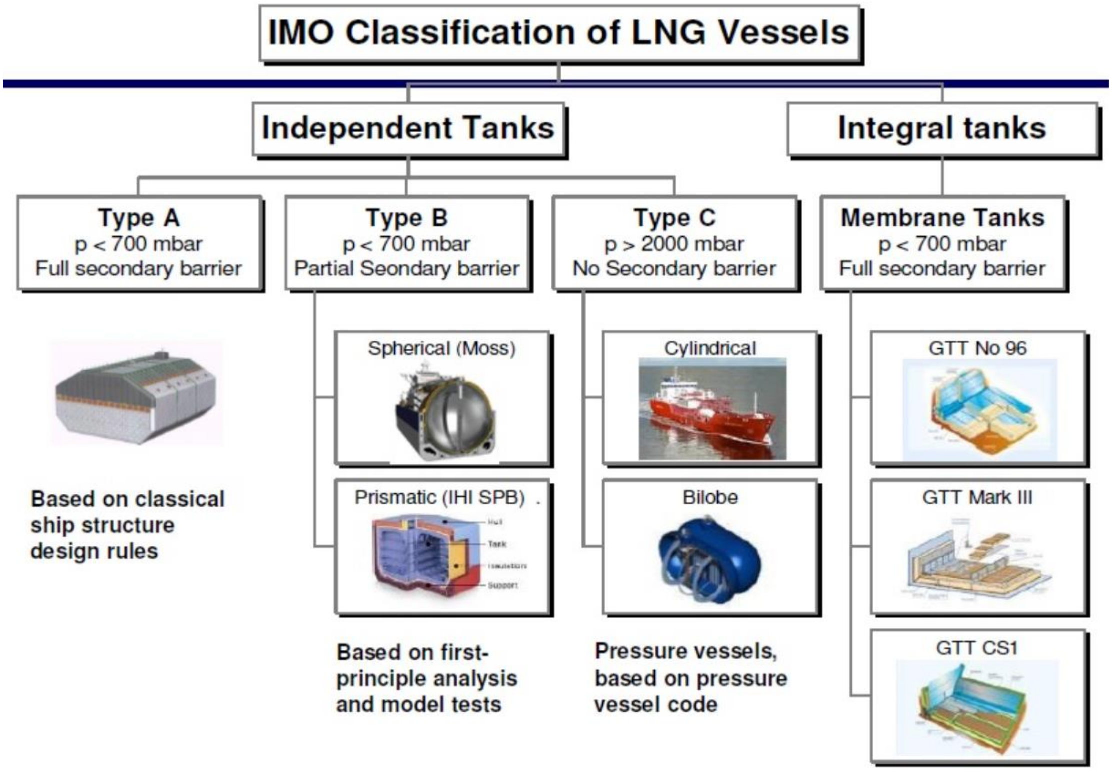
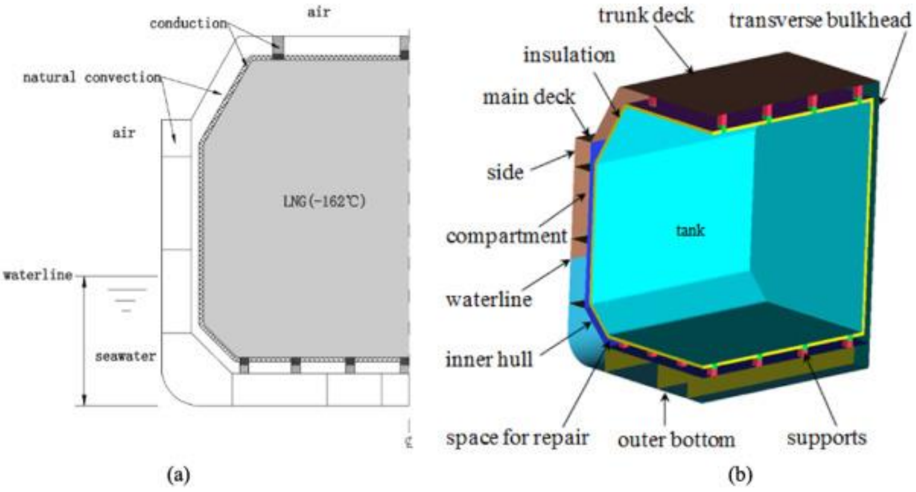


Figure 3.1: IMO classification of LNG vessels

[http://liquefiedgascarrier.com/LNG-vessel-construction.html]

Each of the aforementioned tank designs come with their advantages and disadvantages, which are not going to be discussed in detail as it is not the primary objective of this thesis. Though this thesis' following chapters will need us to focus on a couple of specific tank designs due to their wide use and popularity. These tank designs include integral membrane tanks (Mk III and CS1). Throughout the years these two designs have proven superior to others. What you see below is a general overview of membranes tank internal structure, including its insulation and heat transfer fundamentals.



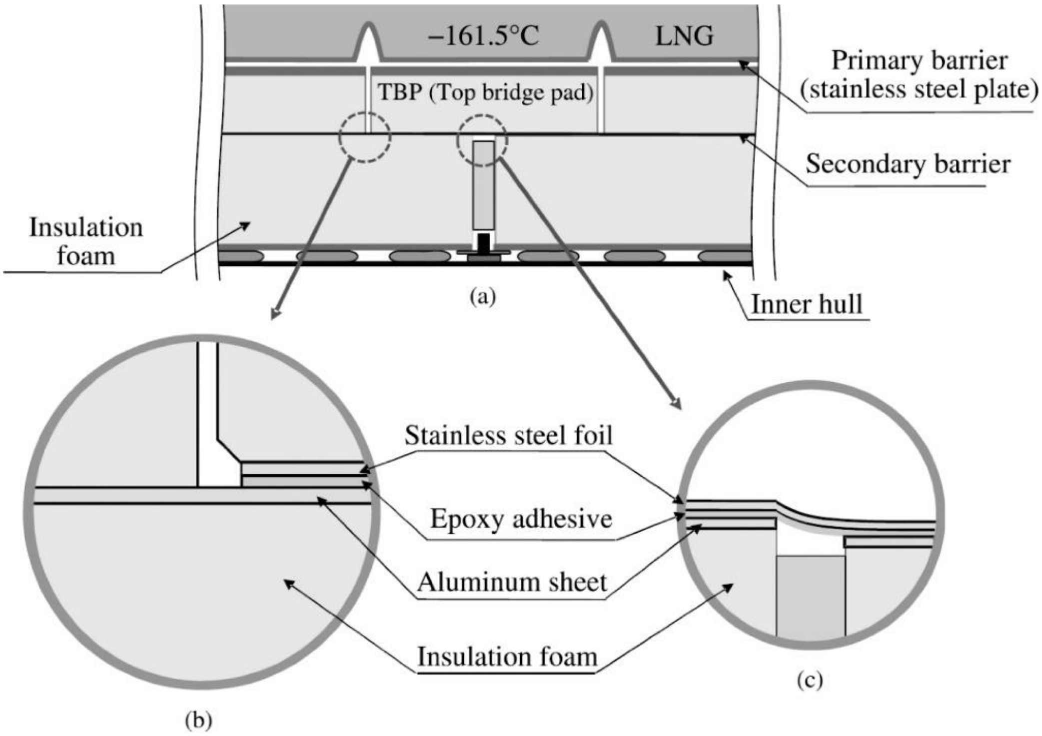
Picture 3.1: (a) Cross section of a typical LNG carrier (b) 3D model of LNG tank.

[https://www.sciencedirect.com/science/article/pii/S0029801817303694]

As you can see there is a first layer of a rigid metal alloy structure (usually stainless steel) that contains the cooled LNG. This layer is designed specifically to sustain its mechanical properties when exposed to low cryogenic temperatures, taking in mind phenomena such as embrittlement / brittle fracture and the fact that the whole ship structure is dynamic and bound to bend and flex under its weight and buoyancy distribution when seagoing. The tanks themselves experience those loads too and they need to be able to bend without risk of embrittlement.

One can consider the first layer of insulation the inside tank structure mentioned above, at least thermodynamically that is. The second layer of insulation is “sandwiched” air. The inside tank containing the LNG is encapsuled by an outside shell so a pocket of air is trapped between them acting as an insulator eliminating the heat transfer trough conduction and taking advantage the heat transfer through convection and rationing where their heat transfer coefficients are much lower.

Following the air gap, the insulation foam comes into play taking advantage of small conduction heat transfer coefficient and porous material, further mitigating heat transfer by introducing convention too. The foam itself is contained withing an aluminum structure separated from the steel structure by epoxy adhesive as otherwise galvanic corrosion would occur between the two. After the foam layer the inner hull ship’s steel structure encapsulates all the mentioned above. The rest of the structure resembles a tanker vessel’s double hull structure designed specifically for redundancy and environmental safety by preventing spills in case of a collision. A cross-sectional area of all the layers mentioned can be observed below.



Picture 3.2: Schematic diagrams of the LNG cargo containment system.

(a) overall drawing, (b) enlarged view of the corner of the top bridge pad, and (c) insulation panels with level difference

[https://pubs.acs.org/doi/pdf/10.1021/ef500626u]

3.2. Boil-off gas phenomenon and problems caused

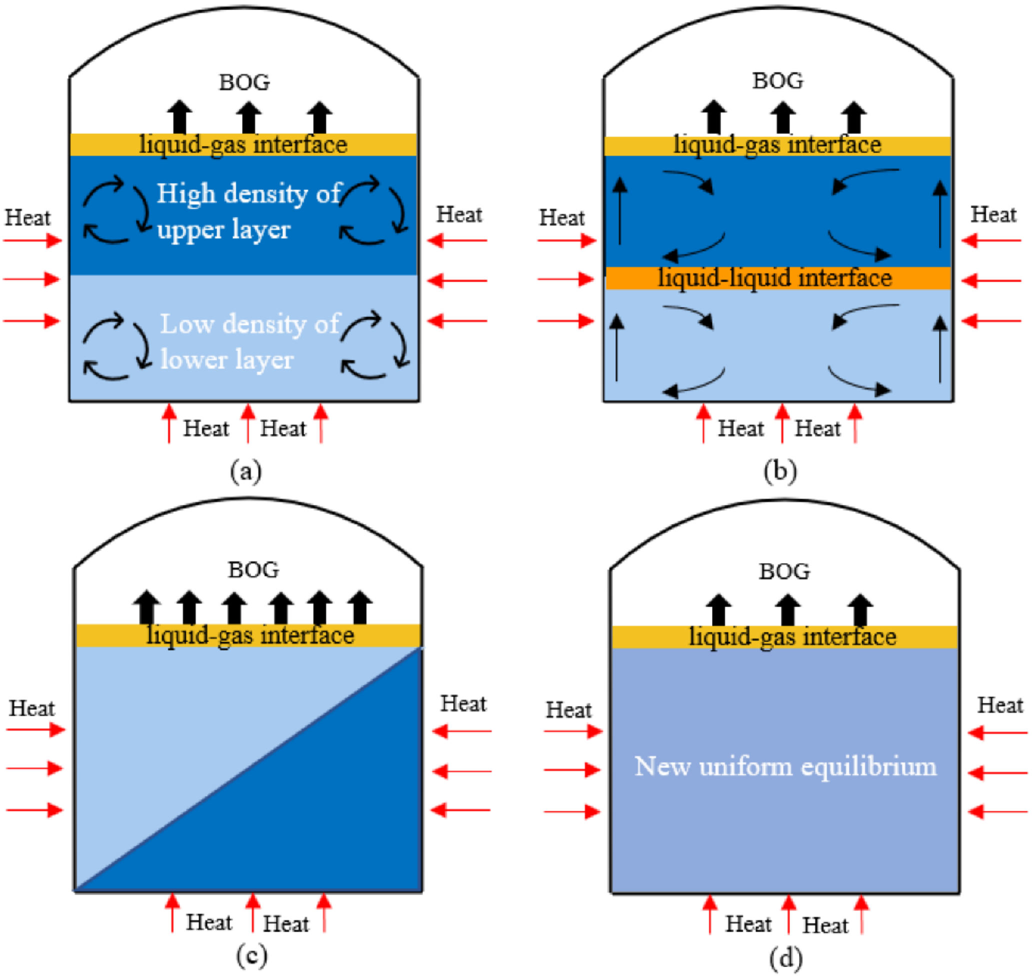
The boiling point of natural gas, in atmospheric pressure is -162℃. Due to the low boiling point of natural gas, it is extremely prone to evaporation especially when considering the surrounding is almost 200℃ higher. This is why the insulation efficiency is crucial to ensure as little heat as possible is transferred into the system. Reasons this evaporation happens though can be attributed to other sources too, as will be examined during the following paragraphs.

First source of heat transfer, as mentioned above, is directly through the higher temperature environment. As mentioned earlier, membrane tanks are the most widely used. The container acts like a barrier with various insulating layers described in Chapter 3.1, carefully placed pockets of air and materials all working in tandem with the goal of separating the gas from its surroundings both physically and thermodynamically. Of course, this insulation cannot be ideal/perfect and unavoidably heat is transferred through conduction, convection and radiation.

The second way thermal energy is introduced to the system is actually in the form of kinetic energy converted into heat which then is absorbed by the cooler natural gas.

- Kinetic energy is introduced to the system by the pumps used to move the LNG causing friction while the liquid is moving through the piping.
- Kinetic energy can also be introduced in the system by the movement of the tank, causing the liquid inside to experience sloshing. For example, in the case of an LNG carrier going rough weather causing it to roll from side to side.
- Heat and kinetic energy can even be generated by the natural movement because of the temperature differential inside the volume of the liquid gas.

Lastly, liquid gas near the edges of the container is the first to be heated due to it being closer to the surface of where heat transfer can occur, this causes a temperature increase in the liquid leading to it moving towards the top, new cooler liquid is then moved to replace it. This phenomenon continues causing constant movement and circulation to the system further contributing to excess heat and kinetic energy entering the system until it reaches an equilibrium.



Picture 3.3: LNG stratification and rollover mechanism in the storage tank.

(a) LNG stratification; (b) LNG interlayer penetration; (c) LNG rollover; (d) the new uniform equilibrium in temperature and density.

[https://www.mdpi.com/2227-9717/10/7/1360]

The natural gas is trying to achieve thermodynamic equilibrium, also known as VLE (Vapor-Liquid Equilibrium). The liquid starts heating up, evaporating and raising the pressure inside the tank. This is extremely hazardous as left uncontrolled the tank will eventually explode. There are however ways to prevent that, two of whom are to keep cooling the natural gas to cryogenic temperatures or release the excess gas in order to relieve the tank's pressure. Both lead to losses, in the former we need to spend energy in order to keep the temperature and pressure down and in the latter, we waste the natural gas, the ship's cargo by letting it escape. After the excess gas is relieved, it is ignited safely in a burner, used as fuel or reliquefied and pumped back in.

When BOG is generated, it causes a phenomenon called LNG ageing. Due to the inhomogeneous nature of the natural gas, different components have different properties such us their boiling point and heating value. This means lighter and more volatile components evaporate first altering the contents of the remaining LNG. High Heating Value (HHV), Lower Heating Value (LHV) as well as liquid density are all affected by the aging. These are important parameters to consider when calculating provided BOG power (Chapter 3.5).

3.3. Boil-off gas management onboard LNG ships

As briefly touched in the previous chapter boil-off gas is unavoidable and needs to be taken care of. There are numerous ways BOG gas can be handled, in the following paragraphs we will analyze ways of treatment of the BOG onboard LNG ships. One solution is to burn the excess gas as fuel, the second one is controlled ignition and release into the atmosphere (environmental restrictions/waste of cargo – no longer in use) and the third is reliquefying it and storing it back.

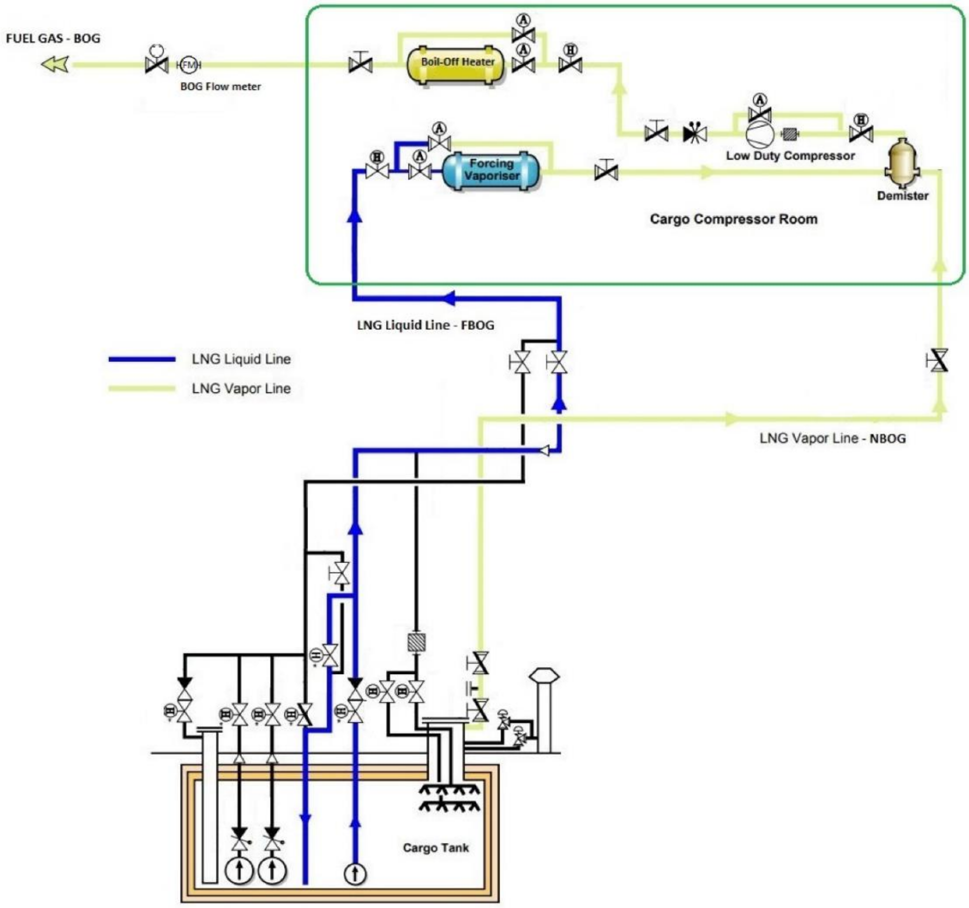
3.3.1. Using BOG as fuel

First management method is using BOG as fuel. This has been one of the first ways to manage the BOG as it required little extra equipment. The gas is collected and compressed in order to raise its pressure and temperature. After this step the BOG is routed to machinery in order to remove impurities and create a homogenous mixture suitable for ignition in the engine. During the early days of LNG shipping the majority of the propulsion plants consisted of boiler and steam turbine arrangements. The boiler is very versatile when considering range of fuels and quality of said fuels it can operate on. That was its main advantage, the drawback however was the low thermal efficiency of such plant when compared to DFDE (Dual Fuel Diesel Electric) and TFDE (Triple Fuel Diesel Electric) engines, therefore they quickly overtook ST (Steam Turbines). Deriving from the military industry, gas turbines (GT) were also used as they had very high power to weigh ratios and very clean combustion of the gas used to power them. They often came alongside forced BOG generators on board in order to supply a constant quantity of BOG needed. During the last decade tried and trusted large marine 2-stroke engines saw advancements in their fuel injection enabling gas injection along with HFO operation and every other fuel in between. The gas itself can be injected directly in the scavenging air or while the piston is on the compression stroke. All available propulsion plants mentioned above, along with a couple more, will be examined during the Chapter 4.

As briefly mentioned earlier, there are instances in which the natural BOG quantity is not enough to meet the vessel’s demands. In this occasion, the required fuel quantity is extracted from the LNG tanks, forced vaporized, heated and then supplied to the engines. The system, piping and machinery, required for the process can be seen in the next page.

Practically an LNGC operates in the following scenarios:

- If the BOG natural production is low and LNG is cheaper versus the alternative fuels, then the ship will force produce BOG to meet its energy demands.
- If the BOG natural production is low and LNG is more expensive than the alternative fuels (rare occasion), then the ship will operate on a mix of LNG mixed with alternative fuels.
- If the BOG natural production is high then the vessel will fully take advantage of the BOG and ignite/release the rest.
- If the vessel is big enough and a reliquefaction plant is economically valuable, then the vessel always reliquefies excess BOG.



Picture 3.4: Forced BOG and supply system used in LNGC

[https://www.mdpi.com/2077-1312/11/10/1980]

3.3.2. Using BOG in the CGU

Moving into the second and least efficient way of managing BOG, is using it in the GCU (gas combustion unit). Excess BOG can be used in a burner in order to create hot steam for use inside the ship, the exhaust gases can then be released into the atmosphere. However, there are environmental restriction which prohibit the release of such gases, resulting in venting the BOG as is. This method is the last resort as doing so means you waste precious cargo, and most importantly energy that could have been used elsewhere. This method used to be implemented during the early days of LNG marine transport.

3.3.3. Reliquefying the BOG

Lastly, reliquefying the generated BOG is also a viable option apart from burning it as fuel and certainly better than venting it. Reliquefication plants aboard LNG carriers saw use in the 1970s with more advanced and more energy efficient installations being developed ever since. This process is based upon the Brayton Cycle, the excess gas is collected and compressed up to 6bar. After the compression stage the compressed gas is passed through a fin plate heat exchanger. There, nitrogen is used to cool the BOG to about -110°C. The nitrogen itself is cooled down to -180°C, this is achieved by compressing it and cooling it using seawater in a shell and tube heat exchanger during several stages.

3.4. Factors affecting BOG production rate

Factors affecting boil of rates are numerous and if combined can cause even more BOG production than the sum of each individual factor combined. It is crucial these factors are taken into account when trying to calculate BOG rate of production and therefore decide which is the best possible way of treatment for each specific occasion.

Factors affecting BOG production include:

- External factors (ambient temperature, pressure, sloshing)
- Storage tank properties (size, shape, insulation)
- Distance travelled and therefore elapsed time

All of the mentioned above contribute, each with its own way, into increasing BOG production. External factors can't be directly eliminated and cause energy leakage into the system. This happens from high ambient temperatures directly transferring thermal energy into the liquid. In addition to that, unwanted movement of the liquid, so called sloshing, can happen just by the very nature of transferring LNG in a ship that constantly moves/rolls/pitches, especially in the case of rough seas. The movement causes kinetic energy to be transferred into the liquid and converted into heat. To add to that, sloshing causes the surface to volume ratio of the liquid to increase therefore promoting extra heat transfer from the surrounding environment air in the tank.

As mentioned in the previous chapters, natural gas can be transported in several different states. Namely natural gas can be transported as:

- Liquified (LNG) at cryogenic temperature
- Pressurized (PLNG) on sub-zero temperatures
- Compressed (CNG) on ambient temperature

LNG is the primary state of transport when maritime transport is concerned. This is because of the increased density making transport much more efficient. Numerus types of tanks designs have emerged through the years each one of them having different characteristics due to their geometry and internal structure and insulation.

Lastly, distance traveled and therefore time elapsed under certain conditions cause the liquid to evaporate. This phenomenon, this evaporation, is called LNG ageing and happens exponentially so having a way to counter this factor is crucial from an economical and practical standpoint. This also means that when dealing with high distance shipping routes it is of high importance to keep boil off rates caused as low as possible to reduce LNG ageing.

3.5. BOG rate and power content calculations

Through the years several different BOG production rate calculation models have been developed. The majority of them make assumptions and simplifications that are acceptable in the realms of preliminary planning. There are whole dedicated research papers each with their own models on BOG calculation. When taking into consideration LNGC carrying capacity [m^3], some models offer accurate results but with limited range of use, while others offer lower accuracy but wider range of use. Given the boundaries of this thesis, we are going to use a method that can give us fast, reliable and much needed results in order to be able to continue further.

3.5.1. BOG power content for a 150000 [m^3] LNGC

The research paper these BOG calculations are based upon is using a MATLAB/Simulink environment by (Dimopoulos & Fragopoulos, 2008) in order to calculate BOG rate of production through a typical journey's timeframe of about 3 weeks. The research establishes the following:

- Starting LNG temperature: – 163°C
- Temperature increase: 0.5 K/day
- Heat transferred into the system: 600kW
- No data on pressure (most probably atmospheric)
- The vessel's cargo capacity: 150000 [m^3]

The rate of BOG evaporation is not constant and due to a phenomenon named LNG ageing process. The LNG is composed by different substances including Methane, Ethena, Propane, Butane and Nitrogen. The lighter and more volatile components, such as nitrogen, evaporate first and basically inflate the BOG rate, while the rest of the heavier substances, such as methane, start evaporating later down the journey. What that translates into is a convex curve representing the natural boil off rate of the LNG, with the minimum point of it being somewhere around the 7th to 8th day mark.

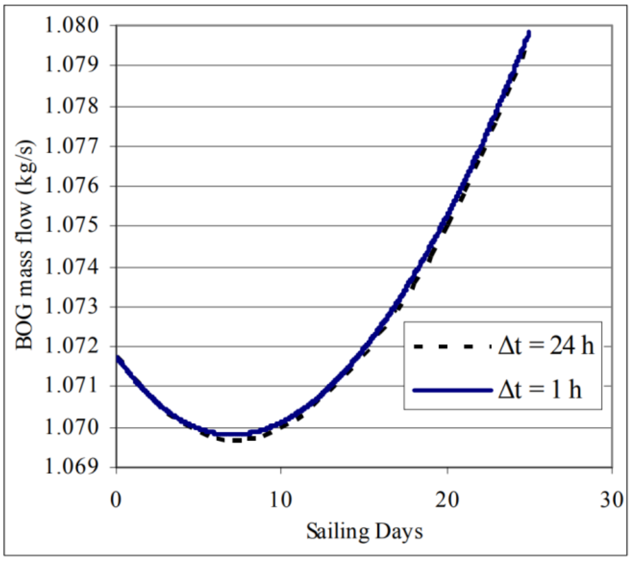


Figure 3.2: Natural BOG mass flow in relation to Sailing Days

[https://dergipark.org.tr/tr/download/article-file/65734]

There are instances however where the ship may force produce BOG in order to meet its energy demands. According to the research paper (Dimopoulos & Fragopoulos, 2008) the diagram of the forced BOG mass flow rate is the following:

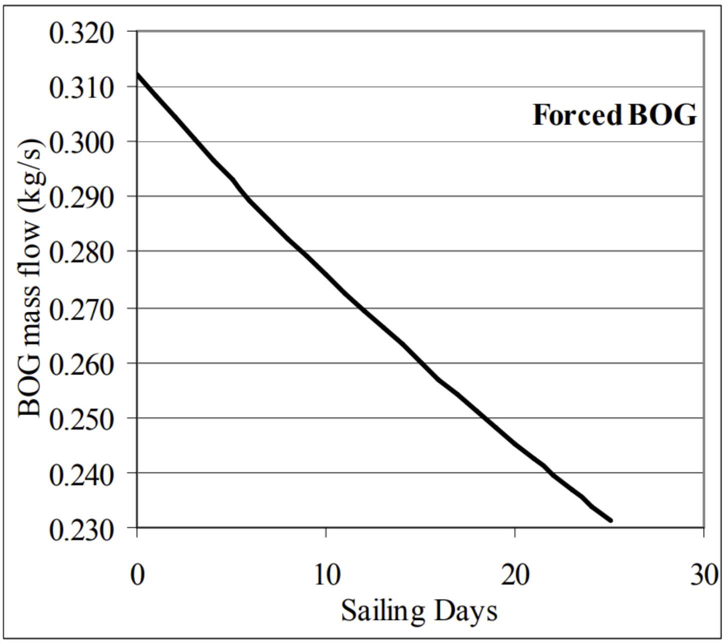


Figure 3.3: Forced BOG mass flow rate in relation to Sailing Days

[https://dergipark.org.tr/tr/download/article-file/65734]

The forced BOG production is regulated in a way which results in the total BOG mass flow reducing as the journey days pass. Summing the Y axis values of previous two figures (natural and forced BOG) results in the total BOG mass flow rate in relation to journey time is as follows:

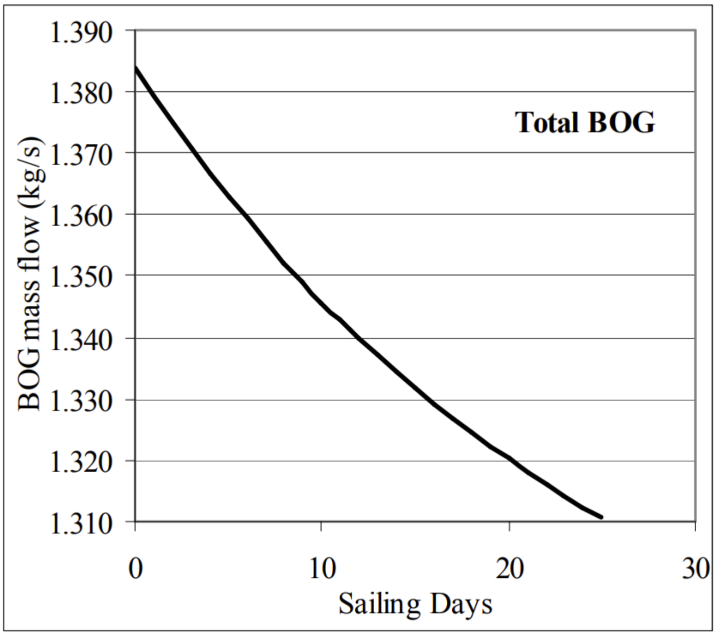


Figure 3.4: Total BOG mass flow rate in relation to Sailing Days

[https://dergipark.org.tr/tr/download/article-file/65734]

Another result of the LNG ageing process mentioned earlier is the increase of its LHV (Lower Heating Value) through the days. This happens because the substances that evaporate first happen to be less energy dense, this translates to lower values of the BOG's LHV at the start of the journey and higher during the last days of the journey, as the LNG ages. The research paper's (Dimopoulos & Fragopoulos, 2008) BOG's LHV variation trough the journey diagram can be seen below:

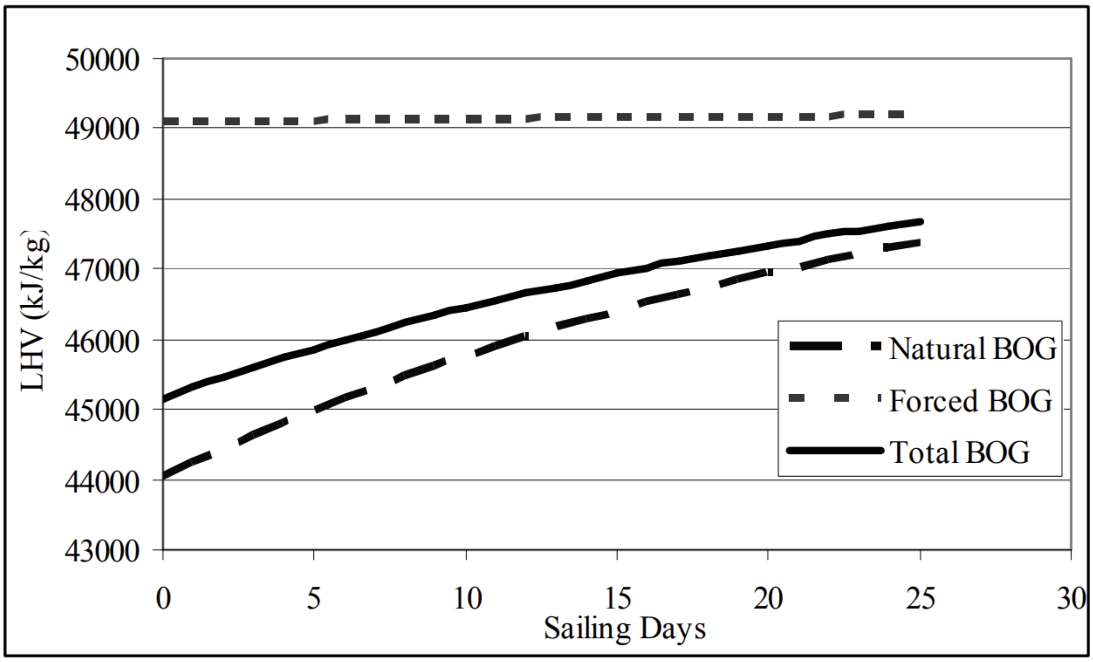


Figure 3.5: Figure of LHV in relation to Sailing Days

[https://dergipark.org.tr/tr/download/article-file/65734]

Using the Engauge Digitizer program [https://markummitchell.github.io/engauge-digitizer/] we can extract values from the previous diagrams regarding BOG mass rates, volume, LHV in relation to vessel Sailing Days. Using that data, we will be able to calculate the power the BOG can provide. It is important to note that these calculations are based off assumptions and simplifications. The results are representative of the real-life values but in no way can they be 100% accurate. The values are categorized based upon the natural BOG generation during the trip, the forced BOG that is deliberately produced from the LNG in order to meet the ship power demands and lastly the sum of the previous two.

	BOG MASS FLOW			BOG LHV (Lower Heat Value)			BOG POWER POTENTIAL		
	NATURAL	FORCED	TOTAL	NATURAL	FORCED	TOTAL	NATURAL	FORCED	TOTAL
JOURNEY DAYS	MASS FLOW (kg/s)	MASS FLOW (kg/s)	MASS FLOW (kg/s)	kJ/kg	kJ/kg	kJ/kg	Power kJ/s (kW)	Power kJ/s (kW)	Power kJ/s (kW)
0	1.071	0.312	1.384	44041	49112	45146	47167	15316	62464
1	1.071	0.308	1.379	44237	49124	45337	47378	15142	62535
2	1.070	0.305	1.375	44434	49133	45475	47545	14964	62536
3	1.070	0.301	1.371	44633	49132	45602	47757	14771	62523
4	1.070	0.297	1.367	44829	49123	45740	47967	14582	62524
5	1.069	0.293	1.363	45016	49111	45874	48122	14405	62535
6	1.069	0.289	1.360	45178	49160	45997	48295	14215	62535
7	1.069	0.286	1.356	45329	49157	46119	48457	14041	62524
8	1.069	0.282	1.352	45480	49158	46248	48618	13873	62522
9	1.069	0.279	1.349	45632	49163	46375	48781	13729	62553
10	1.070	0.276	1.346	45791	49164	46481	48996	13563	62541
11	1.070	0.272	1.343	45938	49154	46564	49154	13388	62524
12	1.070	0.270	1.340	46062	49167	46652	49286	13254	62502
13	1.071	0.266	1.337	46198	49217	46754	49478	13108	62517
14	1.071	0.263	1.334	46305	49208	46861	49592	12962	62532
15	1.071	0.260	1.332	46432	49204	46940	49729	12793	62509
16	1.072	0.257	1.329	46568	49190	47024	49921	12643	62506
17	1.073	0.254	1.327	46647	49187	47143	50052	12496	62556
18	1.073	0.251	1.324	46744	49194	47212	50157	12354	62526
19	1.074	0.248	1.322	46871	49191	47270	50339	12205	62505
20	1.075	0.245	1.321	46967	49175	47348	50490	12060	62526
21	1.076	0.243	1.318	47046	49161	47409	50622	11932	62502
22	1.076	0.240	1.316	47150	49190	47549	50733	11795	62579
23	1.077	0.237	1.314	47254	49252	47550	50892	11668	62485
24	1.078	0.234	1.312	47342	49241	47642	51034	11527	62509
25	1.079	0.232	1.311	47422	49225	47692	51169	11396	62513

Table 3.1: BOG mass flow, LHV (Lower Heat Value), BOG power content

By multiplying the total BOG mass flow by the LHV we get the power that the BOG can provide in the worst-case scenario. It is clear now on why the forced BOG is regulated in order to keep the total BOG mass flow declining over time, as multiplied by the LHV which increases over time results in a constant power value of about 62500 kJ/s (kW) as can be observed in the rightmost column in the above table.

3.5.2. BOG supply across different LNGC sizes

Due to the following case study of this thesis though, the estimate of provided BOG supply rate is not enough, as its only representative of a 150000 [m^3] capacity vessel. Using another method to calculate BOG supply across different LNGC capacities and cross-referencing them at the 150000 [m^3] will grant the needed results, albeit with lower precision.

According to studies, average natural BOR (Boil off Rate) on newly developed LNGC, equipped with more efficient tank insulation arrangements, ranges from 0.10% to 0.15% of the total vessel's capacity [m^3] per day (Đorđe Dobrota, 2013). The Wärtsilä itself states that BOR skew even closer to 0.10%/day. Given the same 150000 [m^3] capacity LNGC (Chapter 3.5.1) and the 0.10 to 0.15%/day evaporation, results in 150 to 225 [m^3] of BOG per day. Same as before, using the Engauge Digitizer app and extracting data from the research paper's diagram seen below (Dimopoulos & Fragopoulos, 2008), we can do calculations and compare their results to the simplified 0.10 – 0.15% rule.

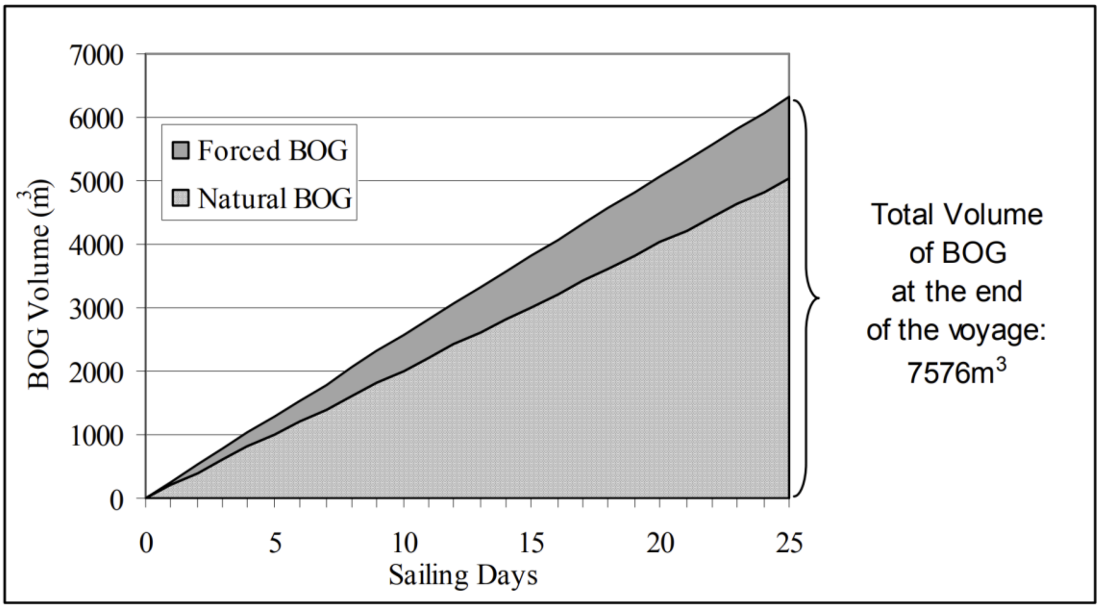


Figure 3.6: Cumulative BOG volume on a 150000 [m^3] LNGC

[https://www.researchgate.net/publication/42539938_A_Dynamic_Model_for_Liquefied_Natural_Gas_Evaporation_During_Marine_Transportation]

After extracting the values for cumulative BOG volume day by day we can easily calculate the daily volume production. Averaging that daily volume production equates to a 201.7 [m^3] daily average. This value is withing the range 150 to 225 [m^3] and thus the simplified way of calculating the natural BOG rate. Although necessary assumptions were made, is suitable for a preliminarily way of calculating BOG production on LNGC similar sized to the 150000 [m^3] carrier used by the research paper (Dimopoulos & Fragopoulos, 2008). In the following page, average BOG daily production calculations can be found.

GENERATED BOG VOLUME			
NATURAL	FORCED	TOTAL	NATURAL
Culmulative Volume (m^3)	Culmulative Volume (m^3)	Culmulative Volume (m^3)	Daily Volume (m^3)
0.0	0.0	0.0	
160.0	99.2	259.2	160.0
391.7	125.3	517.0	231.7
606.5	167.5	774.0	214.8
807.7	221.6	1029.3	201.2
983.5	297.1	1280.6	175.8
1207.6	318.4	1526.0	224.1
1407.7	371.9	1779.6	200.1
1606.9	442.2	2049.1	199.2
1823.6	482.9	2306.5	216.7
1993.9	571.4	2565.3	170.3
2232.6	599.1	2831.7	238.7
2456.5	633.8	3090.3	223.9
2613.5	723.3	3336.8	157.0
2815.2	762.6	3577.8	201.7
3027.1	791.1	3818.2	211.9
3212.7	851.3	4064.0	185.6
3433.6	888.2	4321.8	220.9
3635.4	933.6	4569.0	201.8
3838.6	969.6	4808.2	203.2
4054.3	1003.7	5058.0	215.7
4234.4	1079.6	5314.0	180.1
4434.3	1130.4	5564.7	199.9
4643.3	1174.4	5817.7	209.0
4826.8	1247.4	6074.2	183.5
5041.5	1271.4	6312.9	214.7
AVERAGE BOG PER DAY			**201.7**

Table 3.2: Average natural BOG daily production for the 150000 [m^3] LNGC

At this stage necessary assumptions and simplifications need to be made in order to have a value for the daily average of natural BOG production across different LNGC sizes.

1. Taking into account the 0.10 – 0.15% rule (lower and upper limits) and by considering there is a safety factor built within this range we assume the BOG is not affected dramatically by external factors.
2. Given the vessels size, 150000 [m^3], and the average daily natural production of BOG, 201.7 [m^3], we can find the average BOG production in relation to the total cargo volume: 201.7 / 150000 = 0.00134467 or about 0.134% per day.

The daily natural BOG production (0.10% - 0.15% rule) is calculated based on previous page's aforementioned method. We know the equation is linear, hence we can multiply 0.134% by the cargo capacity in order to find the average BOG production too.

VESSEL CAPACITY [m^3]	DAILY NATURAL BOG PRODUCTION [m^3]		
	LOWER LIMIT 0.100%	UPPER LIMIT 0.150%	AVERAGE 0.134%
125000	125.0	187.5	168.1
130000	130.0	195.0	174.8
135000	135.0	202.5	181.5
140000	140.0	210.0	188.3
145000	145.0	217.5	195.0
150000	150.0	225.0	201.7
155000	155.0	232.5	208.4
160000	160.0	240.0	215.1
165000	165.0	247.5	221.9
170000	170.0	255.0	228.6
175000	175.0	262.5	235.3

Table 3.3: Natural BOG calculations based on LNGC capacity

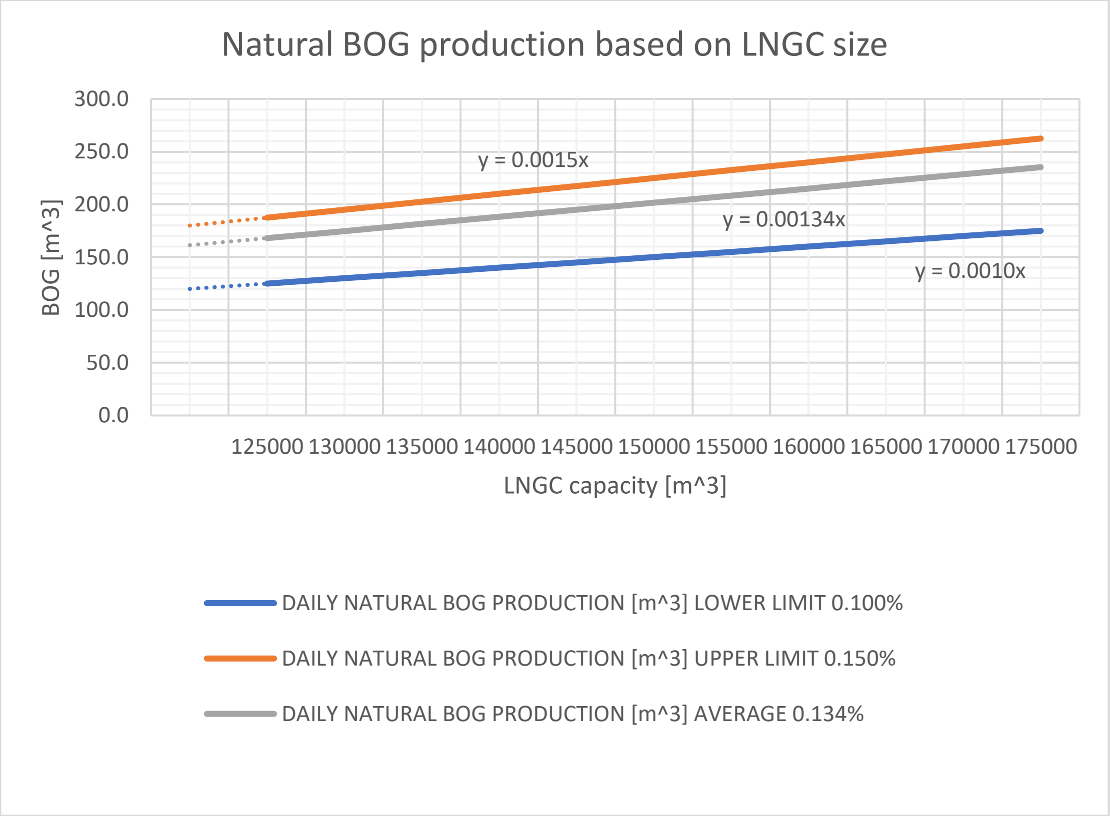


Figure 3.7: Diagram of Natural BOG calculations based on LNGC capacity

Natural occurring BOG usually accounts for the 80 to 90% of the total propulsion plant energy demands on a laden voyage. This percentage drops to 40 to 50% on ballast voyage though (Đorđe Dobrota, 2013). As of now there is no reason to calculate forced BOG values, as that will depend on the size of the case study's vessel.

4. Chapter 4: Parameters leading to case study selection

4.1. Emission regulations

Due to the growing worldwide concern regarding GHG (greenhouse gases) including: carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x) and other particulate emissions (PM) and their effects on global warming, measures to reduce said emissions are becoming ever so stricter. Maritime shipping companies are forced to comply with IMO's (International Maritime Organization) and MARPOL (Marine Pollution) regulations regarding emission restrictions and ECAs (Emission Controlled Areas).

UN (United Nations) have come up with SDGs (Sustainable Development Goals). These include areas where all of us should work towards to, including general human wellbeing, environment preservation and future proofing several aspects of today's world. Many of them are not directly relevant within the boundaries of the current thesis but some of them though are interconnected and some of them are directly linked to this thesis boundaries as they are set directly to combat GHG emissions due to shipping. Notable examples include climate action and life below water goals.

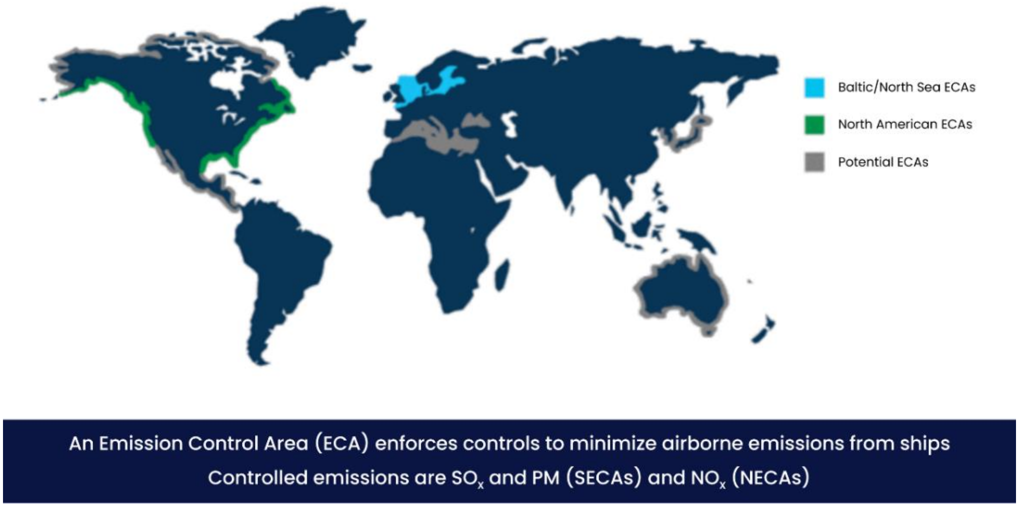
Picture 4.1: Sustainable Development Goals set by UN

[https://sdgs.un.org/goals]

IMO, like many other big organizations are committed to act anyway they can in order to help achieve as many SDGs mentioned above. They can do it is by setting regulations so companies under their influence can follow, which brings us to our point of interest, IGC. Under IMO and SOLAS (Safety of Lives at Sea) influence, IGC is just a convenient acronym that is used to quickly refer to International Code of the Construction and Equipment of Ships Carrying Liquified Gases in Bulk. IGC code entered the SOLAS regulations in 1986 and from then on has been mandatory of all ships carrying liquified gases cargo. Given this thesis parameters we will be focusing ECAs zones. Just for reference, sulfur limits as of 2020 are, according to the official IMO (website):

- 0.10% m/m inside SECAs (Sulfur Emission Control Areas)
- 0.50% m/m outside SECAs

General location of ECAs can be seen below:



An Emission Control Area (ECA) enforces controls to minimize airborne emissions from ships
Controlled emissions are SO_x and PM (SECAs) and NO_x (NECAs)

Picture 4.2: ECAs as of 2023

[https://www.sustainable-ships.org/rules-regulations/eca]

In addition to SECAs, the ECAs also place restrictions to nitrogen oxides:

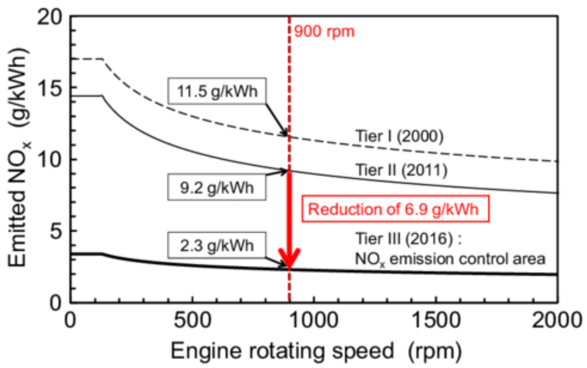


Figure 4.1: Emitted NO_x in relation to engine speed based on IMO tiers

[https://www.researchgate.net/figure/IMO-emission-standards-and-the-required-NO-x-reductions-for-Tiers-I-II-and-III-5_fig4_283776914]

Meaning a ship has three options when operating in ECAs:

1. Burn/operate in lower quality high sulfur fuels (HFO – heavy fuel oil)
2. Operate in higher price low sulfur fuels (MDO – VLSFO - ULSFO)
3. In case on an LNGC, it can operate on LNG (both cheap and low sulfur)

IFO380 classified as HFO (heavy fuel oil) is cheaper and lower quality and usually contains 1.00 – 3.50% Sulfur. It is of lower distillation and so cheaper and more widely accessible across ports when a ship is due to bunkering (refueling process).

Due to the restriction of 0.50% m/m Sulfur the vessels operating in HFO need to be equipped with scrubbers, machinery specifically designed to remove/scrub (hence the name) sulfur oxides from the exhaust gas before releasing them into the atmosphere. The installation of a scrubber is expensive so the shipping company has to make the decision on whether to install scrubber and continue using the HFO or just use more expensive VLSFO.

VLSFO (Very Low Sulfur Fuel Oil) also known as MDO (Medium Diesel Oil) is of higher distillation and so is more expensive than HFO. Its sulfur contents though are 0.10% - 0.50% making it ideal for a ship to operate on outside of SECAs without the need to use a scrubber system.

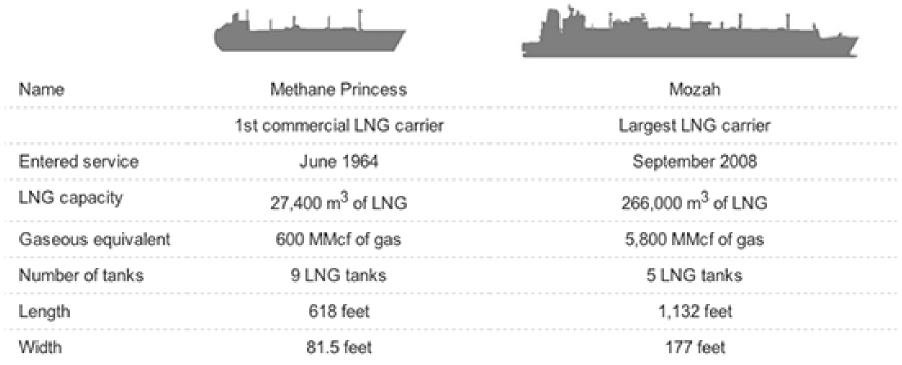
When a ship has the need to enter a SECA it needs to lower its sulfur emissions to lower than 0.10%. The only way this can be achieved is by using ULSFO (Ultra Low Sulfur Fuel Oil). ULSFO sulfur contents do not exceed 0.10% m/m making it ideal for those scenarios. Its price though is higher than VLSFO and HFO.

Lastly LNG is the cleaner fuel of all the aforementioned, with sulfur contents lower than those set by the IMO. This means that LNG can be used even inside the SECAs. Don not be mistaken though as LNG is still a carbon-based fuel and its combustion still produces CO_2. The fact that LNGC already carry natural gas onboard in the form of cargo makes LNG the perfect replacing candidate to VLSFO.

4.2. LNG ship types

The LNG carrier is considered the crown jewel of the marine shipping industry. Part of it has to do with the sophisticated technology used to transport natural gas in liquid form in such low temperatures.

The first ever LNGC started operating in 1959. It wasn't purposefully built to be an LNGC rather it was a heavily modified general cargo carrier. Her first ever successful cargo transfer occurred between Louisiana and the UK. That signaled the start of LNGC era, as the owning company saw its untapped potential and ordered the first two specially designed LNG carriers to enter the industry. From that point on LNG maritime transport started becoming more and more widespread with more shipping companies entering the market year by year.



Name	Methane Princess	Mozah
	1st commercial LNG carrier	Largest LNG carrier
Entered service	June 1964	September 2008
LNG capacity	27,400 m^3 of LNG	266,000 m^3 of LNG
Gaseous equivalent	600 MMcf of gas	5,800 MMcf of gas
Number of tanks	9 LNG tanks	5 LNG tanks
Length	618 feet	1,132 feet
Width	81.5 feet	177 feet

Picture 4.3: First LNGC and largest LNGC as of 2008

[https://www.lngindustry.com/lng-shipping/19062014/first_lng_carrier_entered_service_50_years_ago_802/]

In the following chapter we can observe the yearly increase of LNGC deliveries per year, especially during the last two decades.

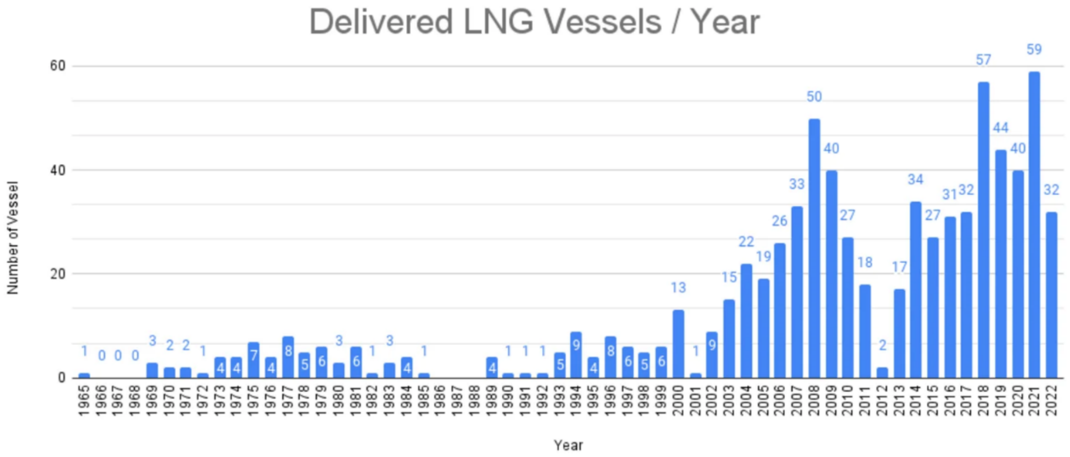


Figure 4.2: Delivered LNGC throughout the years of 1965 – 2022

[https://en.wikipedia.org/wiki/LNG_carrier#/media/File:Delivered_LNG_Vessels_every_Year_from_1965_to_2022.webp]

Taking a look at the South Korean Orderbook we can observe the large market share and value LNGC have over vessel types:

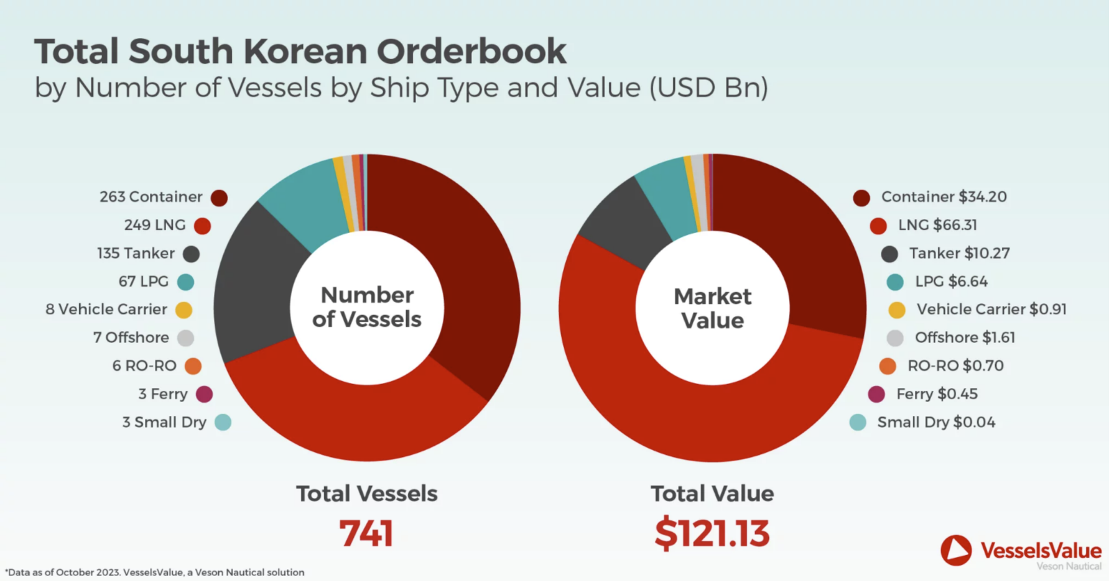


Figure 4.3: South Korean Orderbook

[https://blog.vesselsvalue.com/63-south-korean-orderbook-is-being-built-with-dual-fuel-engines/]

Due to scale economy making larger LNGC was more efficient both from an economical and environmental point of view. This benefits the company, the charterers and the environment carrying more cargo per shipment. LNG carriers started growing in size, while the first purposefully built LNGC were around 27000 cubic meters [m^3] today's ones are reaching sizing up to 266000 [m^3].

- Small size LNG carriers up to 20000 [m^3]
- Medium size LNG carriers 20000 – 40000 [m^3]
- LNG SRVs (Shuttle and Regasification Vessels) with capacity of 40000 – 160000 [m^3]
- Large size LNG carriers 125000 – 267000 [m^3] with subcategories to differentiate them even further. Including:
  1. Conventional ranging from 125000 to 175000 [m^3]
  2. Q-flex ranging from 175000 to 210000 [m^3]
  3. Q-max ranging from 210000 to 267000 [m^3]

LNGC sizes continue to grow as it is beneficial to scale economy. Especially since 2016 when the Panama Canal could accommodate for even bigger ships. The trend is clearly evident below:

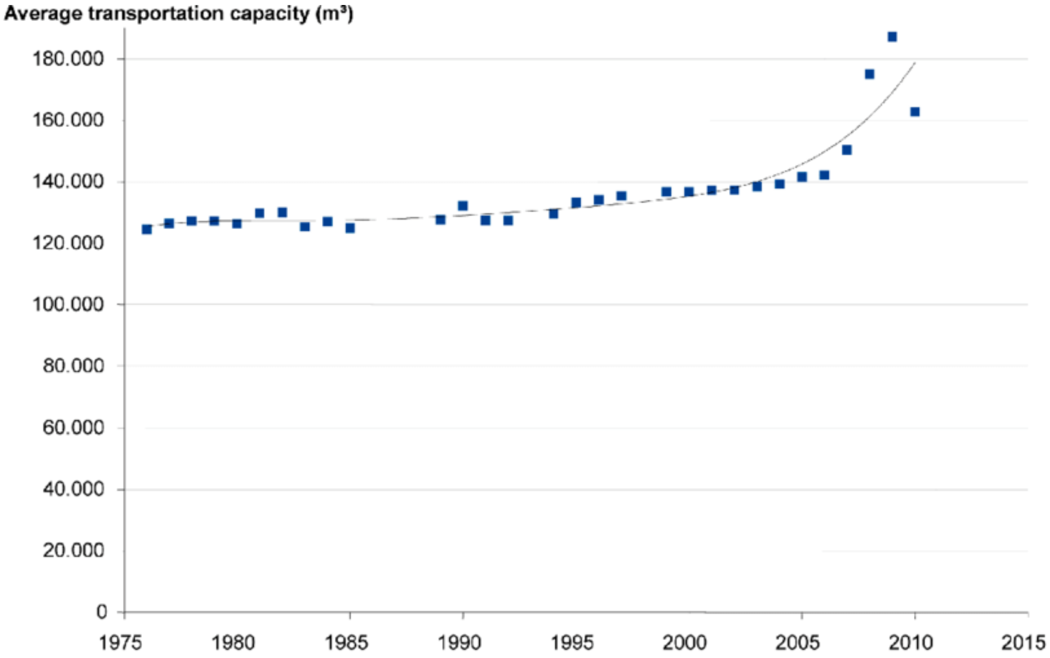


Figure 4.4: Average LNGC vessel capacity throughout year 1965 – 2015

[https://www.researchgate.net/figure/Evolution-in-the-average-capacity-of-LNG-Carrier-Ships_fig3_221909225]

Nowadays, the most common ship size/type across all the mentioned above is the conventional large size LNGC along with Q-flex and Q-max vessels. Taking into consideration the GTT's (Gaztransport & Technigaz) LNG vessels database and a peek at the diagram above, it is clearly evident that the majority of LNGC built in the last decade are of the 160000 to 200000 [m^3] capacity (https://gtt.fr/references-partners/built-vessels). The ones sized at 174000 [m^3] are the most common nowadays and are just the right size in order to meet New Panama Canal restrictions.

4.3. LNGC propulsion types and BOG management

As it was discussed during Chapter 3, BOG is generated causes the tank pressure to increase. One of the ways to relieve this excess pressure is to use the gas which has built up as fuel. This essentially means the ship burns its cargo instead of fuel. As strange as that may sound sometimes it might be more economical to burn the fuel instead of wasting energy to reliquefy it.

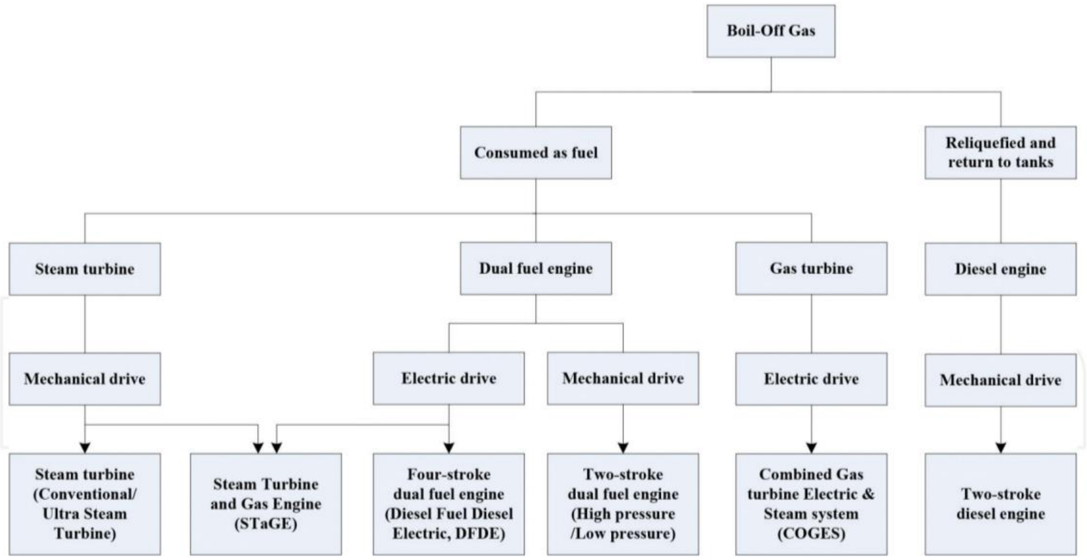
3.1.1. Propulsion plants historic recap

An LNG ship's main propulsion system has changed over the last few decades. The first LNGC was equipped with a steam turbine powered by HFO (Tu Huan, 2019). Their propulsion systems ranged from boilers and steam turbines to large two stroke marine diesel engines. As time went on, BOG usage as fuel become more common.

The first dual fuel propulsion systems installed on LNGC were ST (Steam Turbines). Basically, just boiler and turbine arrangements being able to burn anything from HFO to LNG in order to heat up steam in a closed loop system in. Continuing all the way until the start of 2010's steam turbine propulsion configurations had the largest share among the other propulsion types.

At the start of the 2000's DFDE (Dual Fuel Diesel Electric) and TFDE (Triple Fuel Diesel Electric) propulsion configurations started emerging and quickly overtook ST. Currently they account for more than 1/3 of the total LNGC in operation. Lastly, during the late 2020's due to stricter emission regulations and advancements in 2-stroke engines led to the emergence of MEGI (M-type, Electronically Controlled, Gas Injection), along with XD-F (Dual Fuel 2-stroke Engines) and other lesser popular systems (Ammonia, Hydrogen etc.).

As of today, the most common propulsion plants used in LNGC are DFDE/TFDE along with the quickly emerging MEGI and XDF. All of them will be analyzed in the coming sub-chapters (Tu Huan, 2019) and can be briefly seen below:



Picture 4.4: BOG management and propulsion systems

[https://www.intechopen.com/chapters/64509]

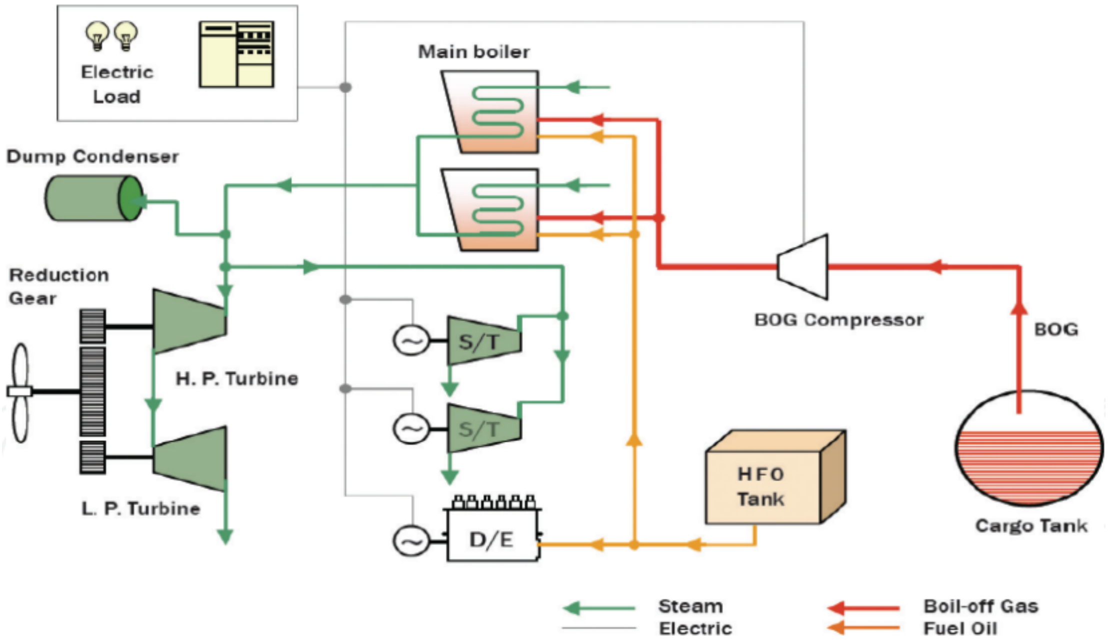
3.1.2. Steam turbine arrangements

As briefly mentioned in Chapter 3.4, ST arrangements were the first to emerge during the early years of LNGC usage. The reason being is that they were reliable and required low maintenance requirements, two things highly valued in merchant shipping.

For redundancy and safety reasons most ST propulsion arrangements (employed on large LNGC) consist of two boilers capable of operating from 100% BOG to 100% HFO and any other ration of BOG/HFO in between. Depending on the fuel used this plant can comply with Tier II and Tier III emission restrictions. The boilers are capable of generation overheated steam at over 60bar at 500°C.

The larger portion of the overheated steam is used to rotate to steam turbines, one HP (High Pressure) and another LP (Low Pressure) one, with both of them being coupled to a central reduction gear which it is designed to rotate the central propeller shaft at the optimal RPM (typically around 100RPM). It is important to note that there are occasions where an intermediate pressure (IP) is coupled on the same shaft as the HP one.

The lesser half of the overheated steam is used to rotate – again for redundancy reasons – two power generating steam turbines. These ST serve exactly the same purpose as the D/G (Diesel Generator) by rotating a generator part used to provide power to the accommodation, motors and any other electrical equipment onboard, one ST generator is enough to meet the ship's maximum power needs at any given moment. In addition to the two aforementioned ST power generators there is a 3rd and sometimes a 4th power generator, conventional 4-stroke D/G. They are able to run directly on MFO and/or HFO and capable of meeting the power output of one of the ST D/G (max power output) in case of the ST D/G being inoperable.



Picture 4.5: LNGC Steam Propulsion Plant

[https://www.intechopen.com/chapters/64509]

Typical large scale LNGC of 125000 – 175000 [m^3] capacities had installed ST power plants capable of offering efficiency of about 30% while using CST (Conventional Steam Turbines). During the recent years by using UST (Ultra Steam Turbines) technology the propulsion plant's overall efficiency pushed to 35%, making them more comparable yet not as energy efficient as DFDE propulsion plants. When operating in

Although ST propulsion was an easy option when LNGC started emerging in the maritime market offering low cost and reliability it has now become redundant as more energy efficient propulsion plants have made their appearance. So, in the premises of this thesis this ST propulsion is low in our list of interests.

3.1.3. Dual Fuel Diesel Electric

During the late 2010's ST propulsion plant popularity started dwindling mainly due to lower efficiency when compared to the newly introduced DFDE (Dual Fuel Diesel Electric). As the name suggest it utilizes BOG and MDO (along with HFO as a 3rd back-up fuel) to operate large 4-stroke engines at their peak efficiency RPM and maximize its specific fuel oil consumption (SFOC). The output power of these engines is used to rotate generators and provide electricity to meet the ship's power needs along with propulsion.

Usually found in configurations of 4 or 5, DFDE engines are designed with a hybrid system in mind. When operating on BOG, these engines are set on gas mode, gas is mixed with air prior to entering the combustion chamber. When operating on MDO or HFO, they are on normal diesel injection mode happening during the compression stroke. The whole system is the same as the one found on normal automotive industry petrol engines, which can be modified so they are able to operate both on petrol and LPG. Similar to the automotive engines mentioned above, this method enables marine DFDE engine injection to happen safely at a relatively low pressure of about 5 bar without needing overcomplicated high pressure piping systems or the hazard of over pressurized natural gas inside the piping leading to the engine. The diesel mode requires in cylinder injection ranging from 60 to 200bar on some engines. It is not posing any danger as diesel flashing point is way higher than that of natural gas. In terms of combustion and emissions, DFDE engines can operate and swap modes seamlessly, operating on MDO or HFO when efficiency and power are on demand and switching to BOG when fuel economy and lower emissions is a concern. A small amount of MDO is injected even on BOG mode acting as an ignitor to the mixture.

Power generated on the DF engines is used to produce electricity and distribute it across different systems. These systems include:

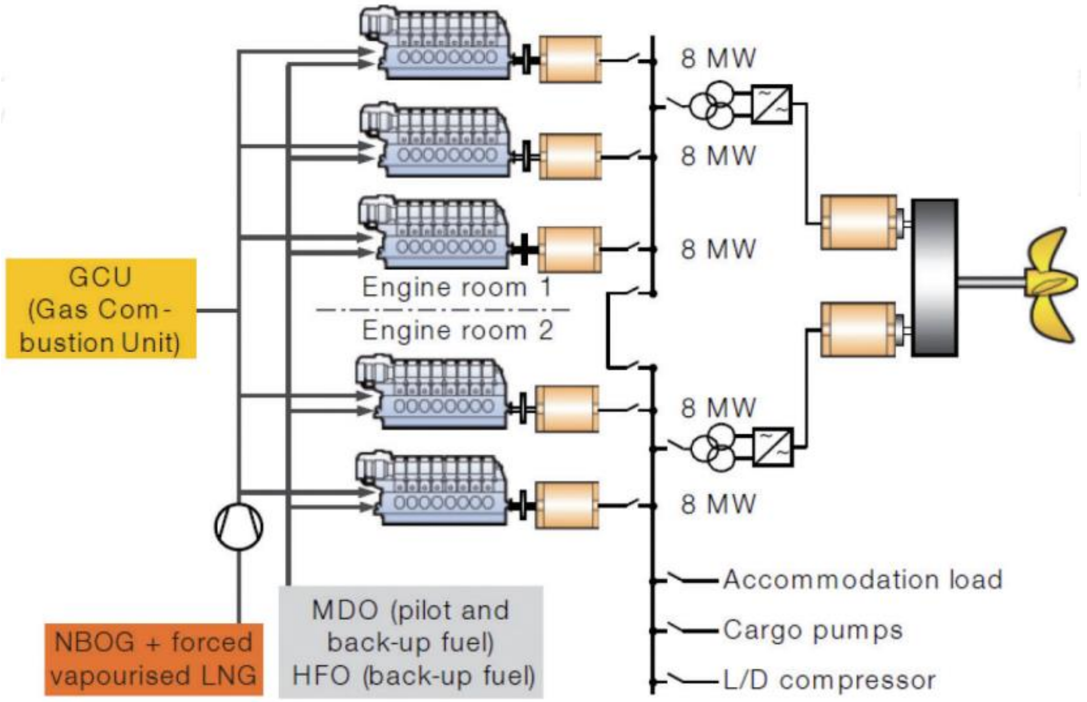
- Accommodation power needs
- Cargo handling equipment
- Varius engine room electrical motors
- Main motors used for propulsion and steering

DFDE plants do a great job at utilizing the generated BOG, with much of the BOG used to directly power the ship. There are however instances where power demand is higher, in this instance the course of action is the following:

- Force vaporize LNG to increase BOG quantities.
- Switch to diesel mode and operate on MGO or HFO

Taking into account that LNG price per kWh is usually lower than that of MGO and HFO it is usually cheaper to force vaporize LNG and operate the engines on BOG. LNG tends to have a more stable price, while MGO and HFO prices tend to change greatly over time. Operating on natural gas comes at the added benefit of cleaner combustion and less emissions, especially when the ship is operating in SECAs. Tier III compliance can be achieved if operated in BOG mode over MGO/HFO.

On the other side of the spectrum, there is the possibility however that BOG production is higher that needed for power generation. The excess gas needs to be handled and the only way this gas is economically viable to be handled in this occasion is to burn in a GCU (Gas Combustion Unit). Using a reliquefaction unit often times requires power greater than that of that stored in the BOG that is going to be reliquefied, so in the majority of the situations the cost outweighs the benefits. Essentially, we are wasting cargo because it's the most cost-effective option.



Picture 4.6: DFDE propulsion plant

[https://www.intechopen.com/chapters/64509]

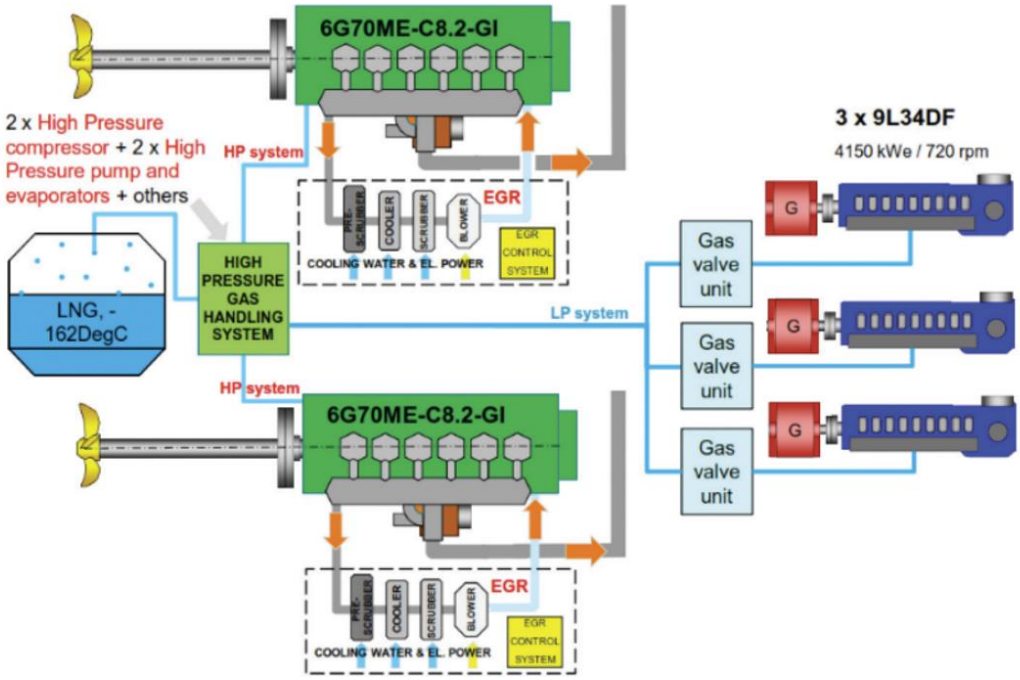
Summing up all the previous paragraphs, when taking into consideration efficiency values, DFDE propulsion plants come close to about 42%, when no energy recovery systems are used. During recent years however:

- Improved PMS (Power Management Systems) result in better management of the load between the engines and therefore overall efficiency.
- Improved PEM (Propulsion Electric Motors) result in motors operating more efficiently on low RPM' s eliminating the need of a gearbox by directly driving the propellers, thus further improving efficiency

Given the above the overall propulsion plant efficiency can exceed even 50%. When compared to ST, DFDE is more space efficient and handles power loads better as ship propulsion and cargo handling procedures do not overlap each other. This means the total installed power aboard a ship can be reduced consisting of only the 4 or 5 DF engines. The drawbacks of this propulsion method are the notably higher maintenance costs, especially when compared to ST, and the way higher initial investment during the shipbuilding phase as DFDE consists of 4 to 5 ICE (Internal Combustion Engines), generators, alternators and electric propulsion motors.

3.1.4. Slow Speed Dual Fuel Engine

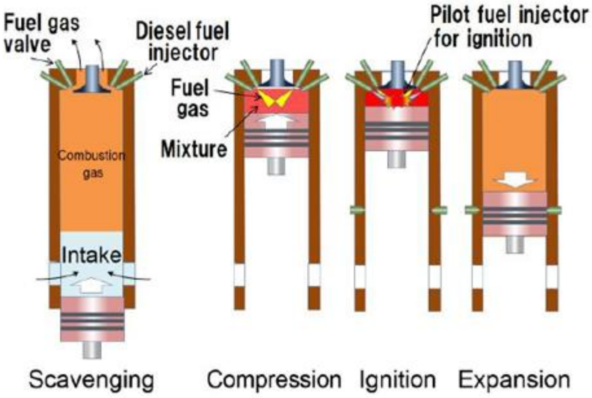
Otherwise known as SSDF, this engine type comes in two variants low and high pressure based on the way the gas is injected. Large two strokes have been the primary propulsion plant merchant vessels have been using for a while meaning that there is a lot of expertise on them from all the parties involved. And so, the emergence and use of SSDF at the start of the 2010's saw a rapid increase.



Picture 4.7: SSDF propulsion plant

[https://www.intechopen.com/chapters/64509]

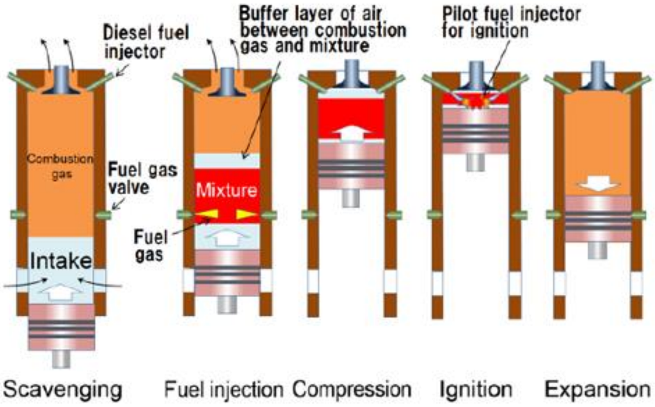
High pressure SSDR (Picture 4.8), ME-GI (electronically controlled engines – gas injection) are equipped with a FGSS (Fuel Gas Supply System) which is able to inject the gas at pressures up to 300 bar. During the compression stroke, shortly after piston reaches TDC (Top Dead Center) the gas is injected into the already ignited diesel pilot fuel. The whole process ensures a knock – free combustion and the ability to achieve high compression ratios. This comes at the drawback of higher NOx emissions, making the use of EGR (Exhaust Gas Recirculation – used to lower oxygen thus combustion temperatures) or SCR (Selective Catalytic Reduction – used to lower already produced NOx emissions) a necessity in order to be able to comply with Tier II and III emission restrictions. The efficiency value of high pressure SSDF plants can reach up to 49%.



Picture 4.8: High Pressure SSDR gas injection

[https://www.yanmar.com/global/about/technology/technical_review/2015/0727_2.html]

Low pressure SSDR (Picture 4.9), XDF is characterized by its high air to fuel ratio. The gas is injected into the cylinder units when the piston is about halfway through the compression stroke (see below picture) meaning the pressure needed for the injection is no higher than 15 bar. This means the FGSS can operate in lower pressures safer and more reliably than its high pressure SSDR counterpart. Similarly, though the final ignition happens at TDC using a small amount of MGO. Operating in lower pressure also means that combustion temperatures do not favor the creation of NOx meaning its easier for XDF to comply with IMO tier III limits (Chapter 3.1). Due to the low pressure, it cannot achieve higher that 48% efficiency.



Picture 4.9: Low Pressure SSDR gas injection

[https://www.yanmar.com/global/about/technology/technical_review/2015/0727_2.html]

Both high and low pressure SSDF engines are accompanied by D/Gs providing electricity to the ship, they operate on low pressure BOG supplied by the FGSS. SSDF are tried and tested propulsion plants offering unmatched redundancy and reliability as well as cheaper manufacturing and servicing than the competition. This makes them very good candidates regarding this thesis scope of work.

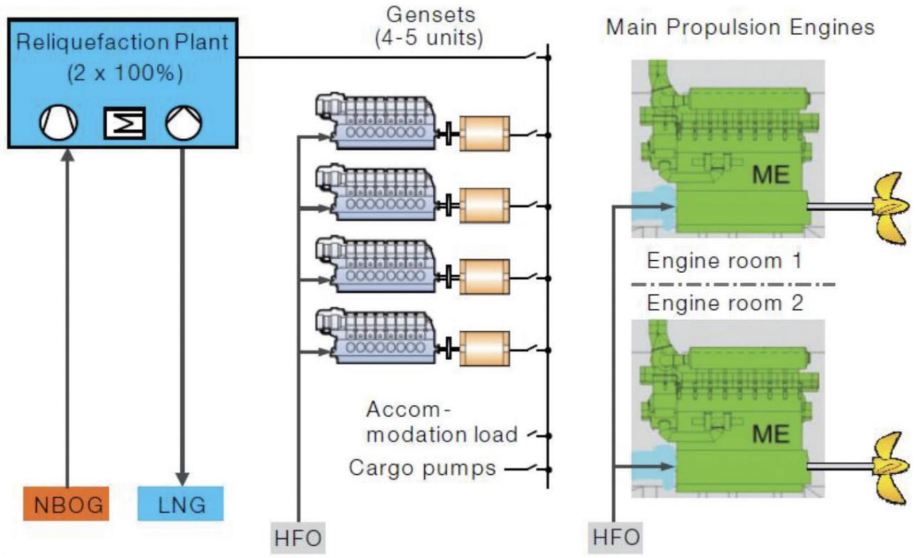
3.1.5. Slow Speed 2-stroke with reliquefaction plant

Following the previous sub-chapter’s 2-stroke focus, the next propulsion plant often found on LNGC is conventional large 2-stroke engines accompanied by D/Gs to meet the ship’s power demands including the reliquefaction plant installed.

The 2-stroke engines installed are of the ME (M-type Electronically controlled) type, meaning their fuel injection and exhaust valve actuation timings are not fixed (controlled mechanically by a camshaft) rather they are controlled by electromagnetic valves. This gives the advantage of a feedback loop system essentially improving engine performance on the fly. These types of engines have entered the market during the early 2010 and have basically overthrown old MC engines (M – type Camshaft), all large 2-stroke engines from now on are expected to be ME ones.

LNCG being the leading edge when considering merchant shipping technology innovations come equipped with 2 of these engines, each one of them driving a separate propeller shaft and propeller. The engine room is separated by a longitudinal bulkhead essentially each side being a mirror of the other. The DFEs installed are usually 4 or 5 as opposed to other merchant ships using 3 or 4. The reason being is that due to the installed reliquefaction plant the energy demands are inflated by about 4 to 7 MW.

The main advantage of such plant is that it can easily manage the BOG by reliquefying it and pumping it back into the tanks. The reliquefaction plant is usually located in the upper deck somewhere among the midship and is easily recognizable. Although the main engines are supplied by conventional HFO, Tier II and III restrictions can be achieved. They run on cheap fuel but run into problems when they enter ECAs and in order to reduce their emissions within the legal limits they revert to MGO.



Picture 4.10: Twin 2-stroke marine engines with reliquefaction plant

[https://www.intechopen.com/chapters/64509]

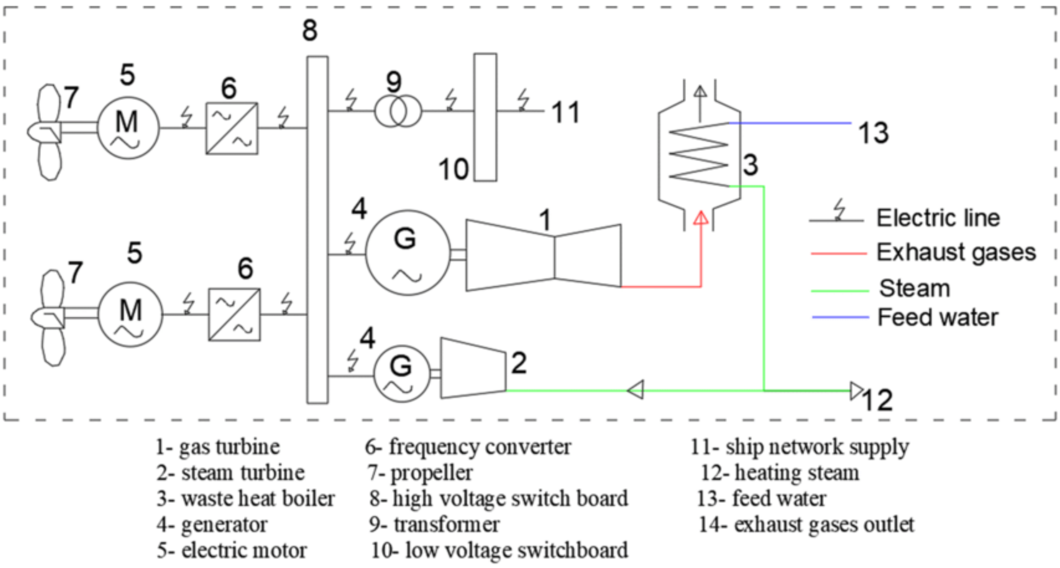
This kind of propulsion plants can achieve efficiently values of about 40%. While 2-stroke marine engines can reach almost 50% as shown on Chapter 4.3.4 the fact that this configuration comes with a reliquefaction plant which itself needs energy to operate leads to the lower value mentioned above. This however is somewhat counteracted by the fact that the whole LNG cargo is transferred as opposed to other BOG management methods that essentially burn it as fuel and therefore decreasing the delivered cargo's quantity. This though depends on whole other set of parameters including, HFO price, MGO price, LNG price and fuel consumption needs. This is the main disadvantage of such plant though, as HFO and MGO prices are generally on the rise and due to the move towards cleaner fuels like LNG makes this choice a poor one in the long run. It will continue to be valuable in the transition period between HFO and LNG towards the 2030's onwards.

3.1.6. Combined Gas Turbine and Steam System

Also known as COGES, this kind of propulsion plant is borrowed by the military industry, first through aircraft engines then from navy ship propulsion plants. This kind of propulsion plants offers excellent performance, emissions and power to weight ratio at the cost of efficiency.

In a more detailed view, this propulsion plant consists of a gas turbine able to operate on marine gas oil MGO) and natural gas (BOG) and everything in between. This gas turbine is directly coupled and rotates a generator giving electrical power to the primary switchboard. The gas turbine's exhaust gases are close to 500°C to 700°C depending on the turbine's efficiency, that means that there is a great amount of wasted heat inside the exhaust gases. For this reason, COGES propulsion plants, as the name suggests, is combined with a waste heat recovery system (WHRS). Basically, a heat recovery steam generator (HRSG) and a steam turbine arrangement. And so, the leftover heat from the exhaust is used to heat up steam and rotate a secondary generator providing extra electrical power.

There are a couple of different configurations. First one consisting one large and one small GT, first one for use when sailing and second one in use for when the vessel is anchored or at port demanding lower power. In addition, it comes equipped with the WHRS mentioned in the previous paragraph. The second configuration consists of two identical GT and their respective WHRS. The two identical GT provide redundancy during voyage as the ship is able to operate with one of them in service giving, during anchorage or at port though this is a disadvantage as there is no auxiliary/smaller GT and the vessel is forced to operate on one of its two GT practically lowering overall efficiency. In both cases the power provided in the main switchboard is used across the ship to meet power demands with the primary consumers being the electric propulsion motors, pumps and accommodation. The total power efficiency of COGES comes at around 42% making it just a little more efficient than the DFDE.



Picture 4.11: COGES propulsion plant

[https://www.researchgate.net/figure/COGES-electric-propulsion-system_fig11_350088001]

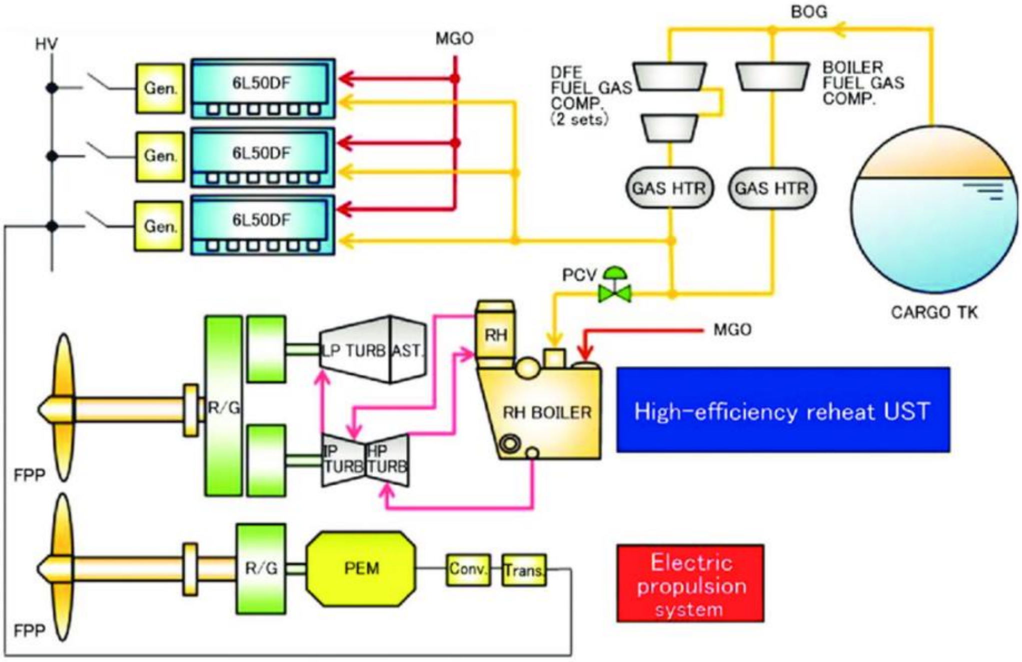
In conclusion, regardless of the two aforementioned arrangements the COGES propulsion plants offers great overall characteristics regarding power output, emissions (easy IMO Tier III compliance), power on demand etc. The main drawback however is the high upfront cost of construction and low thermodynamic efficiency. In simple terms, due to its militaristic nature COGES was more aimed at raw performance, power on demand, redundancy and speed that anything else. So as far as BOG utilization is concerned, yes COGES does a great job at utilizing but at the cost of construction is about 20% higher than conventional marine 2-strokes. From an economical point of view COGES is very similar to DFDE propulsion configuration.

3.1.7. Steam Turbine and Gas Engine

Abbreviated into STaGE, this propulsion system is a newly emerged hybrid developed during the last decade by Mitsubishi Heavy Industries (MHI). Its name, Sayaringo STaGE type came from its older counterpart Sayaendo also developed by MHI, equipped with a single propeller shaft UST propulsion plant (Hiramatsu, et al., 2016).

It consists of a DFE – PEM (Dual Fuel Engine – Propulsion Electric Motor) and UST plant. This propulsion plant combines the best of the two systems, high redundancy and low NO_x and CO_x emissions (Tier II and III when operating in gas mode). The whole engine room is split between port and starboard side, the first containing the UST plant and the later containing the DFE – PEM propulsion system. The starboard side, is occupied by the boiler and the ST. The BOG is routed through the boiler fuel gas compressor, heater and finally fed into the boiler. The thermal energy is then used to heat up water turning it into steam to be used in the ST. The ST themselves drive the one of the twin propeller shafts through a reduction gear.

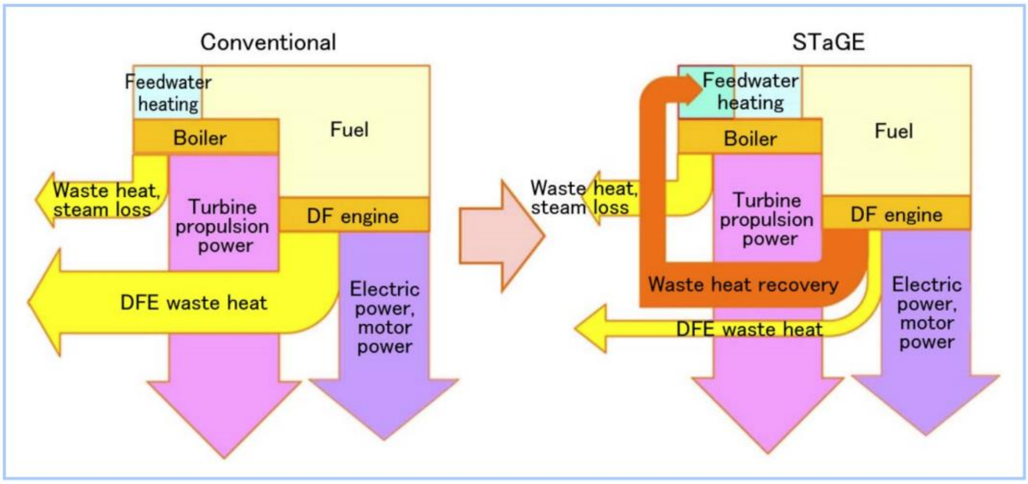
The second part of the STaGE plant is the DFE – PEM part. Similarly, to the UST, the BOG generated in the tanks is routed to gas compressors and heaters, after which it is fed into the DFE which in turn provide electricity to the main switchboard and the PEM. In case of insufficient BOG, MGO is used to supplement the BOG deficiency both in the boiler and on the DFE. The PEM is coupled to the other the other propeller shaft.



Picture 4.12: STaGE propulsion plant

[https://www.researchgate.net/figure/Schematic-main-machinery-of-a-STaGE-propulsion-plant-Mitsubishi-Heavy-Industries-17_fig5_335014378]

The thing that makes the whole arrangement unique is that those two systems are connected by a WHRS. It practically combines the DFE - PEM from the DFDE propulsion plant with the ST and WHRS from the COGES, without the disadvantages of a gas turbine. The thermal energy stored in the DFE exhaust gases and jackets' cooling water after it exits the engines is used to preheat the water entering the boiler thus improving thermal efficiency of the whole system.



Picture 4.13: Comparison of Conventional vs STaGE propulsion WHRS

[https://www.mhi.co.jp/technology/review/pdf/e532/e532003.pdf]

4.4. Case study selection

After gathering the required data and condensing it on the previous chapters, we can start combining the best possible candidates for a case study and comparison with their competitors while having in mind the following:

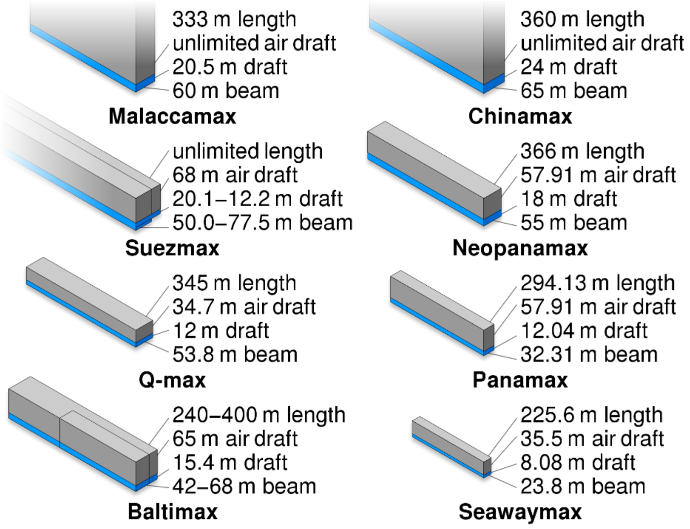
- The preliminary calculation of natural occurring BOG on laden voyage
- The categorization of LNGC propulsion plants along with their characteristics
- The dominant LNGC types and sizes

We can combine the information in order to pick a suitable example for our case study. Before choosing the propulsion plant candidates however, the ship particulars will need to be picked in order to insure compatibility with it. So, as far as propulsion plant is concerned, the process will consist of picking some of the most used propulsion plants in use today and in the foreseeable future and comparing them with a propulsion plant for which there is clear evidence / data that is reliable, efficient and versatile in a manner where it won't be affected by the environment restrictions IMO might force maritime industry to comply with in the coming decades.

4.1.1. Case study ship particulars and BOG rate

As mentioned in chapter 4.2., the most common LNGC built from 2018 onwards are those of 174000 [m^3] capacity (https://gtt.fr/references-partners/built-vessels). The specific dimensions particulars will be decided upon based on general size restrictions as well as take into consideration the dimensions of the first ever STaGE equipped vessel, Diamond Gas Orchid, delivered in 2018. Our vessel of choice will be a no - name vessel and the only need of it will be its particulars and general characteristics.

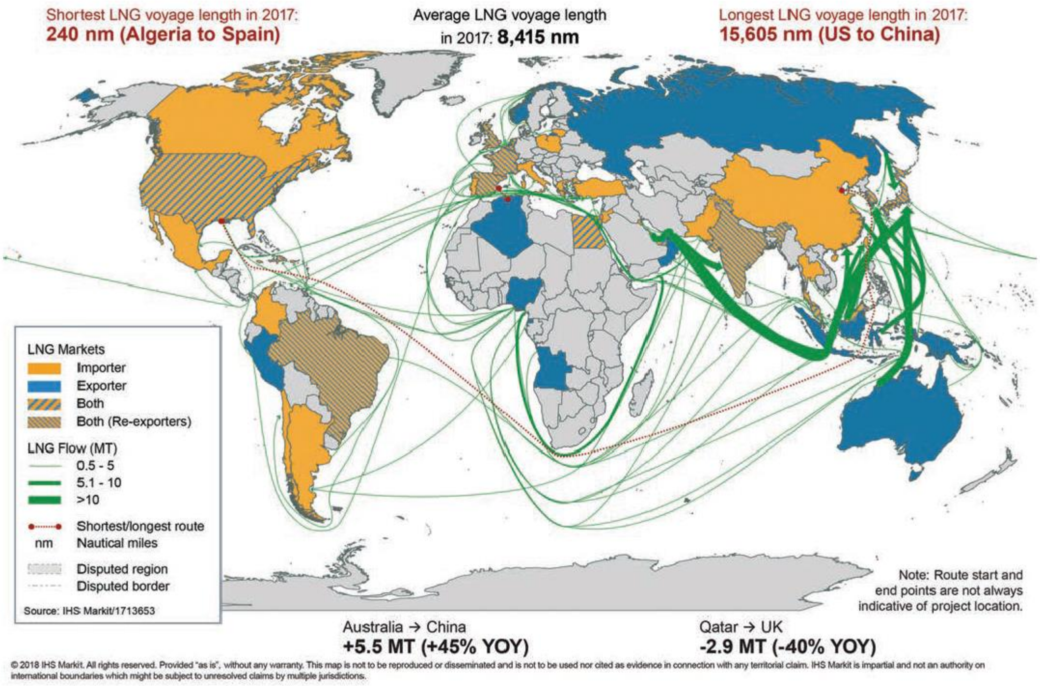
Throughout the years the shipping route passages and port infrastructure are seeing continued modifications in order to be able to accommodate larger ships. Looking at the figure below we can observe the size restrictions different sized canals, ports and infrastructure place as of 2023:



Picture 4.14: Ship dimensions canal restrictions

[https://commons.wikimedia.org/w/index.php?curid=14762296]

In the following map we can observe the most common trading routes and LNGC can operate in. Paying close attention, we can see that China and Qatar are among the most popular places based on the LNG flow through them, meaning the ship will need to comply with Chinamax and Q-max size restrictions. Suezmax and Neopanamax will also be considered important size restrictions to comply with.



Source: IHS Markit.

Picture 4.15: LNG shipping routes as of 2017

[https://blog.energybrainpool.com/en/lng-market-development-and-trends/]

So given the above size restrictions (Q-max) the vessel's particulars are as follow:

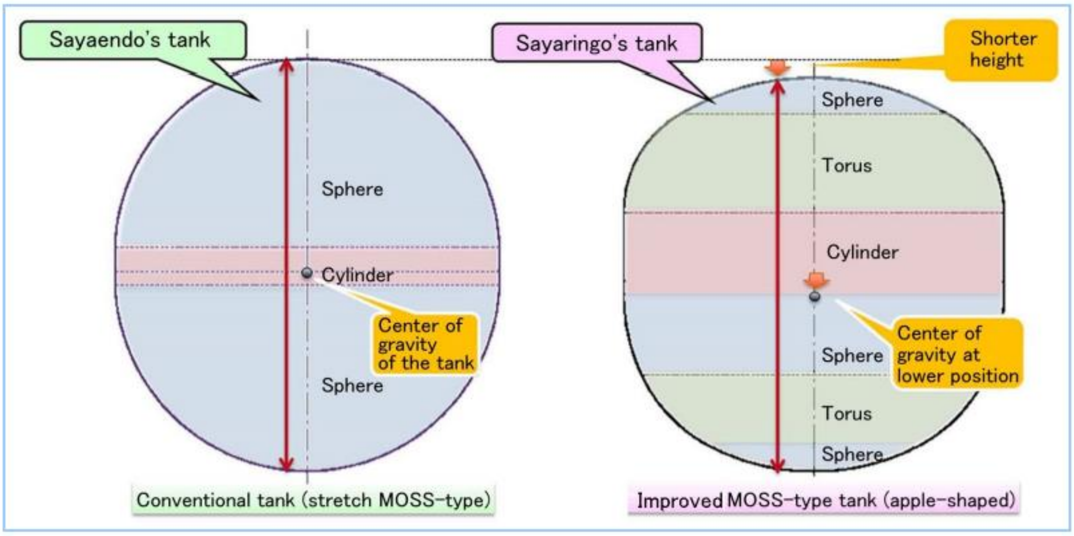
- Length: 345 [m]
- Air Draft: 34.7 [m]
- Draft: 12.0 [m]
- Beam: 53.8 [m]

An LNGC close to 345 [m] however is rare and uncommon with the vast majority of them being around 300 [m] at 174000 [m^3] capacity. Taking into account the Diamond Gas Orchid size (Neopanamax sized) (R.Trauthwein, 2018), we start seeing a more average sized and widely used LNGC.

- Length: 293.5 [m]
- Draft: 11.5 [m]
- Beam: 48.94 [m]
- Capacity: 165000 [m^3] (Mitsubishi Heavy Industries)
- Twin shaft and propeller arrangement

Although we take into account the above, for this case study we will need to lock on specific dimensions, cargo capacity and other characteristics. The reason being is that the only variable between the ships should be the propulsion system. And so, the final particulars and characteristics based on average 174000 [m^3] capacity vessels are (Jallal, 2023):

- Length: 290 [m]
- Draft: 12 [m]
- Beam: 48 [m]
- Twin propeller and rudder arrangement
- Service speed: 19.5 [kn]
- Tank type: Apple shaped Moss Type (Hiramatsu, et al., 2016)
- Tank capacity: 174000 [m^3]
- DWT: 79000



Picture 4.16: Conventional vs improved (apple shaped) MOSS – type tank

[https://www.mhi.co.jp/technology/review/pdf/e532/e532003.pdf]

Length, draft and beam values means this case study ship complies with Neopanamax size restriction. Twin propeller arrangement means each propeller shaft will be independently driven by two different main engines or PEM.

The whole comparison will be conducted between the chosen propulsion plant systems alone, these will be the only variables. The conditions under which the comparison will occur is during laden voyage and include:

1. Loading (low power demand)
2. Maneuvering and/or rough weather (high power demand)
3. Cruising operating conditions (normal power demand)
4. Anchorage (low power demand)
5. Offloading (low power demand)

The reason we are excluding ballast voyage (which would then be a complete round trip) is because we are only interested in examining the BOG utilization by the propulsion plant during laden voyage conditions, where there is actually BOG for use.

Given the diagram on Chapter 3.5.2. representing BOG rate given LNGC capacity we can use that to calculate BOG rates for our case study 174000 [m^3] ship. The equations to be used for BOG calculation at 174000 [m^3] capacity are the following:

- For daily natural BOG production (lower probable production):

  BOG = 0.001 x [tank capacity in m^3]

  BOG = 0.001 x 174000

  BOG = 174 [m^3]

- For daily natural BOG production (higher probable production):

  BOG = 0.0015 x [tank capacity in m^3]

  BOG = 0.0015 x 174000

  BOG = 261 [m^3]

- For average natural BOG production:

  BOG = 0.00134 x [tank capacity in m^3]

  BOG = 0.00134 x 174000

  BOG = 233 [m^3]

We will assume the BOG production per day to be 233 [m^3] for the upcoming calculations on Chapter 5.

4.1.2. Propulsion plant candidates

As it can be clearly seen in the below figure, propulsions plant arrangements in use today and propulsion plants to be used in the future LNGC differ a lot. Most notable difference is the absence of steam propulsion from the order book column (right side of figure). As mentioned in the previous chapters, steam turbine and boiler arrangements all by themselves are not so energy efficient, with values ranging 30 to 35% at best while using the UST. This makes them redundant as newer cheaper and more efficient power plants have emerged. Such plants include ME-GI engines, MAN engines which are ME (M – type electronically controlled) and have GI (gas injection) systems integrated. These two features are the technology which makes them extremely future proof when taking into consideration combustion efficiency and fuel compatibility. As you can see in the above figure, ME-GI have greatly increased their market share over any other propulsion plant type in the order book. The first candidate for our case study is ME-GI engines and their corresponding engine room peripherals.

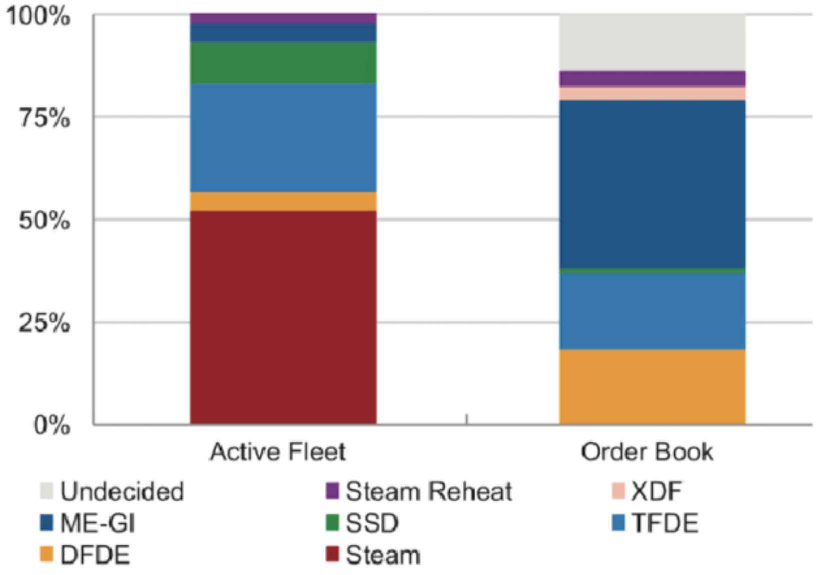


Figure 4.5: LNGC active fleet & order book as of 2016

[https://www.researchgate.net/figure/LNGC-fleet-by-type-of-propulsion-system-by-the-end-of-2016-2_fig1_332104635]

Another key point we should focus our attention to in the previous diagram is the DFDE/TFDE plants. While their combined market share hasn’t changed, accounting for about 35 – 40%, their respective percentages have changed with DFDE rising in popularity and being about equal with TFDE. Both systems use large 4-stroke engines, usually 4 or 5, that can operate on their optimal range and provide electricity across the ship. In the following figure one can easily observe the advantage of a DE (diesel electric) system over a large two stroke engine. The two-stroke engines may be more energy efficient during higher power demand but a DE system using multiple engines operating at peak efficiency is more energy efficient across a wider range of power needs.

They can operate in different fuel types making them versatile, reliable and futureproof. Another major advantage is the ability to operate just as many engines as needed at the time without wasting extra fuel. Their key disadvantage though is the pricier maintenance cost when compared to traditional 2-strokes. Nevertheless, diesel electric propulsion is definitely another good candidate when considering the case study selection.

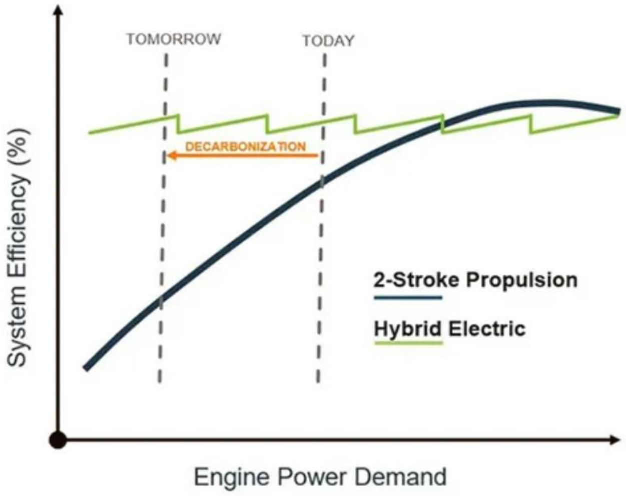


Figure 4.6: Efficiency in relation to engine power demand (hybrid vs 2-stroke)

[https://www.Wartsila.com/marine/products/ship-electrification-solutions/hybrid-electric-lng-carrier]

SSD (SSDF-Slow Speed Dual Fuel) and MEGI plants have very small market share as of 2016 (similar to ME-GI but utilize low pressure gas injection as mentioned in Chapter 4.3.4) but are expected to rise in the coming decades.

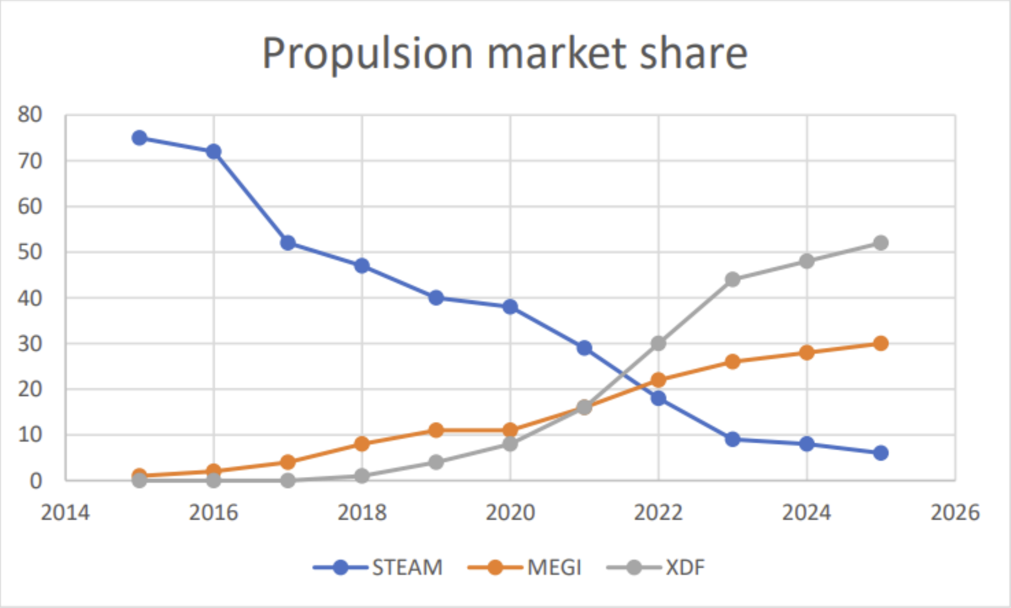


Figure 4.7: Steam, MEGI, XDF predicted market share

[https://www.engineeringscience.rs/images/pdf/36809.pdf]

There is however a portion of undecided costumers on the order book and without a doubt there is no clear winner on which propulsion plants is the best option. In 2018 a unique LNC vessel equipped with the Sayaringo STaGE propulsion plant entered the market. This propulsion plant analyzed in Chapter 4.3.7. is certainly not a popular one but very interesting when considering the following:

- Combines 3 DFEs of the same type of a DFDE plant, meaning the cost of maintenance of those 3 4-stroke DFEs is not as high as the 4 or 5 generators equipped in a DFDE plant.
- It takes advantage of the wasted heat from the DFEs cooling jackets and exhaust gases to be used on a boiler and steam turbine arrangement which itself is proven, reliable and highly efficient.
- The combined arrangement excludes the inefficient gas turbine equipped in a COGES plant with the much more efficient and versatile DFE.
- Both of these features, combine the advantages while leaving out the disadvantages of the DFDE and COGES arrangements.

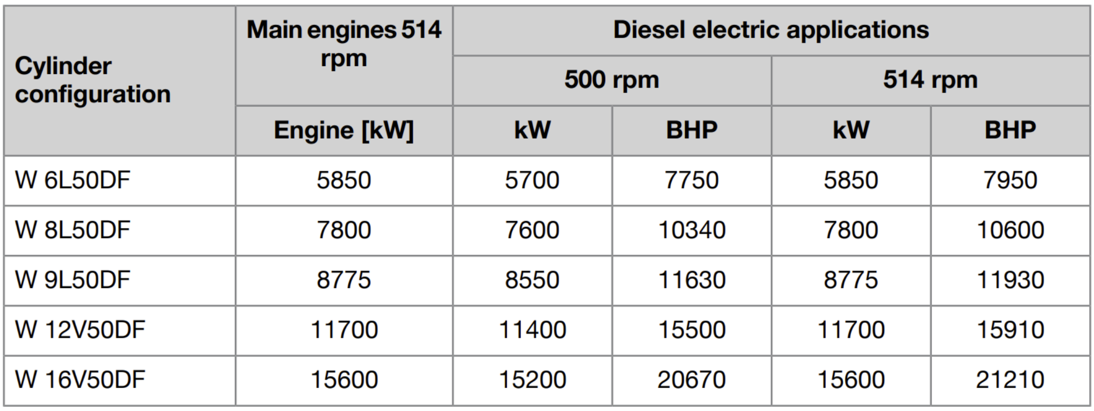
The reasons mentioned above are the motive for the upcoming analysis. In the next chapter we will be comparing the thermal efficiency of the propulsion plant arrangement, specific fuel consumption, power generation and BOG fuel supply percentages across different three different power demands (low – normal – high power demand) for the following propulsion plants:

- DFDE
- ME-GI
- STaGE

5. Chapter 5: Case study

5.1. DFDE

Starting with the DFDE propulsion plants, we will use as a base the 174000 [m^3] vessel chosen in Chapter 4.4.1. We will be choosing to equip Wärtsilä's 50DF engines. The maximum continuous power outputs of these engines are the following:



Cylinder configuration	Main engines 514 rpm	Diesel electric applications			
		500 rpm		514 rpm	
	Engine [kW]	kW	BHP	kW	BHP
W 6L50DF	5850	5700	7750	5850	7950
W 8L50DF	7800	7600	10340	7800	10600
W 9L50DF	8775	8550	11630	8775	11930
W 12V50DF	11700	11400	15500	11700	15910
W 16V50DF	15600	15200	20670	15600	21210

Table 5.1: Wärtsilä 50DF engines cylinder configuration and power outputs

[https://cdn.Wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9]

Most diesel electric 174000 [m^3] LNG vessels come equipped with 4 to 5 identical DF 4-stroke engines. In the last decade that has changed, they usually come equipped with a mix of larger and smaller ones. According to a technical report by ABB marine (ABB marine), the following engine configurations are among the most common on said vessel size:

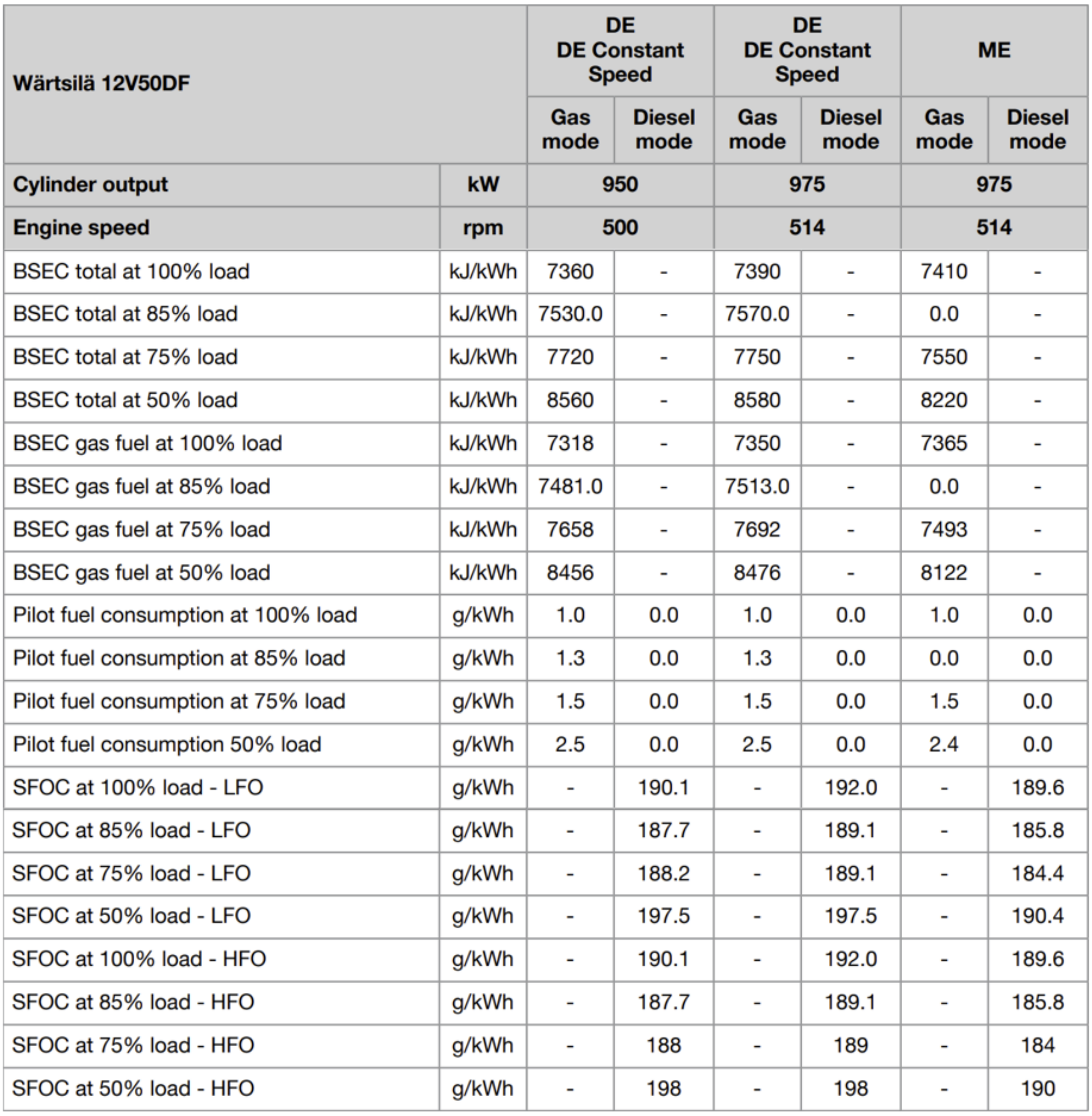
- 2x12V50DF + 2x8L50DF
- 3x12V50DF + 1x6L50DF

For this case study we will be choosing the first option. The installed power in this vessel (diesel electric application at 514RPM) is 2 x 11700 + 2 x 7800 = 39000 [kW]. Some of their advantageous special characteristics are:

- Compact engine room arrangement since all of the power production (port and voyage power needs) is handled by the same engines.
- Ability to switch fuel modes (gas to diesel and vice versa) without affecting power output and electricity generation on most situations.
- Optional ability to fuel share. Essentially running the engine on both BOG and diesel under constant load (useful considering the installation on an LNGC).
- Ability to deactivate fuel injection on up to one third of the cylinders during low load conditions, thus the remaining cylinders can operate on optimal conditions (Skip-Firing operation mode).
- Future proofing especially in case of similar TFDE (triple fuel diesel electric) counterparts.

Specific characteristics regarding fuel consumption for the chosen engines can be seen in the next pages. The ambient conditions deriving directly from the engines' manual (ISO conditions) are as follow (Wartsila DF engine manual):

- total barometric pressure 100 [kPa]
- air temperature 25°C
- relative humidity 30%
- charge air coolant temperature 25°C

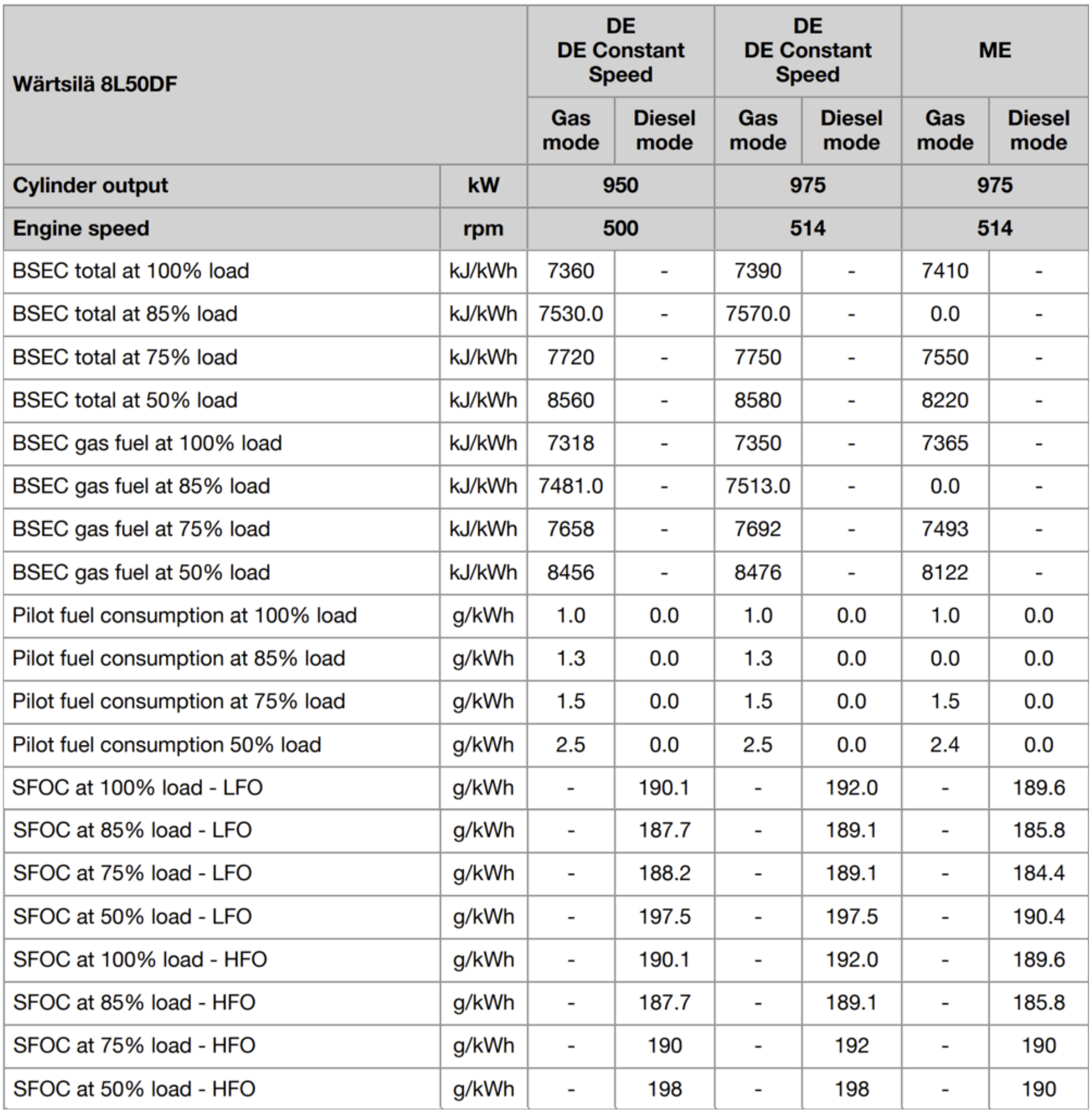


Wärtsilä 12V50DF		**DE DE Constant Speed**		**DE DE Constant Speed**		**ME**	
		Gas mode	**Diesel mode**	**Gas mode**	**Diesel mode**	**Gas mode**	**Diesel mode**
Cylinder output	**kW**	**950**		**975**		**975**	
Engine speed	**rpm**	**500**		**514**		**514**	
BSEC total at 100% load	kJ/kWh	7360	-	7390	-	7410	-
BSEC total at 85% load	kJ/kWh	7530.0	-	7570.0	-	0.0	-
BSEC total at 75% load	kJ/kWh	7720	-	7750	-	7550	-
BSEC total at 50% load	kJ/kWh	8560	-	8580	-	8220	-
BSEC gas fuel at 100% load	kJ/kWh	7318	-	7350	-	7365	-
BSEC gas fuel at 85% load	kJ/kWh	7481.0	-	7513.0	-	0.0	-
BSEC gas fuel at 75% load	kJ/kWh	7658	-	7692	-	7493	-
BSEC gas fuel at 50% load	kJ/kWh	8456	-	8476	-	8122	-
Pilot fuel consumption at 100% load	g/kWh	1.0	0.0	1.0	0.0	1.0	0.0
Pilot fuel consumption at 85% load	g/kWh	1.3	0.0	1.3	0.0	0.0	0.0
Pilot fuel consumption at 75% load	g/kWh	1.5	0.0	1.5	0.0	1.5	0.0
Pilot fuel consumption 50% load	g/kWh	2.5	0.0	2.5	0.0	2.4	0.0
SFOC at 100% load - LFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - LFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75% load - LFO	g/kWh	-	188.2	-	189.1	-	184.4
SFOC at 50% load - LFO	g/kWh	-	197.5	-	197.5	-	190.4
SFOC at 100% load - HFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - HFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75% load - HFO	g/kWh	-	188	-	189	-	184
SFOC at 50% load - HFO	g/kWh	-	198	-	198	-	190

Table 5.2: Fuel consumption characteristics of Wärtsilä 12V50DF engine

[https://cdn.Wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9#page=35&zoom=100,170,78]

- BSEC: Brake Specific Energy Consumption
- SFOC: Specific Fuel Oil Consumption
- Pilot fuel consumption: small quantity of diesel injected along the gas acting as a primer ensuring right timing of the combustion.



Wärtsilä 8L50DF		DE DE Constant Speed		DE DE Constant Speed		ME	
		Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode
Cylinder output	**kW**	**950**		**975**		**975**	
Engine speed	**rpm**	**500**		**514**		**514**	
BSEC total at 100% load	kJ/kWh	7360	-	7390	-	7410	-
BSEC total at 85% load	kJ/kWh	7530.0	-	7570.0	-	0.0	-
BSEC total at 75% load	kJ/kWh	7720	-	7750	-	7550	-
BSEC total at 50% load	kJ/kWh	8560	-	8580	-	8220	-
BSEC gas fuel at 100% load	kJ/kWh	7318	-	7350	-	7365	-
BSEC gas fuel at 85% load	kJ/kWh	7481.0	-	7513.0	-	0.0	-
BSEC gas fuel at 75% load	kJ/kWh	7658	-	7692	-	7493	-
BSEC gas fuel at 50% load	kJ/kWh	8456	-	8476	-	8122	-
Pilot fuel consumption at 100% load	g/kWh	1.0	0.0	1.0	0.0	1.0	0.0
Pilot fuel consumption at 85% load	g/kWh	1.3	0.0	1.3	0.0	0.0	0.0
Pilot fuel consumption at 75% load	g/kWh	1.5	0.0	1.5	0.0	1.5	0.0
Pilot fuel consumption 50% load	g/kWh	2.5	0.0	2.5	0.0	2.4	0.0
SFOC at 100% load - LFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - LFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75% load - LFO	g/kWh	-	188.2	-	189.1	-	184.4
SFOC at 50% load - LFO	g/kWh	-	197.5	-	197.5	-	190.4
SFOC at 100% load - HFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - HFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75% load - HFO	g/kWh	-	190	-	192	-	190
SFOC at 50% load - HFO	g/kWh	-	198	-	198	-	190

Table 5.3: Fuel consumption characteristics of Wärtsilä 8L50DF engine

[https://cdn.Wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9#page=35&zoom=100,170,78]

5.1.1. DFDE: BOG utilization and SGC value

It needs to be investigated to what extent the produced BOG can supply the vessel’s power needs.

1. BOG supply:

   - BOG daily production is 233 [m^3 /day] (Chapter 4.4.1)
   - The hourly production is: 9.708 [m^3/h]
   - LNG is transported in atmospheric pressure (Chapter 2.2)
   - And so: 1 [m^3] of LNG = 454 [kg] of LNG

   Given the above, the average production of BOG is: 4407 [kg/h]

2. BOG LHV:

   - Natural BOG Lower Heat Value ranges from 44000 to 47500 [kJ/kg] depending on its ageing (Chapter 3.5.1.).
   - The value which is going to be used for the calculations is 46000 [kJ/kg].

3. Operating conditions:

   - According to the manual (Wärtsilä), when these engines operate in gas mode they must have a 10% margin for overload, so max load should not exceed 90%. It is also usual practice for crew to operate the engines below their MCR increasing their longevity and fuel consumption. We will assume they operate in 85% load.

   - Normal load conditions:

     Usually 3 (2x12V50DF + 1x8L50DF) out of the 4 engines will be operating. Meaning the power output will be:

     2 x 9945 + 1 x 6630 = 26520 [kW]

   - High load conditions:

     The power needs will require all 4 engines operating (2x12V50DF + 2x8L50DF) with their total power output being:

     2 x 9945 + 2 x 6630 = 33150 [kW]

   - Low load conditions:

     Minimum power needs with 2 of the small engines in operation (2x8L50DF) with output of:

     2 x 6630 = 13260 [kW]

BOG utilization percentages are calculated using data from fuel consumption characteristic tables for the two in question engines and parameters set in the previous page such as BOG supply and LHV:

NORMAL LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	2		
12V50DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	11700	7350	160	1.0	3739	668	100
85	9945	7513	163	1.3	3249	1158	100
75	8775	7692	167	1.5	2935	1472	100
50	5850	8476	184	2.5	2156	2251	100
Remaining BOG supply			1158	kg/h	No. of engines in operation		
					1		
8L50DF		Fuel Consumption Characteristics			BOG utilization for one engine		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	7800	7350	160	1.0	1246	-88	93.0
85	6630	7513	163	1.3	1083	76	100
75	5850	7692	167	1.5	978	180	100
50	3900	8476	184	2.5	719	440	100

Table 5.4: DFDE plant BOG utilization during normal load conditions

HIGH LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	2		
12V50DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	11700	7350	160	1.0	3739	668	100
85	9945	7513	163	1.3	3249	1158	100
75	8775	7692	167	1.5	2935	1472	100
50	5850	8476	184	2.5	2156	2251	100
Remaining BOG supply			1158	kg/h	No. of engines in operation		
					2		
8L50DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	7800	7350	160	1.0	2493	-1334	46.5
85	6630	7513	163	1.3	2166	-1007	53.5
75	4973	7692	167	1.5	1663	-505	69.7
50	2486	8476	184	2.5	916	242	100

Table 5.5: DFDE plant BOG utilization during high load conditions

LOW LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	0		
12V50DF		Fuel Consumption Characteristics			BOG utilization		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	11700	7350	160	1.0	0	4407	0
85	9945	7513	163	1.3	0	4407	0
75	8775	7692	167	1.5	0	4407	0
50	5850	8476	184	2.5	0	4407	0
Remaining BOG supply			4407	kg/h	No. of engines in operation		
					2		
8L50DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	7800	7350	160	1.0	2493	1914	100
85	6630	7513	163	1.3	2166	2241	100
75	5850	7692	167	1.5	1956	2451	100
50	3900	8476	184	2.5	1437	2970	100

Table 5.6: DFDE plant BOG utilization during low load conditions

As far as gas fuel percentage when operating on 85% load is concerned, the resulting natural BOG can:

- Supply for 100% of the vessel's fuel demands during normal seagoing conditions, with 76 [kg/h] excess BOG supply.

  This is indeed near the suggested values of theoretical power the natural BOG can provide in laden voyage, which is estimated to be around 90% (Đorđe Dobrota, 2013).

- Supply for up to:

  $100\% \text{ x } \frac{19890}{33150} + 53.5\% \text{ x } \frac{13260}{33150} = 81.4\%$ during power demanding scenarios

- Fully supply the vessel fuel demands during low power demanding conditions, with 2241 [kg/h] excess BOG.

Even at 100% gas mode there is also a small quantity of diesel pilot fuel injected (about 1% the mass of the gas), so the percentage values of BOG utilized as fuel on Tables 5.4, 5.5, 5.6 will be slightly lower (about 1%). This is negligible.

The remaining fuel needs can be met by the forced BOG (Chapter 3.3.) or diesel fuel depending on what is technically possible at the moment.

In case of excess BOG, it can be burned in the GCU. A full size reliquefaction plant in not found on such vessel size as it is uneconomic (high CAPEX).

The SCG (Specific Gas Consumption) for all engines is calculated to be 160 to 184 [g/kWh] depending on the engine's load. Since we are operating at 85% load the SCG is 163 [g/kWh].

5.1.2. DFDE propulsion plant efficiency

As far as efficiency is concerned according to Wärtsilä's official website (Wärtsilä official website) the 50DF series of engines are capable of as high as 49.4% electrical efficiency.

Setting some parameters for this propulsion's arrangement machinery:

- The power generator's efficiency (98%) is included in Wärtsilä's stated 49.4% electrical efficiency value.
- Electric driven LNG ships of this size usually use two highly efficient synchronous PEM to drive two independent propellers (Chapter 4.1.1). This means use of a 2 input to 1 output gearbox is not needed.
- However, the propellers and the PEM do not have the same optimal RPM ranges. In order to achieve the best possible efficiency a reduction gearbox for each motor/propeller arrangement is needed.

And thus, given the above, the propulsion plant's installed system components along with their efficiency values are the following (Grzesiak, 2018):

- Converters (96%)
- PEM (98%)
- Gearbox (98%)
- Shafting (99%)

Multiplying the above with the engines' efficiency equates to the overall propulsion plant efficiency value being: 45.1%

There are systems and methods used to improve this propulsion plant's efficiency across different load scenarios. First of all, an advanced PMS (power management system) can help achieve better efficiency:

- Baseline: equal load sharing between engines. This power management method requires the minimum effort to apply. However, this is the worst possible load management as it causes the engines to operate outside their optimal load range.
- 3 x 75%: 3 engines operating between 30 and 75% load. When the load is below the stated range, an engine will be shut off, and if it is above an extra engine will come into operation.
- 80/90%: Operating multiple engines in such configuration in order for the majority of them to be operating as close as to 80/90% of MCR (Maximum Continuous Rating) as possible. When the load is exceeded, another engine is to come into operation.
- Optimal: Similar to 80/90% but utilizing Skip-Firing operation mode in order to maximize load between engines while also giving some headroom in engine. This power load management requires the most effort to maintain but results in the best possible efficiency value.

Following that, waste heat recovery systems (WHRS) help take advantage of the wasted heat which can lead to the overall system's efficiency reaching 50%. The following graph represents efficiency in relation to sailing speed:

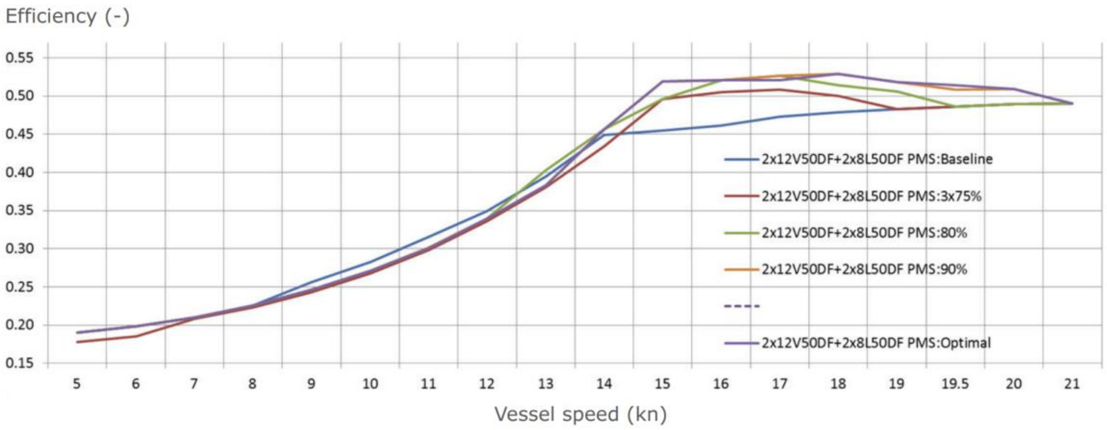


Figure 5.1: Propulsion plant efficiency in relation to speed based on PMS load

[https://library.e.abb.com/public/08233ae06abf4328a34b00cad940ba81/The%20best%20of%20both%20worlds.pdf]

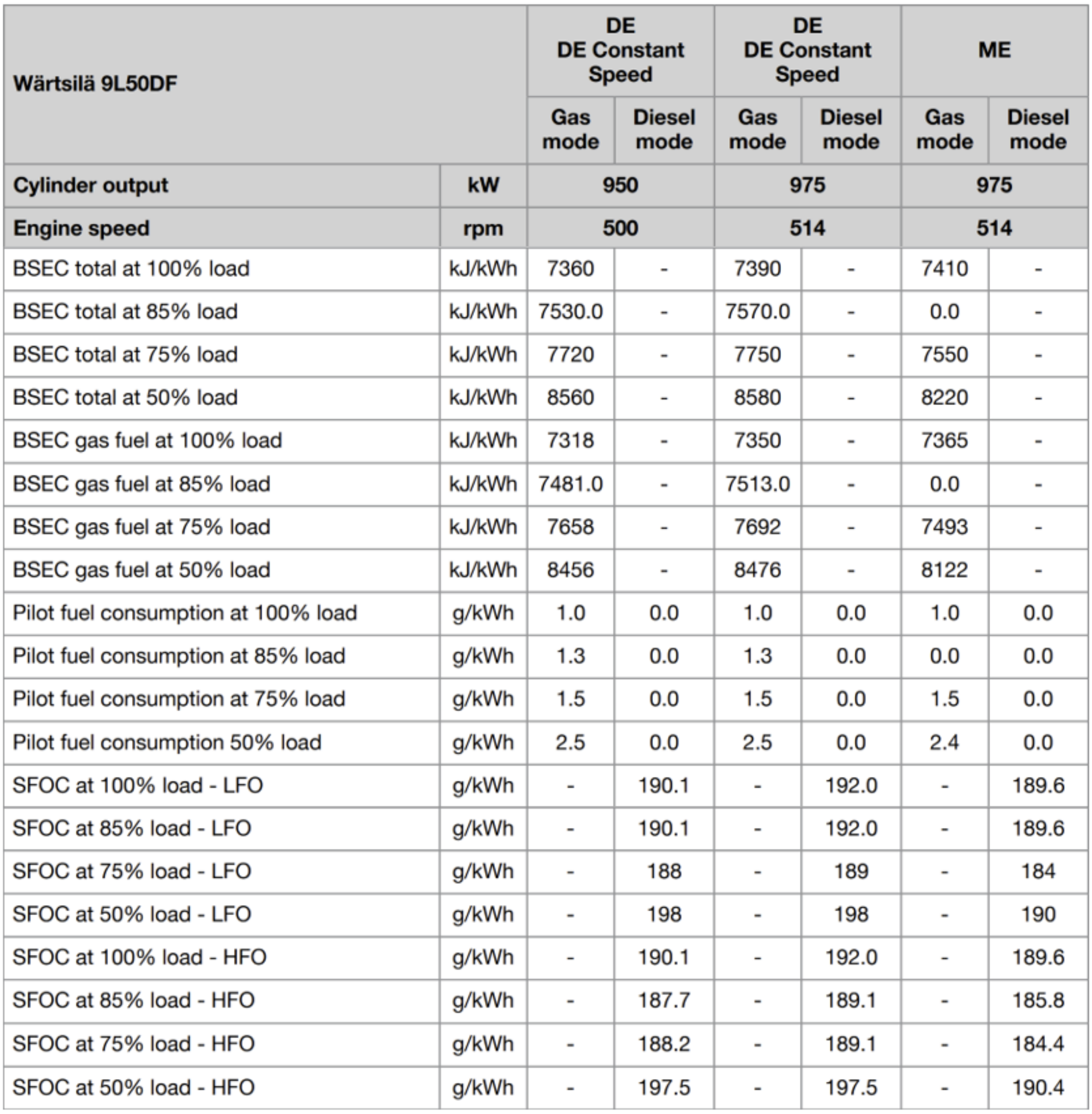
Having the above diagram and given the service speed for our case study vessel at 19.5 [kn] the efficiency is estimated to be 51%. However, other data to be extracted from the above figure is that:

- Using the optimal PMS is showing the best results.
- Most efficient range for all PMS loads seems to be 17kn.
- This results in efficiency of about 52%

5.1.3. Optimized DFDE propulsion plant efficiency

For this optimization we will swapping out the two 8L50DF engines with a 9L50DF and a 6L50DF. Using three different sized engines (2x12V50DF + 1x9L50DF + 1x6L50DF) instead of two means the engines' optimal operational range can vary even more and thus improving efficiency across a larger operational range.

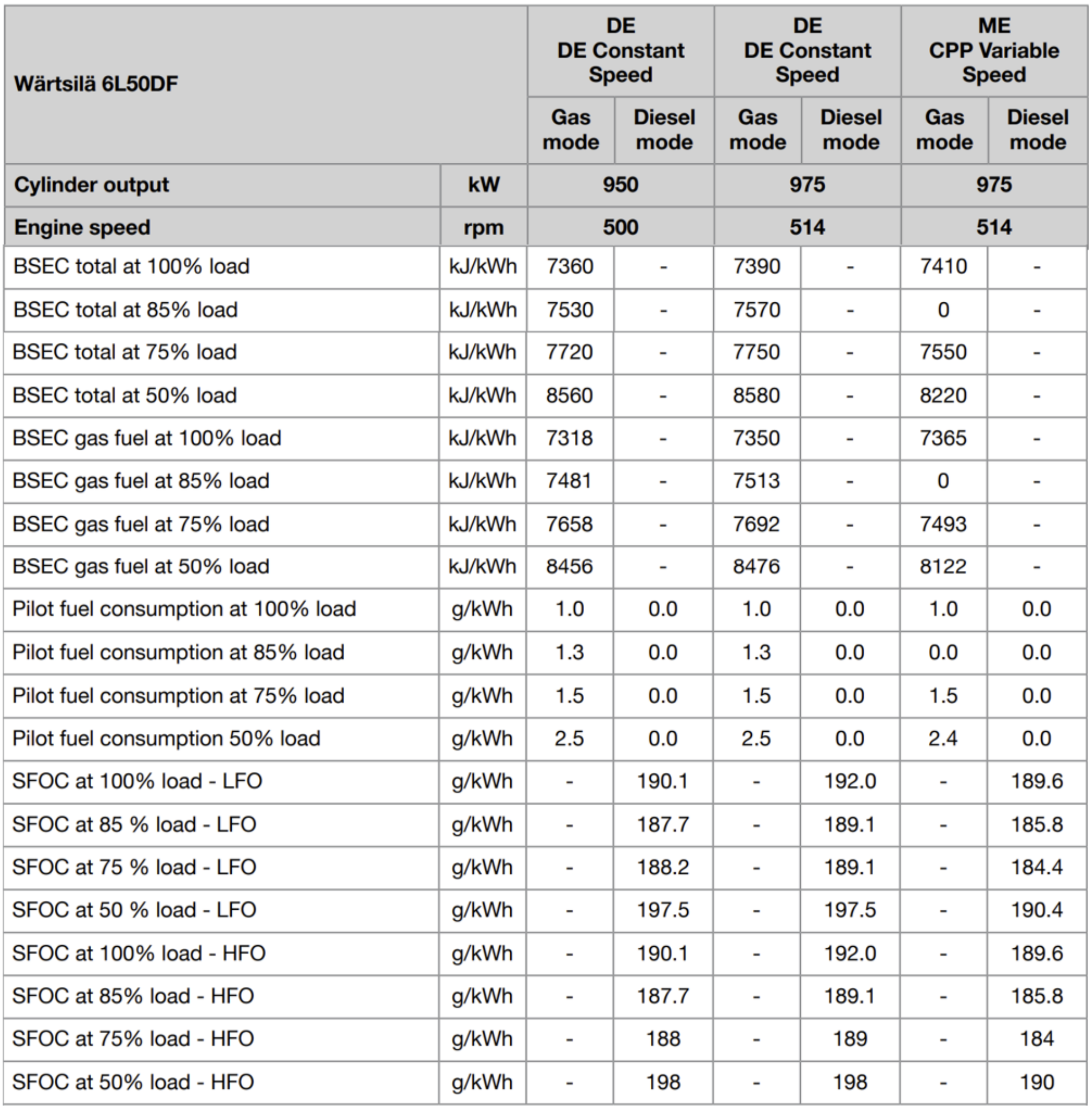
As it can be seen below the fuel consumption characteristics for the 2 new engines (9L50DF + 6L50DF) are identical to the larger engine types (12V50DF) used in Chapter 5.1.2. This eliminates the need of redoing the calculations.



Wärtsilä 9L50DF		**DE DE Constant Speed**		**DE DE Constant Speed**		**ME**	
		Gas mode	**Diesel mode**	**Gas mode**	**Diesel mode**	**Gas mode**	**Diesel mode**
Cylinder output	**kW**	**950**		**975**		**975**	
Engine speed	**rpm**	**500**		**514**		**514**	
BSEC total at 100% load	kJ/kWh	7360	-	7390	-	7410	-
BSEC total at 85% load	kJ/kWh	7530.0	-	7570.0	-	0.0	-
BSEC total at 75% load	kJ/kWh	7720	-	7750	-	7550	-
BSEC total at 50% load	kJ/kWh	8560	-	8580	-	8220	-
BSEC gas fuel at 100% load	kJ/kWh	7318	-	7350	-	7365	-
BSEC gas fuel at 85% load	kJ/kWh	7481.0	-	7513.0	-	0.0	-
BSEC gas fuel at 75% load	kJ/kWh	7658	-	7692	-	7493	-
BSEC gas fuel at 50% load	kJ/kWh	8456	-	8476	-	8122	-
Pilot fuel consumption at 100% load	g/kWh	1.0	0.0	1.0	0.0	1.0	0.0
Pilot fuel consumption at 85% load	g/kWh	1.3	0.0	1.3	0.0	0.0	0.0
Pilot fuel consumption at 75% load	g/kWh	1.5	0.0	1.5	0.0	1.5	0.0
Pilot fuel consumption 50% load	g/kWh	2.5	0.0	2.5	0.0	2.4	0.0
SFOC at 100% load - LFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - LFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 75% load - LFO	g/kWh	-	188	-	189	-	184
SFOC at 50% load - LFO	g/kWh	-	198	-	198	-	190
SFOC at 100% load - HFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - HFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75% load - HFO	g/kWh	-	188.2	-	189.1	-	184.4
SFOC at 50% load - HFO	g/kWh	-	197.5	-	197.5	-	190.4

Table 5.7: Fuel consumption characteristics of Wärtsilä 9L50DF engine

[https://cdn.Wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9#page=35&zoom=100,170,78]



Wärtsilä 6L50DF		**DE DE Constant Speed**		**DE DE Constant Speed**		**ME CPP Variable Speed**	
		Gas mode	**Diesel mode**	**Gas mode**	**Diesel mode**	**Gas mode**	**Diesel mode**
Cylinder output	**kW**	**950**		**975**		**975**	
Engine speed	**rpm**	**500**		**514**		**514**	
BSEC total at 100% load	kJ/kWh	7360	-	7390	-	7410	-
BSEC total at 85% load	kJ/kWh	7530	-	7570	-	0	-
BSEC total at 75% load	kJ/kWh	7720	-	7750	-	7550	-
BSEC total at 50% load	kJ/kWh	8560	-	8580	-	8220	-
BSEC gas fuel at 100% load	kJ/kWh	7318	-	7350	-	7365	-
BSEC gas fuel at 85% load	kJ/kWh	7481	-	7513	-	0	-
BSEC gas fuel at 75% load	kJ/kWh	7658	-	7692	-	7493	-
BSEC gas fuel at 50% load	kJ/kWh	8456	-	8476	-	8122	-
Pilot fuel consumption at 100% load	g/kWh	1.0	0.0	1.0	0.0	1.0	0.0
Pilot fuel consumption at 85% load	g/kWh	1.3	0.0	1.3	0.0	0.0	0.0
Pilot fuel consumption at 75% load	g/kWh	1.5	0.0	1.5	0.0	1.5	0.0
Pilot fuel consumption 50% load	g/kWh	2.5	0.0	2.5	0.0	2.4	0.0
SFOC at 100% load - LFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85 % load - LFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75 % load - LFO	g/kWh	-	188.2	-	189.1	-	184.4
SFOC at 50 % load - LFO	g/kWh	-	197.5	-	197.5	-	190.4
SFOC at 100% load - HFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - HFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75% load - HFO	g/kWh	-	188	-	189	-	184
SFOC at 50% load - HFO	g/kWh	-	198	-	198	-	190

Table 5.8: Fuel consumption characteristics of Wärtsilä 6L50DF engine

[https://cdn.Wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9#page=35&zoom=100,170,78]

The optimized arrangement (2x12V50DF + 1x9L50DF + 1x6L50DF) is compared to the non-optimized version (2x12V50DF + 2x8L50DF) across a range of 15 [MW].

- Starting at about 14 [MW] (low load scenarios).
- Up to about 39 [MW] (high load scenarios).

The power outputs stated in rightmost column of the two following tables indicate the power peaks in which the engines operate most efficiently, under 85% load:

NON OPTIMIZED DFDE PLANT					
ENGINE	12V50DF	12V50DF	8L50DF	8L50DF	COMBINATION PEAK POWER GENERATION [kW]
POWER [kW]	11700	11700	7800	7800	
ENGINE OPERATION COMBINATIONS					
#1	0	0	1	1	15600
#2	1	0	0	1	19500
#3	1	1	0	0	23400
#4	1	1	1	0	31200
#5	1	1	1	1	39000

Table 5.9: Non-optimized DF engine configuration

OPTIMIZED DFDE PLANT					
ENGINE	12V50DF	12V50DF	9L50DF	6L50DF	COMBINATION PEAK POWER GENERATION [kW]
POWER	11700	11700	8775	5850	
ENGINE OPERATION COMBINATIONS					
#1	0	0	1	1	14625
#2	1	0	0	1	17550
#3	1	0	1	0	20475
#4	1	1	0	0	23400
#5	1	1	0	1	29250
#6	1	1	1	0	32175
#7	1	1	1	1	38025

Table 5.10: Optimized DF engine configuration

It is evident that the optimized plant offers more operation combinations and thus smaller dead zones between power peeks. Since the dead zones are smaller, using Skip-Firing mode to bridge the gaps is easier and it ensures the cylinders operate close to 85% load (90% MCR for gas mode).

5.2. ME-GI

Moving on from 4-stroke diesel to slow 2-stroke we get a much different power management method. The same case study vessel (Chapter 4.1.1) is used for this propulsion option as well. Unlike the DFDE, this system's propulsion and power generation is handled by different engines. A vessel of this size is equipped with two 2-stroke engines along with three of four 4-strokes for power generation. This also means the installed power is higher than that of the DE and the space that the engines occupy, therefore the engine room is larger as well. Engine configurations found on such vessels are:

- 2x5G70MEGI + 4x6L34DF
- 2x6G60MEGI + 4x6L34DF
- 2x6G60MEGI + 3x9L34DF

Although MEGI and XDF engines technologies are almost identical, they do have distinctive differences, namely, the gas injection methods as described in Chapter 4.3.4. Apart from that however, efficiency ratings and installed machinery are almost the same. In this part of the case study, we will be choosing the following configuration from the ones mentioned earlier:

- 2x5G70MEGI + 4x6L34DF

Advantages of such propulsion system include:

- Highest efficiency among the other propulsion systems when seagoing under normal weather conditions and optimal speed scenarios.
- High reliability due to decade old marine 2-stroke engine technology and simplistic 2-stroke design without the need for reduction gear.

The diesel generator 6L34DF engine (Picture 5.1) can be seen below followed by the 5G70MEGI engine in the next page (Picture 5.2) along with its special gas injection system (highlight in yellow in Picture 5.3):

Picture 5.1: Wärtsilä 6L34DF engine

[https://www.Wartsila.com/media/news/18-10-2017-Wartsila-dual-fuel-engines-to-power-four-new-lng-carriers]

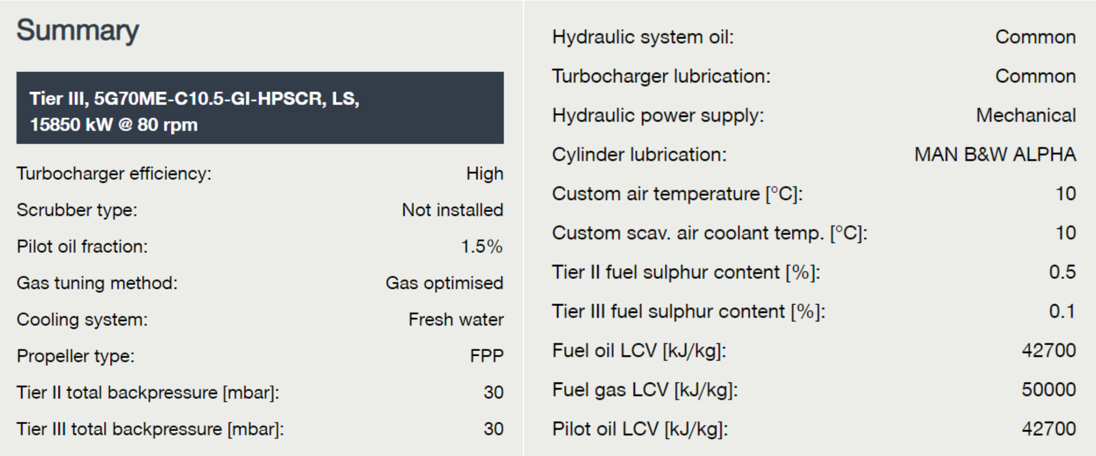
Picture 5.2: MAN B&W 5G70MEGI engine

[https://www.marinelog.com/shipbuilding/engines-fuel/man-notches-up-more-than-100-orders-for-its-me-ga-engine/]

Picture 5.3: MAN B&W ME-GI system

[https://www.man-es.com/marine/products/two-stroke-engines/me-gi]

By visiting MAN's website (MAN CEAS software), engine calculation software can be used in order to get detailed engine specifications and special characteristics for the specific MEGI engines configurations. The input data used for the results can be seen in the next page.



Summary

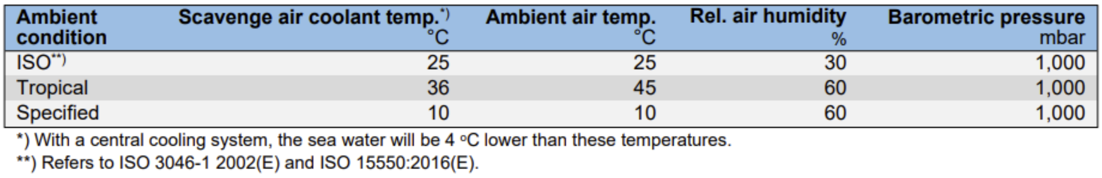
Tier III, 5G70ME-C10.5-GI-HPSCR, LS, 15850 kW @ 80 rpm

Turbocharger efficiency:	High
Scrubber type:	Not installed
Pilot oil fraction:	1.5%
Gas tuning method:	Gas optimised
Cooling system:	Fresh water
Propeller type:	FPP
Tier II total backpressure [mbar]:	30
Tier III total backpressure [mbar]:	30
Hydraulic system oil:	Common
Turbocharger lubrication:	Common
Hydraulic power supply:	Mechanical
Cylinder lubrication:	MAN B&W ALPHA
Custom air temperature [°C]:	10
Custom scav. air coolant temp. [°C]:	10
Tier II fuel sulphur content [%]:	0.5
Tier III fuel sulphur content [%]:	0.1
Fuel oil LCV [kJ/kg]:	42700
Fuel gas LCV [kJ/kg]:	50000
Pilot oil LCV [kJ/kg]:	42700

Picture 5.4: MAN CEAS Input data for engine calculations

[https://www.man-es.com/marine/products/planning-tools-and-downloads/ceas-engine-calculations]

The engine specifications in the next few pages are based on three ambient conditions displayed below. For the purposes of comparison between the two other propulsion plants to be examined, the only ambient condition we are going to use is the ISO specified ambient condition standard, same as the one used for the DFDE plant in Chapter 5.1.



Ambient condition	Scavenge air coolant temp.*) °C	Ambient air temp. °C	Rel. air humidity %	Barometric pressure mbar
ISO**)	25	25	30	1,000
Tropical	36	45	60	1,000
Specified	10	10	60	1,000

*) With a central cooling system, the sea water will be 4 °C lower than these temperatures.

**) Refers to ISO 3046-1 2002(E) and ISO 15550:2016(E).

Picture 5.5: Ambient conditions used for engine calculations

[https://www.man-es.com/marine/products/planning-tools-and-downloads/ceas-engine-calculations]

And so, for the ISO conditions specified above there are four possible combinations for fuel consumption:

1. Tier II diesel mode
2. Tier II gas mode
3. Tier III diesel mode
4. Tier III gas mode

TIER II	HFO MODE			GAS MODE			
Load	Power	Speed	SFOC	Power	Speed	SPOC	SGC
%SMCR	kW	r/min	g/kWh	kW	r/min	g/kWh	g/kWh
100	15850	80	167	15850	80	2.4	135.4
95	15058	78.6	165.3	15058	78.6	2.5	133.9
90	14265	77.2	163.9	14265	77.2	2.6	132.6
85	13473	75.8	162.5	13473	75.8	2.7	131.4
80	12680	74.3	162	12680	74.3	2.8	129.5
75	11888	72.7	161.6	11888	72.7	3	127.8
70	11095	71	159.2	11095	71	3.1	127.3
65	10303	69.3	157.4	10303	69.3	3.3	127.4
60	9510	67.5	158	9510	67.5	3.4	127.7
55	8718	65.5	158.7	8718	65.5	3.6	128.1
50	7925	63.5	159.5	7925	63.5	3.9	128.6
45	7133	61.3	160.7	7133	61.3	4.2	129.4
40	6340	58.9	162	6340	58.9	4.5	130.3
35	5548	56.4	163.4	5548	56.4	4.9	131.1
30	4755	53.6	164.9	4755	53.6	5.5	131.9
25	3963	50.4	166.5	3963	50.4	6.2	132.6

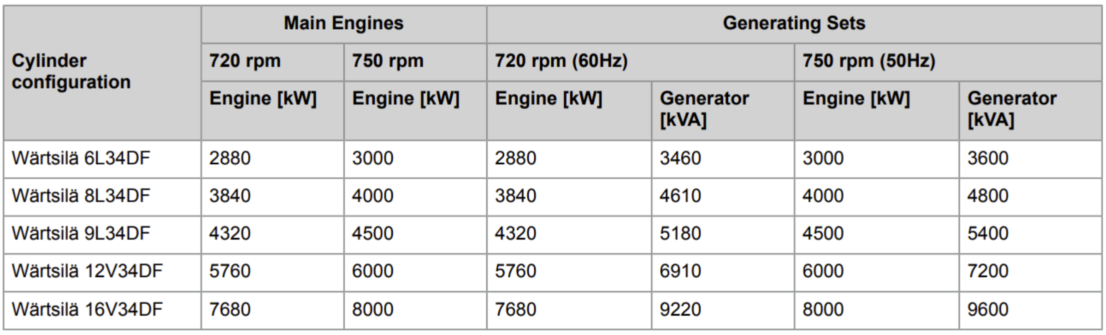
Table 5.11: Tier II 5G70MEGI fuel consumption characteristics

TIER III	HFO MODE			GAS MODE			
Load	Power	Speed	SFOC	Power	Speed	SPOC	SGC
%SMCR	kW	r/min	g/kWh	kW	r/min	g/kWh	g/kWh
100	15850	80	162	15850	80	2.4	135.4
95	15058	78.6	160.5	15058	78.6	2.5	134
90	14265	77.2	159.2	14265	77.2	2.6	132.8
85	13473	75.8	158	13473	75.8	2.7	131.8
80	12680	74.3	157.7	12680	74.3	2.8	131.4
75	11888	72.7	157.6	11888	72.7	3	131.2
70	11095	71	156.2	11095	71	3.1	129.9
65	10303	69.3	155.4	10303	69.3	3.3	129.1
60	9510	67.5	156	9510	67.5	3.4	129.4
55	8718	65.5	156.7	8718	65.5	3.6	129.8
50	7925	63.5	157.5	7925	63.5	3.9	130.3
45	7133	61.3	158.7	7133	61.3	4.2	131.1
40	6340	58.9	160	6340	58.9	4.5	132
35	5548	56.4	161.4	5548	56.4	4.9	132.8
30	4755	53.6	162.9	4755	53.6	5.5	133.6
25	3963	50.4	164.5	3963	50.4	6.2	134.3

Table 5.12: Tier III 5G70MEGI fuel consumption characteristics

- SFOC: Specific Fuel Oil Consumption
- SPOC: Specific Pilot Oil Consumption
- SGC: Specific Gas Consumption

The specifications for the Wärtsilä 34DF engine family are the following:

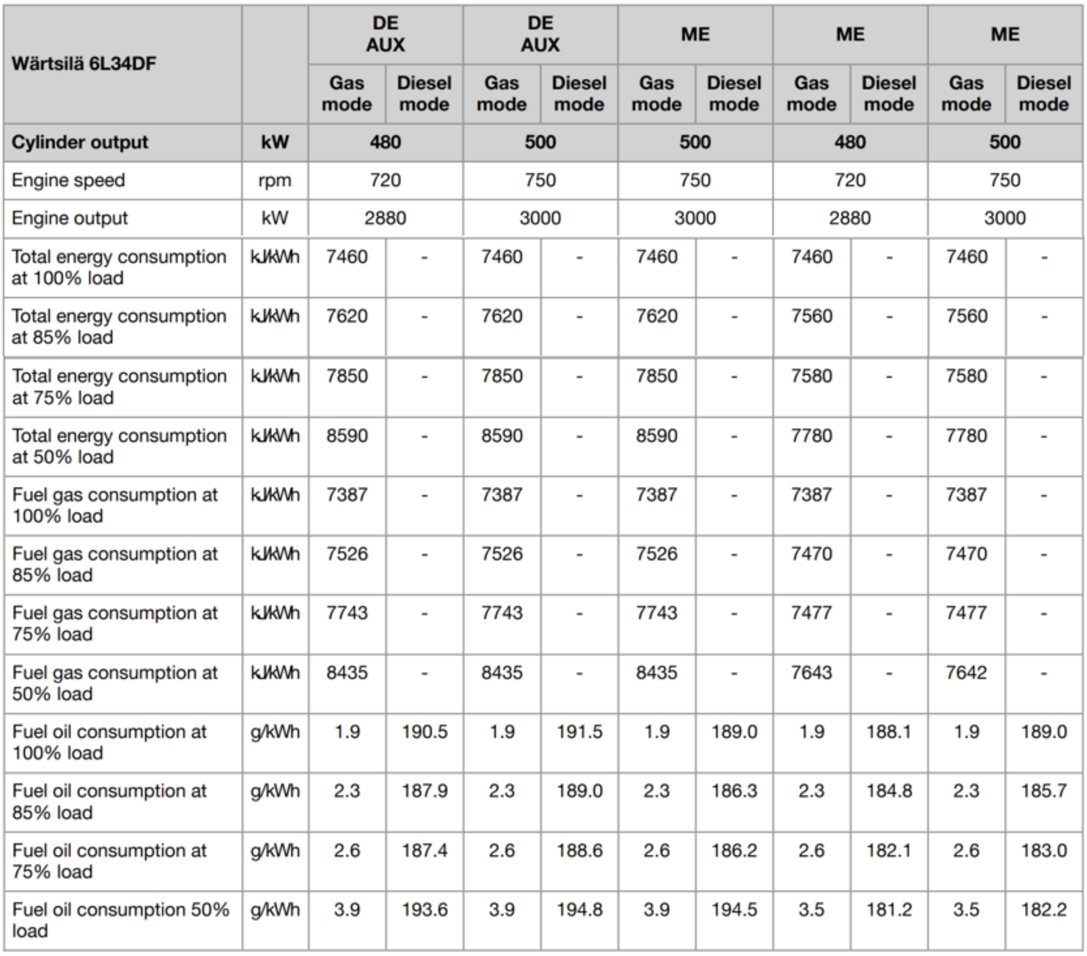


Cylinder configuration	Main Engines		Generating Sets			
	720 rpm	750 rpm	720 rpm (60Hz)		750 rpm (50Hz)	
	Engine [kW]	Engine [kW]	Engine [kW]	Generator [kVA]	Engine [kW]	Generator [kVA]
Wärtsilä 6L34DF	2880	3000	2880	3460	3000	3600
Wärtsilä 8L34DF	3840	4000	3840	4610	4000	4800
Wärtsilä 9L34DF	4320	4500	4320	5180	4500	5400
Wärtsilä 12V34DF	5760	6000	5760	6910	6000	7200
Wärtsilä 16V34DF	7680	8000	7680	9220	8000	9600

Table 5.13: Wärtsilä 34DF engines cylinder configuration and power outputs

[https://www.wartsila.com/docs/default-source/product-files/engines/df-engine/w34df-product-guide.pdf?sfvrsn=5116cb45_23]

For our specific application, we will be using the Wärtsilä 6L34DF configuration. The data that is relevant to us is that found on the first column of the following table. The engine will be operating as a DE AUX (diesel electric auxiliary) in, primarily, gas mode at 720RPM while outputting 2880 [kW] at 100% load.



Wärtsilä 6L34DF		DE AUX		DE AUX		ME		ME		ME	
		Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode	Gas mode	Diesel mode
Cylinder output	**kW**	**480**		**500**		**500**		**480**		**500**	
Engine speed	rpm	720		750		750		720		750	
Engine output	kW	2880		3000		3000		2880		3000	
Total energy consumption at 100% load	kJ/kWh	7460	-	7460	-	7460	-	7460	-	7460	-
Total energy consumption at 85% load	kJ/kWh	7620	-	7620	-	7620	-	7560	-	7560	-
Total energy consumption at 75% load	kJ/kWh	7850	-	7850	-	7850	-	7580	-	7580	-
Total energy consumption at 50% load	kJ/kWh	8590	-	8590	-	8590	-	7780	-	7780	-
Fuel gas consumption at 100% load	kJ/kWh	7387	-	7387	-	7387	-	7387	-	7387	-
Fuel gas consumption at 85% load	kJ/kWh	7526	-	7526	-	7526	-	7470	-	7470	-
Fuel gas consumption at 75% load	kJ/kWh	7743	-	7743	-	7743	-	7477	-	7477	-
Fuel gas consumption at 50% load	kJ/kWh	8435	-	8435	-	8435	-	7643	-	7642	-
Fuel oil consumption at 100% load	g/kWh	1.9	190.5	1.9	191.5	1.9	189.0	1.9	188.1	1.9	189.0
Fuel oil consumption at 85% load	g/kWh	2.3	187.9	2.3	189.0	2.3	186.3	2.3	184.8	2.3	185.7
Fuel oil consumption at 75% load	g/kWh	2.6	187.4	2.6	188.6	2.6	186.2	2.6	182.1	2.6	183.0
Fuel oil consumption 50% load	g/kWh	3.9	193.6	3.9	194.8	3.9	194.5	3.5	181.2	3.5	182.2

Table 5.14: Fuel consumption characteristics of Wärtsilä 6L34DF engine

[https://tech-expo.ru/upload/iblock/8a2/Instruktsiya-po-ekspluatatsii-W_rtsil_-W34DF.pdf]

5.2.1. MEGI: BOG utilization and SGC value

Just like the DFDE case in the previous chapter, it will be examined to what extent the natural occurring BOG can serve the ships power needs.

1. BOG supply and LHV:

- Same calculations as the ones used on DFDE plant (Chapter 5.1.1)
- BOG production is independent of propulsion plant.
- The average BOG production is: 4407 [kg/h]
- LHV of gas assumed to be: 46000 [kJ/kg]

2. Normal seagoing operation, SCG and BOG utilization:

We are going to assume the two main engines operate the majority of the voyage's span at 80% of their MCR on Tier II gas mode.

NORMAL LOAD CONDITIONS		LHV 46000 kJ/kg			No. of engines in operation		
		BOG 4407 kg/h			2		
5G70MEGI		Consumption		Power (x2)	BOG utilization for both engines		
Load	Power	SGC	SPOC		Required	Remaining	BOG fuel
%	kW	g/kWh	g/kWh	kW	kg/h	kg/h	%
100	15850	135.4	2.4	31700	4292	115	100
95	15058	133.9	2.5	30116	4033	374	100
90	14265	132.6	2.6	28530	3783	624	100
85	13473	131.4	2.7	26946	3541	866	100
80	12680	129.5	2.8	25360	3284	1123	100
75	11888	127.8	3.0	23776	3039	1368	100
70	11095	127.3	3.1	22190	2825	1582	100

Table 5.15: BOG utilization by the 2-stroke MEs under normal load conditions

- Power of the main engines at these conditions is: 2 x 12680 = 25360 [kW]
- BOG needs at 80% MCR are: 3284 [kg/h].
- Remaining BOG supply is: 4407 – 3284 = 1123 [kg/h]

During voyage the power demands for electricity are usually lower than when the ship is on port so 3 out of the 4 engines will be operating. We will assume that:

- 2 of them operate close to 85% load while producing: 2 x 2880 = 4896 [kW]
- While the 3rd one operates at 50% load producing 1440 [kW].

Total propulsion plant power output for these conditions will be: 31696 [kW]

NORMAL LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	1123	kg/h	2		
6L34DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	2880	7350	160	1.0	920	203	100
85	2448	7513	163	1.3	800	323	100
75	2160	7692	167	1.5	722	401	100
50	1440	8476	184	2.5	531	592	100

Table 5.16: 2x6L34DF D/Gs operating at 85% load under normal load conditions

NORMAL LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	323	kg/h	1		
6L34DF		Fuel Consumption Characteristics			BOG utilization for one engine		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	2880	7350	160	1.0	460	-137	70.2
85	2448	7513	163	1.3	400	-77	80.8
75	2160	7692	167	1.5	361	-38	89.5
50	1440	8476	184	2.5	265	58	100

Table 5.17: 6L34DF D/G operating at 50% load under normal load conditions

The 2 diesel engines operating at 85% load:

- Will fully operate in 100% gas mode
- Remaining BOG supply is: 1123 – 800 = 323 [kg/h].

This means the 3rd diesel engine under 50% load will:

- Will also fully operate in gas mode
- The remaining BOG supply is 58 [kg/h], it will be combusted in the GCU.

Thus, under normal operating conditions the plants can operate on 100% gas mode.

As for the propulsion plant’s overall SGC value, it is given by the following equation:

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(SCG1\ x\ P1)+(SCG2\ x\ P2)+(SCG3\ x\ P3)}{Ptotal}$$

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(129.5\ x\ 25360)+(163\ x\ 4896)+(184\ x\ 1440)}{31969}$$

$$\mathrm{SCG}_{\mathrm{combined}} = 136.0\ [\mathrm{g/kWh}]$$

Where:

1 = Main engine

2 = D/G at 85% load

3 = D/G at 50% load

P = output power

SCG = specific gas consumption

3. Power demanding operation, SCG and BOG utilization:

We are assuming the main engines operate at 100% of their MCR on Tier II gas mode.

- This means the total power output of the vessel’s main engines at these conditions will be: 31700 [kW]
- The operating conditions for the diesel generators remain the same as in the normal operating scenario.

Total power generation is: 38036 [kW]

Taking a look at Table 5.18, the average production of BOG being 4407 [kg/h] is enough to fully supply the twin main engines:

- At 100% MCR they require 4292 [kg/h].
- The leftover BOG is 4407 – 4292 = 115 [kg/h].

HIGH LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	2		
5G70MEGI		Consumption		Power (x2)	BOG utilization for both engines		
Load	Power	SGC	SPOC		Required	Remaining	BOG fuel
%	kW	g/kWh	g/kWh	kW	kg/h	kg/h	%
100	15850	135.4	2.4	31700	4292	115	100
95	15058	133.9	2.5	30116	4033	374	100
90	14265	132.6	2.6	28530	3783	624	100
85	13473	131.4	2.7	26946	3541	866	100
80	12680	129.5	2.8	25360	3284	1123	100
75	11888	127.8	3.0	23776	3039	1368	100
70	11095	127.3	3.1	22190	2825	1582	100

Table 5.18: BOG utilization by the 2-stroke ME under high load conditions

The remaining BOG can supply for up to 43.3% on one of the 3 D/Gs in operation as it can be observed in the table below.

HIGH LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	115	kg/h	1		
6L34DF		Fuel Consumption Characteristics			BOG utilization for one engine		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	2880	7350	160	1.0	460	-345	25.0
85	2448	7513	163	1.3	400	-285	28.8
75	2160	7692	167	1.5	361	-246	31.8
50	1440	8476	184	2.5	265	-150	43.3

Table 5.19: 6L34DF D/G operating at 50% load under high load conditions

The remaining 2 D/Gs operating at 85% load will need to operate entirely in forced BOG or Diesel as the natural BOG supply is 100% utilized by the other engines:

HIGH LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	0	kg/h	2		
6L34DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	2880	7350	160	1.0	920	-920	0
85	2448	7513	163	1.3	800	-800	0
75	2160	7692	167	1.5	722	-722	0
50	1440	8476	184	2.5	531	-531	0

Table 5.20: 2x6L34DF D/Gs operating at 85% load under high load conditions

And thus, power generation attributed to natural BOG utilization, under high load scenarios is:

$$100\% \text{ x } \frac{31700}{38036} + 43.3\% \text{ x } \frac{1440}{38036} + 0\% \text{ x } \frac{4896}{38036} = 85.0\%$$

As for the SGC values of the MEGI propulsion plant under high load conditions:

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(SCG1\ x\ P1)+(SCG2\ x\ P2)+(SCG3\ x\ P3)}{Ptotal}$$

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(135.4\ x\ 31700)+(163\ x\ 4896)+(184\ x\ 1440)}{38036}$$

$$\mathrm{SCG}_{\mathrm{combined}} = 141\ [\mathrm{g/kWh}]$$

4. Low load operation, SCG and BOG utilization:

We are assuming that:

- The main engines operate at Tier III at 25% load producing: 7926 [kW]
- 3 out of 4 D/Gs will operate at 85% load producing: 3 x 2448 = 7344 [kW]
- The 4th D/G will operate at 65% load producing: 1440 [kW]

Total power generation is: 16710 [kW]

LOW LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	2		
5G70MEGI		Consumption		Power (x2)	BOG utilization for both engines		
Load	Power	SGC	SPOC		Required	Remaining	BOG fuel
%	kW	g/kWh	g/kWh	kW	kg/h	kg/h	%
50	7925	130.3	3.9	15850	2065	2342	100
45	7133	131.1	4.2	14266	1870	2537	100
40	6340	132	4.5	12680	1674	2733	100
35	5548	132.8	4.9	11096	1474	2933	100
30	4755	133.6	5.5	9510	1271	3136	100
25	3963	134.3	6.2	7926	1064	3343	100

Table 5.21: MEGI engines operating in gas mode Tier III at 25% load

LOW LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	3343	kg/h	3		
6L34DF		Fuel Consumption Characteristics			BOG utilization for all engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	2880	7350	160	1.0	1381	1962	100
85	2448	7513	163	1.3	1199	2143	100
75	2160	7692	167	1.5	1084	2259	100
50	1440	8476	184	2.5	796	2547	100

Table 5.22: 3x6L34DF D/Gs operating at 85% load under low load conditions

LOW LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	2143	kg/h	1		
6L34DF		Fuel Consumption Characteristics			BOG utilization for one engine		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	2880	7350	160	1.0	460	1683	100
85	2448	7513	163	1.3	400	1743	100
75	2160	7692	167	1.5	361	1782	100
50	1440	8476	184	2.5	265	1878	100

Table 5.23: 6L34DF D/Gs operating at 50% load under low load conditions

The BOG would be more than enough to supply for low-speed maneuvering power demands. Remaining BOG production is 1878 [kg/h].

As far as average SGC consumption using the following formula:

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(SCG1\ x\ P1)+(SCG2\ x\ P2)+(SCG3\ x\ P3)}{Ptotal}$$

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(163\ x\ 7344)+(184\ x\ 1440)+(134\ x\ 7926)}{16710}$$

$$\mathrm{SCG}_{\mathrm{combined}} = 151\ [\mathrm{g/kWh}]$$

5.2.2. MEGI propulsion plant efficiency

This propulsion plant's overall efficiency is a combination of the following:

1. The two main engines
2. The four power generation engines

The 34DF series used in this propulsion plant have around 48.6% electrical efficiency (Wartsila Official Website). As for the large two stroke engines, the engine and shafting system results in 51.2% efficiency rating (Grzesiak, 2018). The combined overall efficiency is given by the following equation:

$$\eta = \frac{Total\ power\ output}{Total\ power\ input} = \frac{31700 + 8640}{61914 + 17778} = 50.6\%$$

Where:

- Power input of the main engines: $\frac{31700}{51.2\%} = 61914$ [kW]
- Power input of the DFEs: $\frac{8640}{48.6\%} = 8640$ [kW]

Using AE economizers and WHRS is possible to improve the overall efficiency further than that calculated above. Taking a look at the following figure seems to suggest the previous stating:

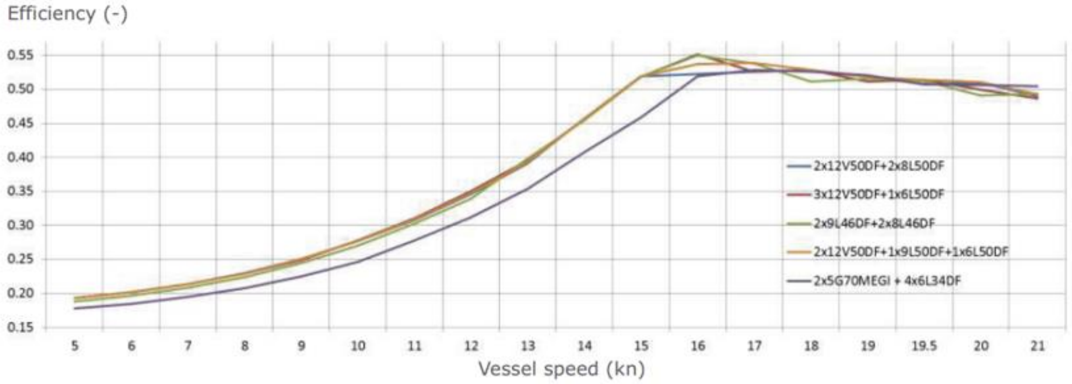


Figure 5.2: MEGI propulsion plant overall efficiency

Given the service speed of our case study vessel at 19.5 [kn] as it can be observed from the above figure, it is estimated to be 51%. Close to the one calculated above.

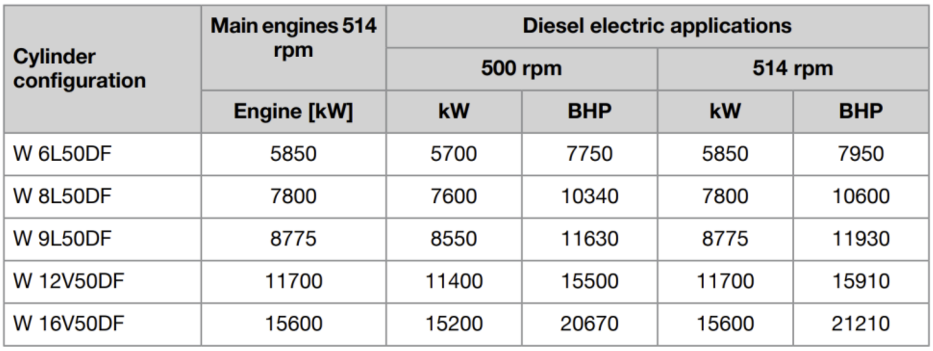
5.3. STaGE

The last propulsion plant to be examined is the Steam Turbine and Gas Engine combination arrangement. This propulsion plant is not as widespread and does not hold a large market-share as the last two we examined (DFDE-MEGI), but it does have some very interesting characteristics like low CO_2 and NO_x emissions, reliability, versatility and future-proofing. This propulsion plant utilizes 3 Wärtsilä 6L50DF engines (Hiramatsu, et al., 2016), an MHI-MBR-XX boiler and an MHI-MRXX-II turbine (specific model to be determined later). We will approach the analysis in two parts, first of which will be the DF generators and later the Boiler and ST arrangement.

The advantageous characteristics of this propulsion plant include:

- DFEs able to utilize Skip-Firing function in order to maximize load between the remaining cylinders and sustain high efficiency.
- Fewer and smaller cylinder count DFE than the DFDE plant thus reducing OPEX (operational expenses).
- Boiler and ST arrangement which are known to be very reliable while maintaining very low OPEX (UST plant Mitsubishi).
- Installed WHRS uses DFE exhaust and cooling jacket heat to preheat water coming into the boiler, this increases the overall system efficiency.
- Twin rudder design offers high maneuverability and ability to share propulsion load between ST and PEM asymmetrically. Meaning it can fully load the ST (asymmetrical load) and maneuver the ship will one of the rudders (Hiramatsu, et al., 2016).
- This whole hybrid system ensures very low SO_x, NO_x, CO_2 emissions.

Starting from the Gas Engines (DF generators):



Cylinder configuration	Main engines 514 rpm	Diesel electric applications			
		500 rpm		514 rpm	
	Engine [kW]	kW	BHP	kW	BHP
W 6L50DF	5850	5700	7750	5850	7950
W 8L50DF	7800	7600	10340	7800	10600
W 9L50DF	8775	8550	11630	8775	11930
W 12V50DF	11700	11400	15500	11700	15910
W 16V50DF	15600	15200	20670	15600	21210

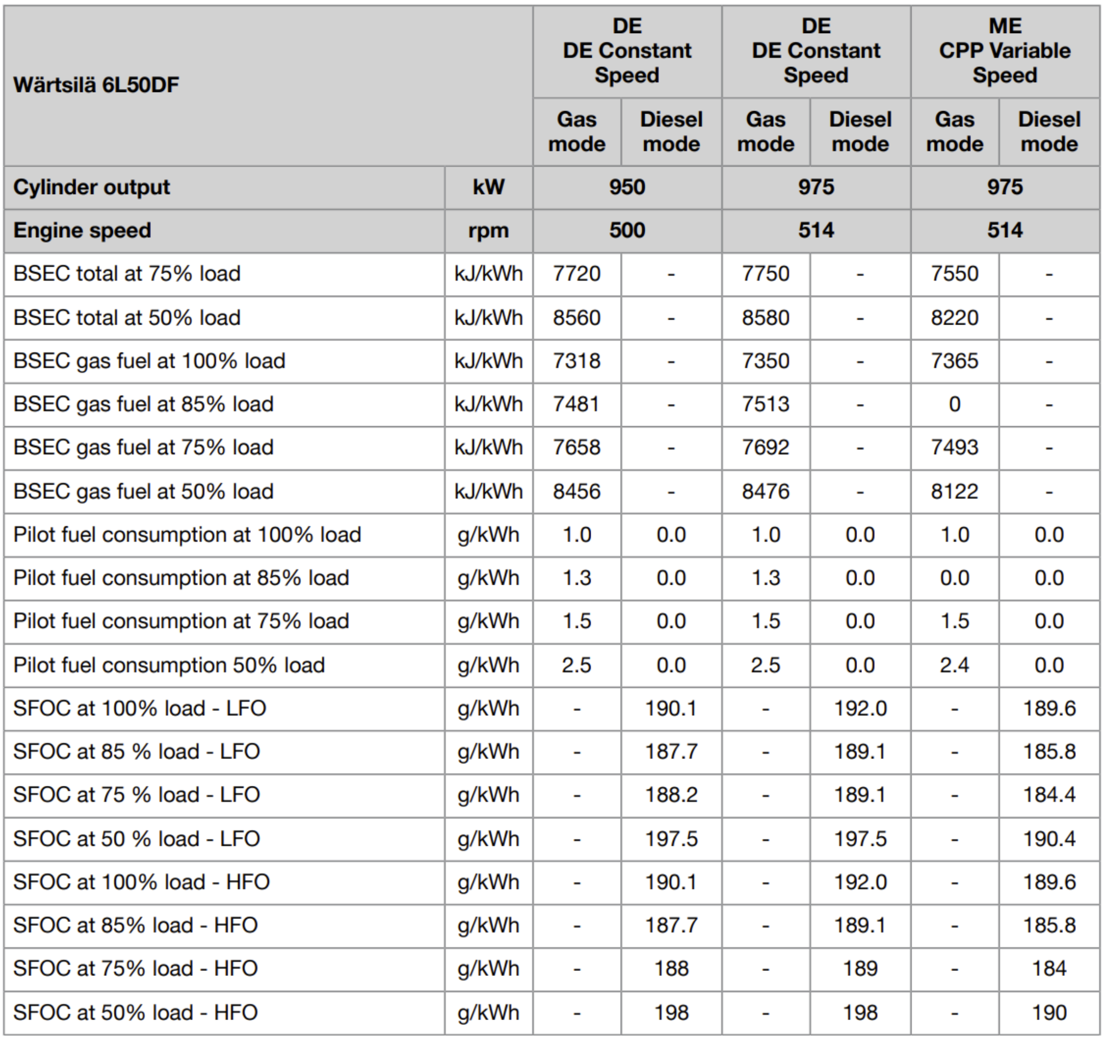
Table 5.24: Wärtsilä 6L50DF engine power output

[https://cdn.Wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9]

Same as before the ambient conditions deriving directly from the engines' manual are as follow (Wartsila DF engine manual):

- total barometric pressure 100 [kPa]
- air temperature 25°C
- relative humidity 30%
- charge air coolant temperature 25°C

Below, fuel characteristics for the 6L50DF engine can be observed.



Wärtsilä 6L50DF		**DE DE Constant Speed**		**DE DE Constant Speed**		**ME CPP Variable Speed**	
		Gas mode	**Diesel mode**	**Gas mode**	**Diesel mode**	**Gas mode**	**Diesel mode**
Cylinder output	**kW**	**950**		**975**		**975**	
Engine speed	**rpm**	**500**		**514**		**514**	
BSEC total at 75% load	kJ/kWh	7720	-	7750	-	7550	-
BSEC total at 50% load	kJ/kWh	8560	-	8580	-	8220	-
BSEC gas fuel at 100% load	kJ/kWh	7318	-	7350	-	7365	-
BSEC gas fuel at 85% load	kJ/kWh	7481	-	7513	-	0	-
BSEC gas fuel at 75% load	kJ/kWh	7658	-	7692	-	7493	-
BSEC gas fuel at 50% load	kJ/kWh	8456	-	8476	-	8122	-
Pilot fuel consumption at 100% load	g/kWh	1.0	0.0	1.0	0.0	1.0	0.0
Pilot fuel consumption at 85% load	g/kWh	1.3	0.0	1.3	0.0	0.0	0.0
Pilot fuel consumption at 75% load	g/kWh	1.5	0.0	1.5	0.0	1.5	0.0
Pilot fuel consumption 50% load	g/kWh	2.5	0.0	2.5	0.0	2.4	0.0
SFOC at 100% load - LFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85 % load - LFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75 % load - LFO	g/kWh	-	188.2	-	189.1	-	184.4
SFOC at 50 % load - LFO	g/kWh	-	197.5	-	197.5	-	190.4
SFOC at 100% load - HFO	g/kWh	-	190.1	-	192.0	-	189.6
SFOC at 85% load - HFO	g/kWh	-	187.7	-	189.1	-	185.8
SFOC at 75% load - HFO	g/kWh	-	188	-	189	-	184
SFOC at 50% load - HFO	g/kWh	-	198	-	198	-	190

Table 5.25: Fuel consumption characteristics of Wärtsilä 6L50DF engine

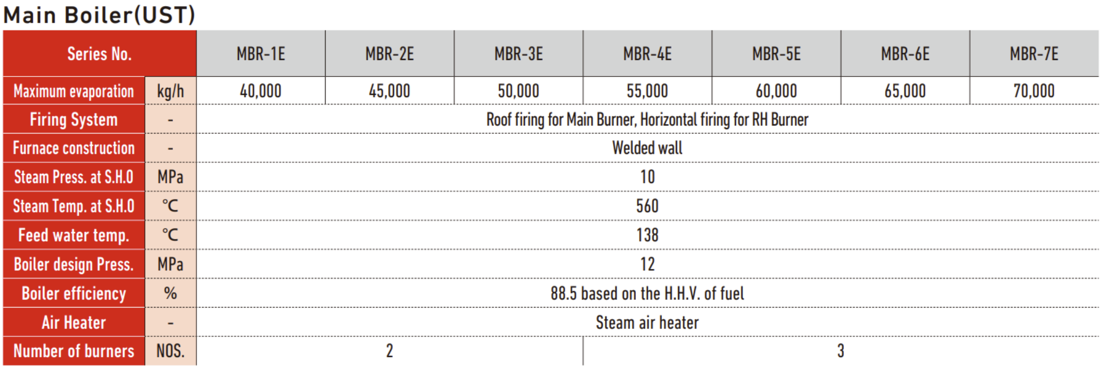
[https://cdn.Wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9#page=35&zoom=100,170,78]

These engines can produce 5850 [kW] at 514RPM each, meaning their installed power output will be 3 x 5850 = 17550 [kW]. As for the boiler and steam turbine arrangement (MBR-XX boiler and MHI-MRXX-II turbine), there is no specific data regarding specific models used. However, knowing that:

- The STaGE power management system (propulsion and electricity needs are met by the same engines) is very similar to the DFDE previously examined (Chapters 5.1), means their total installed power is 30 – 40 [MW].
- The ST needs to have similar power output to one of the two 2-stroke engines installed in the MEGI propulsion plant as they serve the same function (drive one of the twin propellers).
- According to a paper published in the Maritime University of Szczecin (Grzesiak, 2018) the estimated installed power of a STaGE plant is around 30000 [kW].

We can safely assume that the ST should be of producing about 14000 [kW], similar to 15850 [kW] of one of the 2-stroke MEGI engines examined in Chapter 5.2. As a result, given the 3 gas engines installed produce 17550 [kW] and the ST power output results in the combined output being 31550 [kW].

Taking a look at Mitsubishi Heavy Industries product detail information catalogue, we can choose the boiler and steam turbine combination of the STaGE plant considering the assumptions made above.

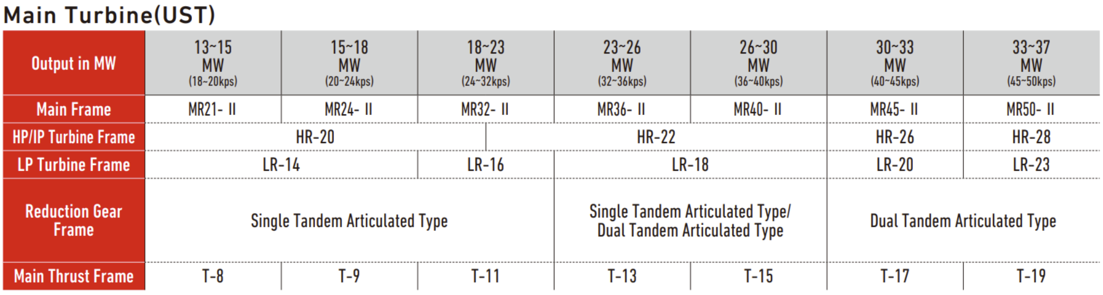


Main Boiler(UST)

Series No.		MBR-1E	MBR-2E	MBR-3E	MBR-4E	MBR-5E	MBR-6E	MBR-7E
Maximum evaporation	kg/h	40,000	45,000	50,000	55,000	60,000	65,000	70,000
Firing System	-	Roof firing for Main Burner, Horizontal firing for RH Burner						
Furnace construction	-	Welded wall						
Steam Press. at S.H.O	MPa	10						
Steam Temp. at S.H.O	℃	560						
Feed water temp.	℃	138						
Boiler design Press.	MPa	12						
Boiler efficiency	%	88.5 based on the H.H.V. of fuel						
Air Heater	-	Steam air heater						
Number of burners	NOS.	2			3			

Table 5.26: MHI product page main boiler (UST)

[https://www.mhi.com/group/mhimme/company/lib/cp_catalogue_e.pdf#page=11]



Main Turbine(UST)

Output in MW	13~15 MW (18~20kps)	15~18 MW (20~24kps)	18~23 MW (24~32kps)	23~26 MW (32~36kps)	26~30 MW (36~40kps)	30~33 MW (40~45kps)	33~37 MW (45~50kps)
Main Frame	MR21- II	MR24- II	MR32- II	MR36- II	MR40- II	MR45- II	MR50- II
HP/IP Turbine Frame	HR-20		HR-22			HR-26	HR-28
LP Turbine Frame	LR-14		LR-16	LR-18		LR-20	LR-23
Reduction Gear Frame	Single Tandem Articulated Type			Single Tandem Articulated Type/ Dual Tandem Articulated Type		Dual Tandem Articulated Type	
Main Thrust Frame	T-8	T-9	T-11	T-13	T-15	T-17	T-19

Table 5.27: MHI product page main turbine (UST)

[https://www.mhi.com/group/mhimme/company/lib/cp_catalogue_e.pdf#page=11]

And so, we choose the MBR-1E boiler along with a MR21-II turbine. The ST power output range is 13 – 15 [MW] which perfectly meets the 14000 [kW] power needs.

5.3.1. STaGE BOG utilization and SGC value

Like the previous two propulsion plant analysis, BOG utilization by the STaGE propulsion plant arrangement will be examined.

1. BOG supply and LHV
    - Same calculations as in DFDE and MEGI plants (Chapters 5.1.1 and 5.1.2)
    - BOG production is: 4407 [kg/h]
    - LHV of gas assumed to be: 46000 [kJ/kg]
2. Normal seagoing operation, SCG and BOG utilization:

We will assume the 2 DFEs operate at 85% load while the 3rd one operates at 50% load. This means:

- The 2 DFEs operating at 85% load will be outputting 2 x 4973 = 9946 [kW]
- The 1 DFE operating at 50% load will outputting 4388 [kW]
- Totaling 14334 [kW]

NORMAL LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	2		
6L50DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	5850	7350	160	1.0	1869	2538	100.0
85	4973	7513	163	1.3	1624	2783	100.0
75	4388	7692	167	1.5	1467	2940	100.0
50	2925	8476	184	2.5	1078	3329	100.0
Remaining BOG supply			2783	kg/h	No. of engines in operation		
					1		
6L50DF		Fuel Consumption Characteristics			BOG utilization for one engine		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	5850	7350	160	1.0	935	1848	100.0
85	4973	7513	163	1.3	812	1971	100.0
75	4388	7692	167	1.5	734	2049	100.0
50	2925	8476	184	2.5	539	2244	100.0

Table 5.28: 3x6L50DF engines under normal load conditions

- BOG needs for the 2 engines operating at 85% load is 1624 [kg/h]
- The remaining BOG supply is 4407 – 1624 = 2783 [kg/h]
- BOG needs for the one engine operating at 75% load is 734 [kg/h]
- Thus, remaining BOG supply is: 2049 [kg/h]

Due to limitation regarding the UST plant fuel consumption data, we will need to make some assumptions in order to proceed. Similar UST plants used have:

- Estimated SFC (diesel) of 243 [g/kWh] (Sihna & Nik, 2012).
- The STaGE plant's SFC (diesel) is about 230 [g/kWh] (Grzesiak, 2018).

LHV of gas is almost 1.2 times the LHV of diesel (50000 [kJ/kg] as opposed to 42000 [kJ/kg]). These are the values many manufacturers set as a baseline.

This translates to SFC and SGC ratios too. It can be observed in Table 5.11 by dividing SFC by the SGC. Their ratio is very close to 1.2.

The manufacturer LHV of gas is assumed to be 50000 [kJ/kg]. In our case though, we have assumed LHV of gas to be 46000 [kJ/kg].

This means assumed LHV of gas is 1.1 times the LHV of diesel. Meaning the SFC will be 1.1 times greater than SGC.

Thus, the bullet point data above can be converted:

- Estimated SGC (gas) of 221 [g/kWh].
- The STaGE plant's SGC (gas) is about 210 [g/kWh].

Boiler and ST operating conditions:

- We are assuming the boiler and turbine operates on 80% load.
- We make the assumption the SGC doesn't deviate that much (5% deviation) in the operational range of the boiler (25% - 100%).
- The power output at 80% load will be 80% x 14000 = 11200 [kW].

Multiplying SGC by the power output:

210 x 11200 = 2352000 [g/h]

Converting that to [kg/h]:

2352000 / 1000 = 2352 [kg/h]

So, in the normal load scenario the boiler estimated BOG needs are: 2352 [kg/h]

Total BOG requirements in normal load scenarios will be:

1624 + 734 + 2352 = 4710 [kg/h]

This means the natural occurring BOG can supply for:

$100\%\ x\ \frac{4407}{4710}$ = 93.6% of the fuel needs under normal load conditions

Albeit with the necessary assumptions for the boiler load due to insufficient data.

The total power output under normal load conditions is:

9946 + 4388 + 11200 = 25534 [kW]

As for overall SGC value under normal load conditions, it is given by the following equation:

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(SCG1\ x\ P1)+(SCG2\ x\ P2)+(SCG3\ x\ P3)}{Ptotal}$$

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(163\ x\ 9946)+(167\ x\ 4388)+(210\ x\ 11200)}{25534}$$

$$\mathrm{SCG}_{\mathrm{combined}} = 184.3\ [\mathrm{g/kWh}]$$

Where:

1 = DFEs at 85% load

2 = DFE at 75% load

3 = Boiler + ST at 80% load

P = output power

SCG = specific gas consumption

3. High load conditions, SCG and BOG utilization:

We will assume the 2 DFEs operate at 100% load while the 3rd one operates at 85% load. This means:

- The 2 DFEs operating at 100% load output 2 x 5850 = 11700 [kW]
- The one DFE operating at 85% load outputs 4973 [kW]
- Their total power output is 16673 [kW]

HIGH LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	2		
6L50DF		Fuel Consumption Characteristics			BOG utilization for both engines		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	5850	7350	160	1.0	1869	2538	100.0
85	4973	7513	163	1.3	1624	2783	100.0
75	4388	7692	167	1.5	1467	2940	100.0
50	2925	8476	184	2.5	1078	3329	100.0
Remaining BOG supply			2538	kg/h	No. of engines in operation		
					1		
6L50DF		Fuel Consumption Characteristics			BOG utilization for one engine		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	5850	7350	160	1.0	935	1603	100.0
85	4973	7513	163	1.3	812	1725	100.0
75	4388	7692	167	1.5	734	1804	100.0
50	2925	8476	184	2.5	539	1999	100.0

Table 5.29: 3x6L50DF engines under high load conditions

- BOG needs for the 2 engines operating at 100% load are 1869 [kg/h]
- The remaining BOG supply is 4407 – 1869 = 2538 [kg/h]
- BOG needs for the one engine operating at 85% load are 812 [kg/h]
- Thus, remaining BOG supply is: 1725 [kg/h]

As for the boiler operating conditions, just like before:

- We make the assumption the SGC doesn't deviate that much (+/– 5% deviation) in the operational range of the boiler (25% - 100%).
- We are assuming the boiler and turbine operate on 100% load.
- The power output at 100% load will be 14000 [kW].

Multiplying SGC by the power output:

210 x 14000 = 2940000 [g/h]

Converting that to [kg/h]:

$\frac{3255000}{1000}$ = 2940 [kg/h]

So, in the worst-case load scenario the boiler estimated BOG needs are: 2940 [kg/h]

Total BOG requirements in this high load scenario will be:

1869 + 812 + 2940 = 5621 [kg/h]

And thus, the natural occurring BOG can supply for:

$\frac{4407}{5621}$ = 78.4% of the fuel needs in high load scenarios

The total power output under high load conditions is:

11700 + 4973 + 14000 = 30673 [kW]

As for overall SGC value under high load conditions:

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(SCG1\ x\ P1)+(SCG2\ x\ P2)+(SCG3\ x\ P3)}{Ptotal}$$

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(160\ x\ 11700)+(163\ x\ 4973)+(210\ x\ 14000)}{30673}$$

$$\mathrm{SCG}_{\mathrm{combined}} = 183.3\ [\mathrm{g/kWh}]$$

4. Low load conditions, SCG and BOG utilization:

We are assuming the 1 DFE operate at 85% load:

- The DFE will be producing 4973 [kW]
- This enough for any power needs (accommodation, motors, bridge etc.)

For the boiler:

- Making the necessary assumptions as before the boiler SGC does not deviate much
- It is operating at 50% load producing 50% x 14000 = 7000 [kW]
- Due to the design of the STaGE propulsion system instead of 25% load per propeller (25% on the PEM and 25% on the ST) we can transfer 50% load to the ST driven propeller. This is described in the beginning of Chapter 5.3.

LOW LOAD CONDITIONS		LHV	46000	kJ/kg	No. of engines in operation		
		BOG	4407	kg/h	1		
6L50DF		Fuel Consumption Characteristics			BOG utilization for one engine		
Load	Power	BSEC	SGC	PILOT SFOC	Required	Remaining	BOG fuel
%	kW	kJ/kWh	g/kWh	g/kWh	kg/h	kg/h	%
100	5850	7350	160	1.0	935	3472	100.0
85	4973	7513	163	1.3	812	3595	100.0
75	4388	7692	167	1.5	734	3673	100.0
50	2925	8476	184	2.5	539	3868	100.0

Table 5.30: 2x6L50DF engines under high load conditions

- The required BOG by the DFEs is: 812 [kg/h]
- The remaining supply is 3595 [kg/h]

As for the boiler the required BOG supply is:

210 x 7000 = 1447000 [g/h]

Converting:

$$\frac{1447000}{1000} = 1447 \text{ [kg/h]}$$

The natural BOG is capable of fully suppling the vessel in low load conditions. The excess BOG is:

4407 – 812 – 1447 = 2148 [kg/h]

As for SGC value under low load conditions:

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(SCG1\ x\ P1)+(SCG2\ x\ P2)+(SCG3\ x\ P3)}{Ptotal}$$

$$\mathrm{SCG}_{\mathrm{combined}} = \frac{(163\ x\ 4973) + (210\ x\ 7000)}{12850}$$

$$\mathrm{SCG}_{\mathrm{combined}} = 177.5 \text{ [g/kWh]}$$

5.3.2. STaGE propulsion plant efficiency

The Wärtsilä 6L50DF engines have an electrical efficiency of 49.4% when operating at 100% load, just like the DFDE plant in Chapter 5.1. To find the total efficiency of the DE part of STaGE, we will need the propulsion plant's installed system components along with their efficiency values (Grzesiak, 2018):

- Converters (96%)
- PEM (98%)
- Gearbox (98%)
- Shafting (99%)

Which is equal to 45.1%.

We will now focus on the other half of the propulsion plant, the UST system. UST systems are known to have around 35% efficiency, though with improved superheat and reheat technologies modern UST's efficiency can reach 40%.

Such UST plants have the following component efficiency values (Grzesiak, 2018):

1. Boiler efficiency 88.5% (MHI-MBR-1E)
2. Steam turbine 46%
3. Gearbox 98%
4. Shafting 99%

Totaling in 39.5% efficiency for the UST plant.

The combined efficiency of the STaGE propulsion plant is:

$$\eta = \frac{Total\ power\ output}{Total\ power\ input} = \frac{14000 + 17550}{35443 + 38914} = 42.4\%$$

Where:

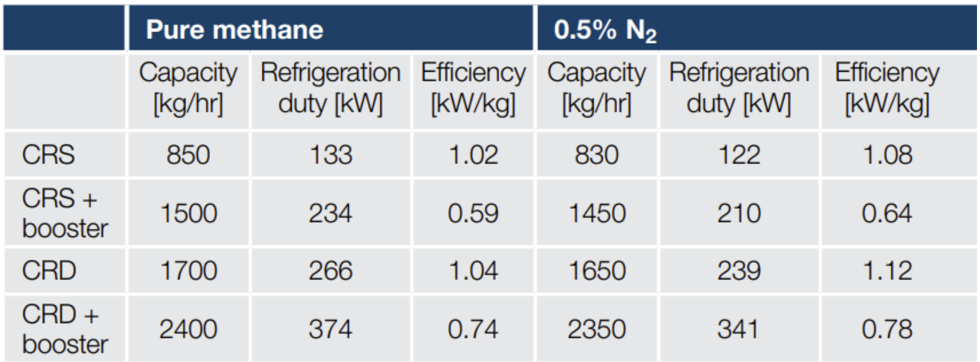
- Power input the ST propulsion: $\frac{14000}{39.5\%}$ = 35443 [kW]
- Power input the DFEs: $\frac{17550}{45.1\%}$ = 38914 [kW]

We have to keep in mind though the wasted heat recovery from the DFDE part of the plant. The WHRS drawing heat from the DFEs cooling jackets and exhaust gases is responsible for up to 5% overall efficiency gains (Eunice & Prause, 2020).

This means the overall efficiency of the STaGE propulsion system is estimated to be around 47.4%.

5.4. Partial reliquefaction

A full reliquefaction plant is uneconomical with too high of a CAPEX. In 2020 however Wärtsilä released the Compact Reliq (Wärtsilä Compact Reliq), a compact reliquefaction (RLQ) unit designed specifically for medium ships like the one in this case study. The company claims this system is very light on maintenance, in need of it once every drydocking. The technical specifications can be seen below:



	Pure methane			0.5% N_2		
	Capacity [kg/hr]	Refrigeration duty [kW]	Efficiency [kW/kg]	Capacity [kg/hr]	Refrigeration duty [kW]	Efficiency [kW/kg]
CRS	850	133	1.02	830	122	1.08
CRS + booster	1500	234	0.59	1450	210	0.64
CRD	1700	266	1.04	1650	239	1.12
CRD + booster	2400	374	0.74	2350	341	0.78

Table 5.31: Wärtsilä Compact Reliq technical specifications

We will calculate for each of the RLQ systems listed above the excess BOG supply reliquefaction savings across the 3 different propulsion plants.

The average time a ship operates its main propulsion system per year is 5000 hours. We assume:

- 2500 hours are laden voyage
- 10% of those (250 hours) are in low load conditions
- 5% of those (125 hours) are under high load conditions

Laden voyage hours per year [h]		2500	DFDE	MEGI	STaGE
Load condition	Operation percentage [%]	Operating hours [h]	Excess BOG [kg/h] after utilizing it for fuel		
Normal Load	85	2125	76	323	-303
High Load	5	125	-1007	-956	-1214
Low Load	10	250	2241	1878	2148

Table 5.32: Laden voyage operation hours

Where the minus (-) symbol is displayed means the natural BOG supply is not enough for a complete 100% gas mode operation.

It is safe to assume the majority of the LNG is pure methane. In reality it is closer to 90% (Chapter 1.1). Having the RLQ capacity for each system and produced BOG under normal and low load (we exclude high load as there is no BOG left) we can calculate the BOG leftover after reliquefaction across the different RLQ systems, as shown on Table 5.33 of the following page.

RLQ System	RLQ capacity [kg/h]	Load condition	DFDE	MEGI	STaGE
			Excess BOG supply [kg/h] after RLQ		
CRS	850	Normal Load	0	0	0
		Low Load	1391	1028	1298
CRS + booster	1500	Normal Load	0	0	0
		Low Load	741	378	648
CRD	1700	Normal Load	0	0	0
		Low Load	541	178	448
CRD + booster	2400	Normal Load	0	0	0
		Low Load	0	0	0

Table 5.33: Excess BOG supply after the RLQ process

Knowing:

- Operating hours per year under normal and low load conditions
- RLQ system capacity
- Excess BOG supply

We can calculate reliquefied BOG per year as shown below:

RLQ System	DFDE	MEGI	STaGE
	Total BOG RLQ per year [tn/year]		
CRS	374	899	213
CRS + booster	537	1061	375
CRD	587	1111	425
CRD + booster	722	1156	537

Table 5.34: BOG RLQ per year for each propulsion system

As for the RLQ systems' fuel needs:

- The refrigeration power needs for the different RLQ systems are known and can be found in the technical specifications Table 5.31.
- We assume the power generation sets (V50DF, L50DF, L34DF) operate most of the time at 85% load requiring 163 g/kWh. They are the ones that provide power to the RLQ system.
- Assuming that power losses from D/Gs to the requalification system's switchboard are minimal, we can calculate the LNG fuel used for the RLQ plant's operation:

RLQ System	Refrigeration duty [kW]	LNG consumpiton for operation [kg/year]
CRS	133	51488
CRS + booster	234	90587
CRD	266	102975
CRD + booster	374	144785

Table 5.35: LNG consumption for each RLQ system operation

Using the information from Tables 5.34 and 5.35:

- LNG spent for RLQ plant operation
- BOG reliquefied back into LNG

We can calculate the net BOG that is saved and reliquefied back into LNG. The reliquefied gas per year for each propulsion plant and RLQ system combination can be seen below:

RLQ System	DFDE	MEGI	STaGE
	LNG RLQ [tn/year]		
CRS	323	847	161
CRS + booster	446	971	284
CRD	484	1008	322
CRD + booster	577	1011	392

Table 5.36: LNG RLQ per propulsion plant and RLQ system

Now depending on LNG spot rate this can achieve different amounts of savings. The initial investment value is also very difficult to predict.

5.5. EEDI calculation for each propulsion plant

Energy Efficiency Design Index (EEDI) is used to represent a ships efficiency based on the carbon dioxide emission per ton per mile transferred [gCO_2 / ton-mile]. According to the MPEC (Marine Environment Protection Committee), the formula used for EEDI can be used for LNG carrier propulsion plants like the ones used in this case study. The formula basis is the following:

$$\boxed{\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}**\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}}$$

Picture 5.6: EEDI formula

DFDE				
S/N	Parameter	Formula or Source	Value	Unit
1	V_{ref}	Vessel service speed	19.5	kn
2	Capacity	DWT of case study vessel	89000	DWT
3	MPP_{MOTOR}	MCR of PEM	14000	kW
4	η	efficiency of converter, alternator and PEM	0.918	-
5	P_{ME}	$0.83 \times MPP_{MOTOR} / \eta$	12658	kW
6	P_{AE}	$(0.025 \times 2 \times MPP_{MOTOR}) + 250$	950	kW
7	$C_{F\ LNG}$	Fuel based coefficient for LNG	2.750	-
8	$C_{F\ MDO}$	Fuel based coefficient for MDO	3.206	-
9	$SFC_{ME\ LNG}$	Specific Fuel Consumption of LNG	187.7	g/kWh
10	$SFC_{ME\ PilotFuel}$	Specific Fuel Consumption of diesel pilot fuel	1.5	g/kWh
11	$SFC_{AE\ LNG}$	Specific Fuel Consumption of AE LNG	206.8	g/kWh
12	$SFC_{AE\ PilotFuel}$	Specific Fuel Consumption of AE diesel pilot fuel	2.5	g/kWh
11	$EEDI_{DFDE}$	$[(2 \times P_{ME} \times C_{F\ LNG} \times SFC_{ME\ LNG}) +$ $(2 \times P_{ME} \times C_{F\ PilotFuel} \times SFC_{AE\ PilotFuel}) +$ $(P_{AE} \times C_{F\ LNG} \times SFC_{ME\ LNG} +$ $P_{AE} \times C_{F\ PilotFuel} \times SFC_{AE\ PilotFuel})] /$ $(V_{ref} \times Capacity)$	7.88	gCO_2/tnm

Table 5.37: DFDE EEDI calculations

MEGI				
S/N	Parameter	Formula or Source	Value	Unit
1	V_{ref}	Vessel service speed	19.5	kn
2	Capacity	DWT of case study vessel	89000	DWT
3	MCR_{MEGI}	MCR of MEGI engine	15850	kW
5	P_{ME}	0.75 x MCR_{MEGI}	11888	kW
6	P_{AE}	(0.025 x 2 x MCR_{MEGI}) + 250	1042.5	kW
7	$C_{F\ LNG}$	Fuel based coefficient for LNG	2.750	-
8	$C_{F\ MDO}$	Fuel based coefficient for MDO	3.206	-
9	$SFC_{MEGI\ LNG}$	Specific Fuel Consumption of MEGI LNG	161.6	g/kWh
10	$SFC_{MEGI\ PilotFuel}$	Specific Fuel Consumption of MEGI diesel pilot fuel	3	g/kWh
11	$SFC_{AE\ LNG}$	Specific Fuel Consumption of AE LNG	206.8	g/kWh
12	$SFC_{AE\ PilotFuel}$	Specific Fuel Consumption of AE diesel pilot fuel	2.5	g/kWh
13	$EEDI_{MEGI}$	[(2 x P_{ME} x $C_{F\ LNG}$ x $SFC_{ME\ LNG}$) + (2 x P_{ME} x $C_{F\ PilotFuel}$ x $SFC_{ME\ PilotFuel}$)+ (P_{AE} x $C_{F\ LNG}$ x $SFC_{AE\ LNG}$ + P_{AE} x $C_{F\ PilotFuel}$ x $SFC_{AE\ PilotFuel}$)]/ (V_{ref} x Capacity)	6.49	gCO_2/tnm

Table 5.38: MEGI EEDI calculations

STaGE				
S/N	Parameter	Formula or Source	Value	Unit
1	V_{ref}	Vessel service speed	19.5	kn
2	Capacity	DWT of case study vessel	89000	DWT
3	MPP_{MOTOR}	MCR of PEM	14000	kW
4	η	efficiency of converter, alternator and PEM	0.918	-
5	P_{ME-MPP}	0.83 x MPP_{MOTOR} / η	12658	kW
6	MCR_{ST}	MCR of ST	14000	kW
7	P_{ME-ST}	P_{ME-ST} = 0.83 x MCR_{ST}	11620	kW
8	P_{AE}	(0.025 x (MPP_{MOTOR} + P_{ME-ST})) + 250	950	kW
9	$C_{F\ LNG}$	Fuel based coefficient for LNG	2.750	-
10	$C_{F\ MDO}$	Fuel based coefficient for MDO	3.206	-
11	$SFC_{ME\ LNG}$	Specific Fuel Consumption of LNG	187.7	g/kWh
12	$SFC_{ME\ PilotFuel}$	Specific Fuel Consumption of diesel pilot fuel	1.5	g/kWh
13	$SFC_{AE\ LNG}$	Specific Fuel Consumption of AE LNG	206.8	g/kWh
14	$SFC_{AE\ PilotFuel}$	Specific Fuel Consumption of AE diesel pilot fuel	2.5	g/kWh
15	SFC_{ST}	Specific Fuel Consumption of ST	230	g/kWh
16	$EEDI_{STaGE}$	[(P_{ME-MPP} x $C_{F\ LNG}$ x $SFC_{ME\ LNG}$ + P_{ME-MPP} x $C_{F\ PilotFuel}$ x $SFC_{AE\ PilotFuel}$) + P_{ME-ST} x $C_{F\ LNG}$ x $SFC_{ME\ LNG}$ + (P_{AE} x $C_{F\ LNG}$ x $SFC_{ME\ LNG}$ + P_{AE} x $C_{F\ PilotFuel}$ x $SFC_{AE\ PilotFuel}$)] / (V_{ref} x Capacity)	8.32	gCO_2/tnm

Table 5.39: STaGE EEDI calculations

6. Chapter 6: Results

After calculating all the needed data for the comparison of the following propulsion systems:

- DFDE (Dual Fuel Diesel Electric)
- MEGI (MAN ME 2-stroke Gas Injection)
- STaGE (Steam Turbine and Gas Engine)

We can create the following table:

Propulsion Systems		DFDE	MEGI	STaGE
Efficiency [%]	Non-Optimized	45.1%	50.6%	47.4%
	Optimized	50.0%	[-]	[-]
SGC [g/kWh]	Normal Load	163	136	184
	High Load	163	141	183
	Low Load	163	151	177
Power [kW]	Normal Load	26520	31696	25534
	High Load	33150	38036	30673
	Low Load	13260	16710	11973
Fuel attributed to BOG [%]	Normal Load	100%	100%	93.6%
	High Load	81.4%	85.0%	78.4%
	Low Load	100%	100%	100%
Remaining BOG supply [kg/h]	Normal Load	76	323	-303
	High Load	-1007	-956	-1214
	Low Load	2241	1878	2148
Total BOG [tn/year] used as fuel and/or combusted	Normal Load	9364.9	9364.9	10008.8
	High Load	676.8	670.4	702.6
	Low Load	1101.8	1101.8	1101.8
	SUM	11143.4	11137.0	11813.1
Diesel Pilot Fuel [tn/year] (Estimated to be about 1.5% w/w of gas fuel)	Normal Load	138.1	130.2	150.1
	High Load	10.2	10.1	10.5
	Low Load	8.1	9.5	8.5
	SUM	156.3	149.7	169.1
EEDI [gCO$_2$/tnm]		7.99	6.49	8.32

Table 6.1: DFDE – MEGI – StaGE comparison

Important things regarding the Table 6.1:

1. Regarding Efficiency Values
    - Optimized efficiency values for DFDE system specifically are based on WHRS and improved PMS implemented recently. Results are promising but due to limited real-world data, they are yet to be proven 100%.
    - MEGI also has room for efficiency improvement in the range of 1 – 2% using WHRS. Though, they are also in very early stage and thus we have yet to see promising results.
    - As for the STaGE system, this thesis was conservative and underestimated efficiency values as specific values of boiler and ST arrangement system are yet to be released officially from the manufacturer. It is possible that the WHRS and ST arrangement grant greater efficiency gains to the whole system.
2. Specific Gas Consumption
    - Calculations for both DFDE and STaGE systems were made based on the assumption that Gas LHV is 46000 [kJ/kg]. This value was established based on BOG ageing and other reasons explained in Chapter 3.5.1.
    - MEGI engine data was directly pulled from the manufacturer’s engine manual. The manual assumes Gas LHV at 50000 [kJ/kg].
    - Given the last two bullet points, the SGC for DFDE and STaGE could be about 8% lower than the stated.
    - The lower the load the better the SGC values of STaGE plant become. This makes it ideal for situations where frequent low speed maneuvering is needed. The exact opposite is true for MEGI plants, while the DFDE PMS systems manage to keep the load thus their SGC constant.
3. Generated Power
    - Under normal operating conditions DFDE and STaGE operate at 26 [MW] this is enough for 22 [MW] for propulsion (11 [MW] for each propeller shaft) and the remaining for various other power needs like accommodation, bridge, water colling motors, sea chest motor and steering gear motors.
    - MEGI propulsion plant is assumed to operate at 32 [MW] and although this might be a bit overestimated, it is certain that is going to be higher than the other two plants. Due to better SGC values companies can afford to operate the 2-stroke engines at higher load than their DFDE counterparts.
    - The same is true for high load conditions with MEGI being able to operate with almost the same fuel demand under higher power output.
    - During low load conditions DFDE and STaGE plants operate on lower power outputs but offer far greater maneuvering and ahead/astern timing.

4. Fuel attributed to natural BOG
    - Natural BOG in such vessels will either be used on burnt on GCU. DFDE and MEGI propulsion plants can operate 100% on gas mode under normal and low load conditions. Their excess BOG is burnt in the GCU and used for heating throughout the ship.
    - STaGE having the worse fuel economy over the other two plants needs forced BOG to operate 100% on gas under normal load.
    - Under high load however all three plants need forced BOG to operate entirely on gas mode.
5. Remaining BOG supply
    - Positive values represent excess BOG supply, in which case it will be burned in the GCU
    - Negative values mean the natural BOG is not enough to supply for the propulsion plant gas needs. In this case forced producing BOG will be the most probable option.
6. Total BOG used
    - This value accounts for the total BOG that is used as fuel and/or used in the GCU. In both cases this viewed as LNG cargo loss and it is represented by tones per year [tn/year].
    - Having a partial RLQ plant on board like the one described in Chapter 5.4 can reduce BOG use per year.
7. Diesel Pilot Fuel used
    - As referenced several times during the past chapters, even when an engine operates entirely on gas mode a small amount of diesel fuel is injected to function as primer for the air fuel mixture.
    - This ratio is estimated to be around 1 – 2% depending on current engine load. We assume the ratio to be 1.5% w/w of the gas fuel used.
    - For the calculation, gas fuel demands were multiplied by 1.5% across the different power loads and propulsion plants. Taking into account the operating conditions and duration as stated on Chapter 5.4.

Depending on the RLQ system used, the yearly BOG losses per propulsion plant are reduced and are as follow:

Propulsion Systems		DFDE	MEGI	STaGE
Total BOG [tn/year] used as fuel and/or combusted		11143.4	11137.0	11813.1
Total BOG [tn/year] used as fuel while the excess is partially reliquified	CRS	10820.9	10289.6	11652.1
	CRS + booster	10697.5	10166.2	11528.7
	CRD	10659.9	10128.6	11491.1
	CRD + booster	10566.4	10125.9	11420.9

Table 6.2: BOG use [tn/year] based on RLQ system and plant

Viewing the values above as percentage of BOG use reduction over the plants with no RLQ arrangement results in the following table:

Propulsion Systems		DFDE	MEGI	STaGE
BOG % savings depending on the RLQ system installed	CRS	2.9%	7.6%	1.4%
	CRS + booster	4.0%	8.7%	2.4%
	CRD	4.3%	9.1%	2.7%
	CRD + booster	5.2%	9.1%	3.3%

Table 6.3: BOG reduction use based on RLQ system and plant

As we can observe different propulsion plants and different partial RLQ plants give varying results.

- The MEGI propulsion plant seems to benefit from the CRS + booster arrangement as the bigger RLQ plants offer minimal improvement.
- The DFDE plant seems to benefit from a CRD + booster arrangement as it seems to significantly improve BOG savings.
- Lastly the STaGE propulsion, being the most power hungry may not be economically viable to install a RLQ plant as even the largest of them offer minimal results.

The three bullet points mentioned above neglect the initial investment and maintenance cost of the RLQ plants. Meaning an economic analysis might suggest completely different optimal combination.

Lastly, special characteristics per propulsion plant along with BOG utilization ways for each plant.

Special Characteristics		
DFDE	MEGI	STaGE
ENGINE ROOM SIZE		
Small	Normal	Small
FUEL COSTS		
Medium	Low fuel but added lubricating cylinder oil	Medium - High
MAINTAINANCE COSTS		
High 4 x 4-stroke engines (39 cylinders) 2 x PEM (Low maintenance) Auxiliary machinery	High 2 x 2-stroke engines (12 cylinders) 4 x 4-stroke engines (24 cylinders) Auxiliary machinery	Low 3 x 4-stroke engines (18 cylinders) 1 x Boiler (Very low maintenance) 1 3-stage ST (Very low maintenance) Auxiliary machinery
RELIABILITY + REDUNDANCY		
High reliability High redundancy	High reliability Medium redundancy	High reliability Medium redundancy
MANEUVERABILITY		
High	Low	Medium High
BOG UTILIZATION – RELIQUEFACTION PLANT		
Burn as fuel and partial RLQ	Burn as fuel and partial RLQ	Burn as fuel or used in the GCU

Table 6.4: DFDE – MEGI – STaGE special characteristics

All three of the examined propulsion plants fully utilize the produced BOG under high load conditions. All three also have leftover BOG during low load operation. Both low and high load conditions are rare in an LNGC voyage. However, under normal operation loads the DFDE and MEGI have leftover BOG. This is important as they spent the majority of their time in operation under this condition. As was suggested, equipping some kind of partial RLQ system in DFDE and MEGI plants can achieve 5.2% and 8.7% BOG savings, respectively, during the ship's operation.

7. Conclusions

With the environment taking a toll by human emission generation clever energy management and improving efficiency has become a necessity. Maritime transport has been and will continue to be one of the leading ways of transferring LNG.

This thesis calculated the BOG supply for a conventional LNGC with a carrying capacity of 174000 [m^3]. Using the calculated BOG supply and several different propulsion plant types it was concluded that many of them operate and consume around 90% of the natural BOG supply on most of the situations. The common practice is to force produce more if needed and control combust the rest if excess BOG is generated.

Moving into the main part of the thesis, making the necessary assumptions, using the BOG supply, the BOG LHV, setting up the installed propulsion plants, specific engine models and their SGC it became possible to calculate the BOG utilization by the propulsion plants for 3 different power load scenarios.

After the comparison some key points were evident. Yes, a 2-stroke powered propulsion plant will offer the best possible efficiency during normal seagoing operation, but lack greatly when the vessel speed reduces to lower than 13 to 14 [kn]. A PEM driven ship does not have the same peak efficiency as a 2-stroke driven one but manages to maintain its efficiency during lower speed maneuvers. With the increasing number of ships requiring delicate maneuvering at low speeds near ports and passages densely packed with terminals and other ships it is important to maintain high efficiency under these conditions. Same goes for the STaGE plant, due to the propulsion plant PMS it can retain high maneuverability during low-speed operation while also being economically viable during normal voyage conditions. As for the emissions the STaGE plant has the lowest followed by the DFDE and the MEGI plant at last.

Concluding, at first glance it is easy to judge each propulsion system by its efficiency value and SGC/SFC, though when looking deeper there are more characteristics that define each plant. The DFDE and MEGI plants have high maintenance costs but lower fuel consumption costs, with the MEGI having the lowest fuel costs. The STaGE system has the lowest maintenance costs coupled with a reliable almost maintenance-free boiler and ST arrangement. As for the BOG utilization by each system, it follows the SGC and efficiency values for each plant. STaGE being the more inefficient utilizes the most of the available BOG followed by the DFDE and MEGI plants. The remaining BOG is of a small supply but important nonetheless, having a partial RLQ system can save thousands of tons of LNG from evaporating during an LNGC lifetime.

8. Recommendations

Having three different propulsion plant methods under investigation meant several assumptions needed to be made in order for this thesis to be completed in a timely manner. Thus, some recommendations and future project ideas will be given so one can use by building on top of this thesis.

One of the future ideas is for an in-depth analysis of the STaGE propulsion system. It is undoubtably one of the most interesting propulsion plant arrangements to date. Its unique features being the asymmetrical engine room with one propeller shaft driven by the ST and the other driven by PEM and the combination of 4-stroke engines coupled with boiler and ST arrangement. The DFE engines are already known, with exact model and specifications values. As for the boiler and ST models assumptions needed to be made because of the limited data. The efficiency of the system is also unspecified, without any official source stating it. A future project could undertake finding the exact models for the boiler and ST arrangement along with the energy recovered from the WHRS. With this data available one could calculate specific efficiency values along with SGC values for the overall system across the whole operational range. Of course, EEDI and EEXI would also be more representative values in determining the plant's efficiency. Moving into the economics of such plant, CAPEX, OPEX could also be calculated. Values for EEDI, EEXI, CAPEX and OPEX could then, be used to compare the STaGE plant with others. Such plant has great future proofing as the DFDE engine could be replaced with TFDE, using alternative fuel sources. The boiler and ST arrangement have very low maintenance OPEX and proving good efficiency gains can result in this arrangement being a great choice when deciding a newbuilding's propulsion.

The second recommendation is about the partial reliquefaction method. As stated, CAPEX for reliquefaction on anything smaller that Q-max LNGC is too high to be a viable option. Most LNGC just use the available BOG for fuel and burn the rest on a GCU. In this thesis however, it was presented that partial reliquefaction can save lots of LNG tons per year let alone across a 25-year lifespan of an LNGC. This means the RLQ systems presented could be economically viable with a low enough of CAPEX. The intricacies of such system are numerous and worth examining. A detailed technical and economic analysis of a partial reliquefaction system is the only way to prove its viability as only recently has seen real life use and its long-term benefits are still unknown.

Lastly, as mentioned on Chapter 5.1 DFDE plants and generally power generating sets coupled with PEM can greatly benefit from advanced PMS. Developing an advanced powered management system that can be used on already deployed DFDE ships in operation can achieve low effort efficiency gains. This PMS can be the primary guide on load management between engines, start and stop parameters, and engine operation combinations. On newbuildings, this could mean installing different engine combinations in order to improve the load sharing and optimal engine combination and consequently improving the efficiency across a wider operational range.

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