AN ANALYSIS OF THE PROPULSION AND POWERING OPTIONS FOR LNG CARRIERS

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DECLARATION

I, Effiong Ekanem Attah, confirm that the work presented in this thesis is my own. Where information has been gathered from other sources, I confirm that this has been indicated in the Thesis.

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August 15, 2020.

ABSTRACT

The work presented in this thesis provides a comprehensive analysis of the propulsion and powering options for future LNGCs (Liquid Natural Gas Carriers) using academic methods and operational measurements.

An analytical study of the LNGC fleet using the EEDI methodology was used initially from which it was concluded that the legislated performance requirements of the current EEDI protocol is insufficient to stimulate the design improvements needed to reduce the CO_2 footprint of the LNGC fleet. The research further demonstrated that multiple baselines for different LNGC propulsion technologies would yield improved reductions of CO_2 more compatible with the long term IMO (International Maritime Organisation) goal of reducing CO_2 emissions by 50%. The issue of methane slip was also considered in the analysis because it has an impact on propulsion efficiency and the knowledge that methane is also a greenhouse gas. A method of calculating methane slip was developed to be included in proposed modified EEDI calculations revealing the need to ensure a holistic approach to atmospheric emissions impact is needed.

Using modelling and simulation methods, case studies were undertaken to explore improvements to the current designs. Furthermore, when a comparative analysis of the different modern designs and upgraded options were carried out, it was seen that modern DFDE (dual fuel diesel engine) designs showed the highest efficiency and operational flexibility of the various options, due to its flexibility in the use of multiple prime movers which increases the reliability of these engines.

By analysing the operational data carried out during practical case studies on-board LNGCs, it was determined that the operational profile differs markedly from the design profiles often presented in the literature. Sea trials conditions were found to be non-representative of realistic operational conditions hence the research focused on identifying methods where trial profiling could be better used to predict actual performance. Finally, the research also highlighted the specific operational safety practices carried out by ship operators which reduce the efficiency of the vessel below the design point and identified tested methods to reduce inefficiencies in these practices.

IMPACT STATEMENT

The LNG Shipping industry and its associated propulsion systems is largely an under-researched area as shown by the insufficiency of reference material encountered during this research. This coupled with the constant change of propulsion technologies within the industry largely exacerbates the dearth of knowledge required in this constantly changing field. One key knowledge gap identified is in the design and operation of LNG Carriers (LNGCs) with regards to efficiency. This research tackled this deficit by covering three areas; analytical study of the current and future fleet using the Energy Efficiency Design Index (EEDI), Case studies of LNGCs in actual sea going operations, and design improvements of LNGCs to achieve improvements in efficiency.

The EEDI analytical study highlighted its inadequacy in stimulating design improvements within the LNGC industry as the single baseline method adopted for the different propulsion system offers a selective and ineffective outcome. Methane slip was also identified and analysed, and its adverse impact of not including it in EEDI calculations. This work proposed multiple baselines for the LNGC industry as well as creating a factor to include methane emissions into EEDI calculations. The case studies highlighted a clear disparity between the design and actual operational characteristics of LNGCs due to a prioritisation of the safety operation of these vessels by ship operators. The design improvements on LNGCs showed that the DFDE while matched with the Direct Drive Diesels (DDD) systems in terms of efficiency, the use of multiple prime movers increases the reliability of the DFDE design over and above the DDD systems. The efficiency gains of the Steam Turbine Propulsion System (STPS) were not sufficient to favourably compare with other modern LNGC propulsion systems.

The multiple baselines proposed will ensure specific technological improvements would be carried out so as to achieve the IMO goal of reducing CO_2 emissions by 50%. The quantification and reduction of methane slip would yield similar results. The proposed method for improving operational efficiency not only has commercial benefits but also can be included in the design of LNGCs so as to satisfy the safety operation required by operators. The design improvements highlight future direction for LNGCs so as to achieve efficiency improvements, emissions reduction, and regulatory compliance.

ACKNOWLEDGEMENTS

I would like to give a special thanks to my supervisor, Professor Richard Bucknall, for the support and patience he has given me through what has been a very fulfilling PhD. Mere words can't express my appreciation for all the help he has accorded me.

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Dedication

This work is dedicated to my daughter Inyang, my country Nigeria, and to London, a city very much after my heart.

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NOMENCLATURE

The following nomenclatures have been used in this Thesis.

[Nomenclature]	[Definition]
$\eta_{electrical}$	Electrical Efficiency
BOR	Boil Off Rate (%)
C_f	Carbon Factor
COP	Coefficient of Design Performance
COP_{comp}	Design Power of compressor (KWh/kg)
DWT	Deadweight (Tonnes)
EEDI	Energy Efficiency Design Index (gCO_2/tNM)
EEOI	Energy Efficiency Operational Indicator (tCO_2/t.NM)
MCR	Maximum Continuous Rating (KW)
P_{AE}	Auxiliary Engine Power (KW)
P_{ME}	Main Engine Power (KW)
R_{Reliq}	Ratio of Boil of Gas to Re-liquefied Boil Off Gas
SFC	Specific Fuel Consumption (g/KWh)
V_{ref}	Reference Speed (Knots)

ABBREVIATIONS

The following abbreviations have been used in this Thesis.

[Abbreviation]	[Definition]
BOG	Boil Off Gas
BOR	Boil Off Rate
CAPEX	Capital Expenditure
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CPP	Controllable Pitch Propeller
DC	Direct Current
DDD	Direct Drive Diesel
DF	Dual Fuel
DFDE	Dual Fuel Diesel Electric
DNV	Det Norske Veritas
ECA	Emissions Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EFD	Energy Flow Diagram
EGWHRS	Exhaust Gas Waste Heat Recovery System
EPA	Emissions Protected Area
FBO	Forced Boil Off
FPP	Fixed Pitch Propeller
FSRU	Floating Storage and Re-gasification Unit
GCU	Gas Combustion Unit
GHG	Green House Gases
GI	Gas Injection
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HHI	Hyundai Heavy Industry
hp	High Pressure

HRSG	Heat Recovery Steam Generator
HTS	High Temperature Superconductivity
IFO	Intermediate Fuel Oil
IMO	International Maritime Organisation
ip	Intermediate Pressure
ISO	International Standards Organisation
LCC	Life Cycle Cost
LD	Low Duty
LNG	Liquefied Natural Gas
LNGC	Liquefied Natural Gas Carrier
lp	Low pressure
LSDO	Low Sulphur Diesel Oil
MARPOL	Marine Pollution
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
ME-GI	M-Type Electronically controlled Gas Injection
MEPC	Marine Environment Protection Committee
MHI	Mitsubishi Heavy Industries
MPP	Maximum Propulsive Power
MT	Main Turbine
NG	Natural Gas
OPEX	Operating Expenditure
OPL	Off Port Limits
SEEMP	Ship Energy Efficiency Management Plan
SSDE	Slow Speed Diesel Engine
SSDR	Slow Speed Diesel with Re-liquefaction plant
STPS	Steam Turbine Propulsion System
T/A	Turbo Alternator
UCL	University College London
WHRS	Waste Heat Recovery System

1.

INTRODUCTION

1.1 Background and Motivation

The use of natural gas (NG) has increased dramatically over the past two decades. This is mainly as a result of supply abundance, low cost and reduction of Nitrogen Oxide (NOx) and Sulphuric Oxide (SOx) emissions. Another advantage that NG offers is it produces less Carbon Dioxide (CO_2) emissions, than the other established fossil fuels, as highlighted in Figure 1. Over the past 20 to 25 years, the main driver has been cost, although over the past 10 years the impact of CO_2 emissions is becoming more a relevant factor. This has led to NG becoming an even more dominant fuel for electricity generation and heating in many countries.

Type of Fuel	Emission factors ($t\ CO_2$ / t fuel)
Heavy Fuel Oil	3.114
Light Fuel Oil	3.151
Diesel/Gas Oil	3.206
Liquefied Petroleum Gas (Propane)	3.000
Liquefied Petroleum Gas (Butane)	3.030
Liquefied Natural Gas	2.750
Methanol	1.375
Ethanol	1.913

$$CO_2 \text{ Emissions} = \text{Fuel consumption} * \text{Emission factor}$$

Figure 1: CO_2 Emission Factors per fuel type. Source: [1]

To meet ongoing rise in demand, Natural Gas (NG) is increasingly being stored and transported in liquid form, Liquefied Natural Gas (LNG). By cooling to -160°C it occupies 600 times less volume thereby making it easier and cheaper to transport to market by use of specially designed cryogenic vessels - LNG Carriers (LNGC).

Use of LNGCs is a cost effective way of transporting NG over long distances where long transmission pipelines do not exist. However, transportation must occur between specially designed LNG terminals. At the loading port NG is liquefied and loaded into the LNGCs whilst at the unloading port the LNG is re-gasified, after which it is typically distributed by a national grid pipeline to consumers [1].

According to the Clarkson's LNGC Fleet database [2] As at September 2017 there are 495 LNGCs in operation [2] which range from the smaller vessels used for coastal operations (Length: 80m Capacity: 2500m^3) to the large QMax type (Length: 345m, Capacity: 267,000m^3), although the majority of LNGCs are in the 285m – 295m length, 160,000 m^3 - 180,000 m^3 capacity range [2]. These LNGCs utilise three different propulsion systems, with steam turbine propulsion (STPS) being widely used, whilst the remainder are propelled by either dual fuel diesel electric (DFDE) or the slow speed 2-stroke diesel engine with the latter option usually equipped with a re-liquefaction plant, installed in the cargo areas of the vessel to handle the boil off gas.

LNG is transported at -160^{o}C and at near atmospheric pressure in unpressurised, highly insulated tanks. Due to insulation limitations and sloshing in the tanks on passage, the LNG cargo will boil off slowly. It is of great importance that LNGCs have the means to handle the boil off gas (BOG) on-board the vessel. NG is a known greenhouse gas so should not be vented to atmosphere and the loss of BOG would potentially negate the economic case. It is this need to handle BOG and the fact that the use of NG to fuel boilers is relatively simple that has influenced LNGCs to employ the SPTS over other propulsion systems since LNGCs were first introduced in October 1958.

SPTS has proved extremely reliable in LNGCs but is a less efficient propulsion system when compared to other propulsion types used by other merchant ships. This is due to the inherent constraints of the Rankine Cycle. Initially, there was little motivation to develop more efficient types of propulsion system for LNGCs since the state of the LNG tank insulation was such that, on loaded voyages, the natural boil off flow from the cargo was sufficient to satisfy the fuel requirement for propulsion. Even if more efficient gas burning propulsion plants had been available at that time, such designs could not have been used without providing an alternative solution for dealing with the excess boil off gas (BOG) [3].

More recently, improvement in insulation technology in LNGCs has resulted in significantly lower LNG cargo boil off rates leading to there now being insufficient natural gas boil off to fuel the LNGC. This has resulted in a requirement for the use of forced boil off gas or use of an alternative fuel, such as IFO180 or HFO360, to supplement the BOG shortfall [3].

Consequently, there has been renewed interest in using propulsion systems that are more fuel efficient and/or re-liquefaction plant installed among the cargo systems (for converting BOG back to LNG) to gain an economic advantage over the standard STPS. Furthermore, over the same period, the International Maritime Organisation (IMO) has begun to introduce more stringent regulations governing the emissions in exhaust gases from ships, including Oxides of Nitrogen (NOx) and Carbon Dioxide (CO_2). The result has been a shift from the STPS towards the DFDE and Slow Speed Diesel Engine (SSDE). When analysing statistical data from Clarkson's World Fleet Register [4] it is found that from the 1960s through to the 1990s, STPS was employed by nearly all LNG carriers. By the 2000s, the proportion of STPS installations in the new deliveries had fallen to 69% and in the current decade this has fallen to 21%. When considering the future order book STPS is expected to fall to 12% [4]. However, the future trend in technological preferences is uncertain due to rapid development in propulsion technologies.

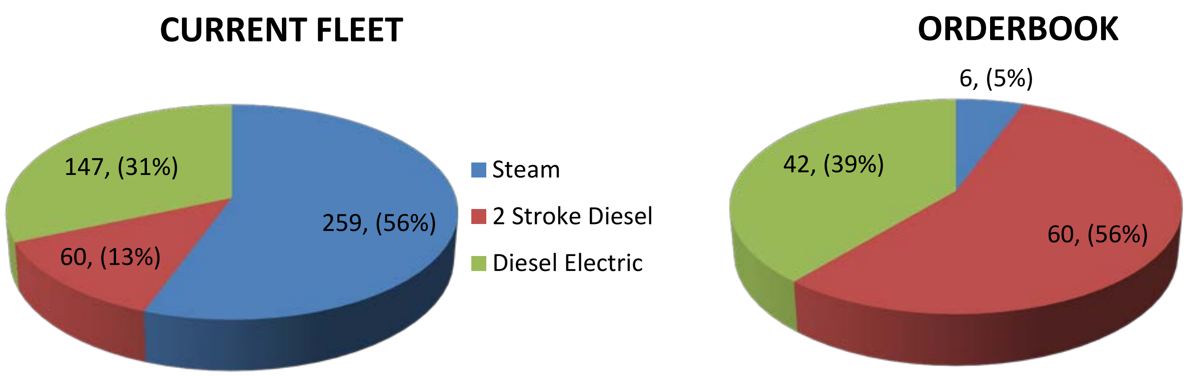


Figure 2a: LNG Fleet/Orderbook 2017 Source:[4]

In 2014, DFDE propulsion was the preferred alternative for modern LNGCs to replace STPS in new builds as shown in Figure 2b. The higher thermal efficiency of the DFDE offers significant financial savings when operating the vessel (OPEX) over a LNGC's life cycle compared to STPS. However, the recent development of the Gas Injection Direct Drive Diesel (DDD) has led to a paradigm shift in propulsion choice for LNGCs over the last three years. Analysing the order book in 2014 showed that the DFDE was the propulsion system of choice but by 2017 this preference had been displaced by the DDD [6].

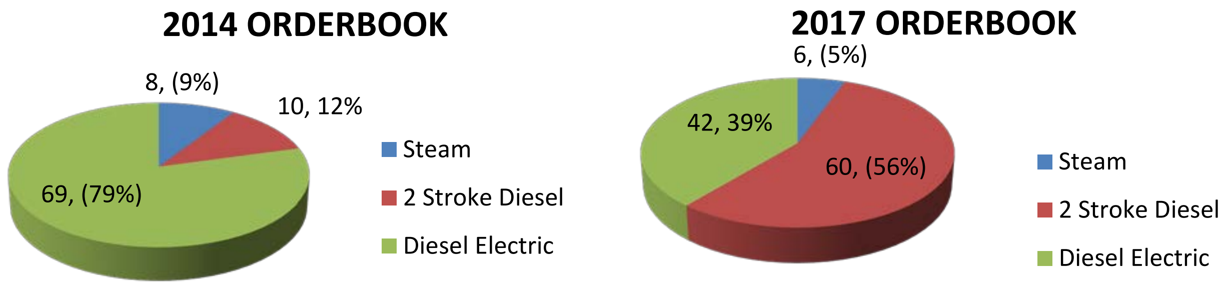


Figure 2b: LNG Fleet and Orderbook Source: [6]

As can be seen from Figure 2b, the preference of propulsion system for LNG carriers has changed several times within the past 10 years. Initially, the STPS was the propulsion of choice, which then became the DFDE, and is now currently the two-stroke option. However, the future trend is uncertain due to rapid development in propulsion technologies. This, coupled with the fact that since the turn of the century the rate of delivery of LNGCs has been increasing and is now at a rate that now averages ten times higher than it was previously as shown in Figure 3, it may be of value to analyse the performance of propulsion systems especially since there is an expected lifetime of 40 years for each of these vessels. The choice of propulsion would have wide ranging implications in terms of efficiency (cost) and emissions (environment).

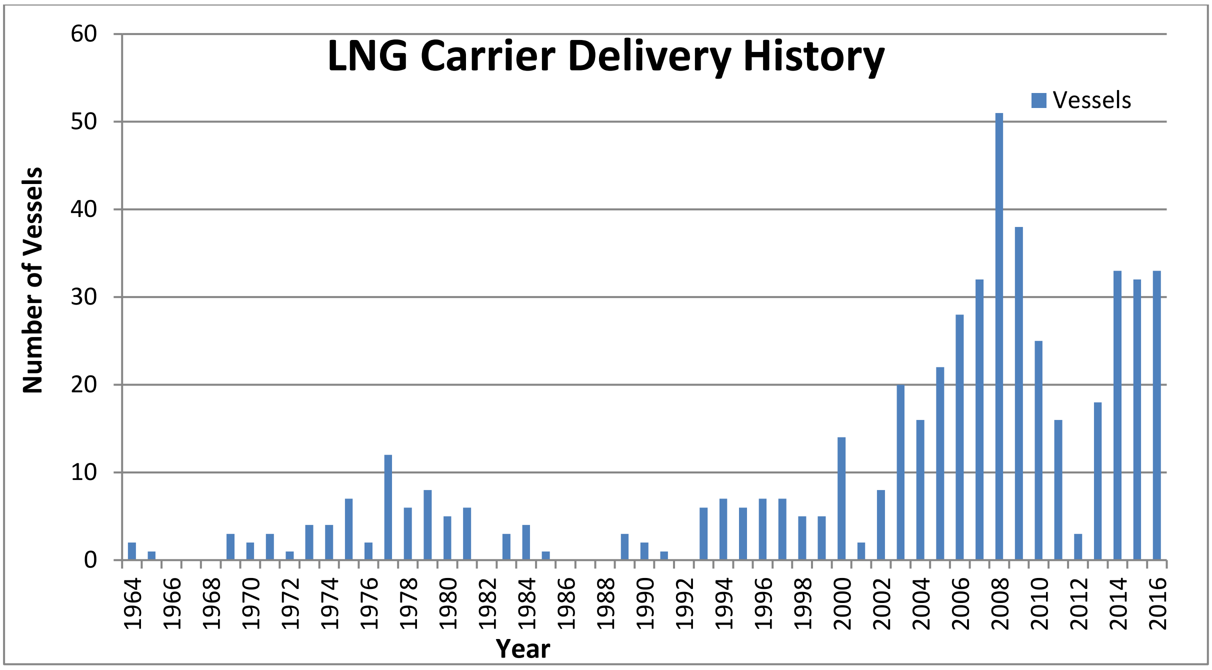


Figure 3: LNG Carrier Delivery History Source: [6]

This thesis will attempt to characterize the different LNGCs propulsion systems, model new designs and implications for the future in terms of efficiency and emissions. The thesis covers reviews and analysis from both theoretical and practical viewpoints and includes observations from onboard LNGCs.

1.2 Aims and Research Objectives

The overarching aim of this research is to contribute knowledge to the field of LNG marine transport by analysing and characterising the different LNGC propulsion options in terms of efficiency and emissions. This research will make recommendations for the future direction of propulsion systems ensuring that optimal choices for future propulsion systems are identified.

In order to achieve the aim stated above, the following objectives will have to be satisfied.

* Undertake a comprehensive literature review of the propulsion systems to understand the current status and expected future challenges in the design of future LNG carrier propulsion systems. The move from steam propulsion to diesel electric and diesel mechanical is expected to bring about new challenges with regards to energy efficiency and emissions.

* Analyse the Steam Turbine Propulsion System (STPS) from a both a quantitative and qualitative perspective. The quantitative analysis is carried out using the Energy Efficiency Design Index (EEDI) to measure the energy efficiency of new designs. The qualitative analysis is carried out using case studies of real life operation of these vessels. For the case studies, the Energy Efficiency Operational Indicator (EEOI) is used for analysis of efficiency and emissions. Develop thermodynamic models which are able to comprehensively characterise behaviour of the propulsion systems, verify and validate the developed model using data obtained from the case study, and/or practical data obtained from industry. Using these validated models, carry out further analysis by considering a variety of scenarios to optimise the energy conversion process, improve efficiency while reducing emissions.

* Analyse Dual Fuel Diesel Electric (DFDE) propulsion from a quantitative and qualitative perspective. The quantitative analysis is carried out using the Energy Efficiency Design Index (EEDI), the IMO mandated tool used to measure the energy efficiency of new designs. The qualitative analysis is carried out using case studies of real life operation of these vessels. For the case studies, the Energy Efficiency Operational Indicator (EEOI) is used for analysis of efficiency and emissions. There will also be analysis of the options to improve operational efficiency including practical demonstration and analyse results.

* Analyse two-stroke direct drive propulsion from a qualitative perspective. The quantitative analysis is carried out using the Energy Efficiency Design Index (EEDI), the IMO mandated tool used to measure the energy efficiency of new designs. Upcoming LNGC designs are also analysed in terms of design and operational efficiency.

* Carry out an in-depth comparative analysis of the three main propulsion options, using findings from the literature review, the EEDI analysis, the case studies, modelling & validation, and scenario simulation. It is expected that the results from

this research, in addition to contributing valuable insight into LNG efficiency and emissions performance, will also provide a pathway for future design of LNG carrier propulsion systems. Also, as there is a current move towards the use of NG fuel for other merchant vessels, therefore the results from this research can be extended beyond the current scope.

1.3 Outline of thesis

Chapter 1: This section indicates a background introduction to the research. It captures the current trends and developments of propulsion systems as related to LNG Carriers. The aims and research objectives, publications as part of this research, contribution to the field of study, and thesis outline are also presented in this chapter.

Chapter 2: In this chapter, a comprehensive literature review is conducted into the propulsion systems of LNG Carriers. It starts with an introduction, then a discourse on the history of the propulsion systems, a focus on the modern propulsion systems, and concludes with an outlook on the future designs and concepts.

Chapter 3: This chapter defines the research question. It focuses on the research gaps identified in the literature review, generating questions the answers to which would close these identified research gaps and contribute to the breadth and depth of knowledge.

Chapter 4: This chapter focuses on the steam propulsion system- the most numerous of the propulsion system options in service. The analysis focuses on the energy efficiency in design of the current ship types. It augments the analysis with case studies, and also goes on to develop validated models of this system. These validated models are then used to develop improved designs of this system.

Chapter 5: This chapter focuses on the diesel electric propulsion system. Being the presently preferred propulsion future option, the analysis also focuses on energy efficiency in design of current and future ship types. A set of case studies are also used to augment the analysis, while also analysing practical demonstration of improvements technologies examples on current DFDE designs.

Chapter 6: This chapter focuses on the direct drive diesel propulsion options, as well as considering other propulsion designs not currently in commercial operation. This chapter analysis covers the energy efficiency of two-stroke designs, for both current and future designs. The analysis of other potential design options, in terms of design and operational efficiency, is also covered in this chapter.

Chapter 7: This chapter presents an overview of comparisons between the aforementioned propulsion systems. It starts with a comparative analysis of the energy efficiency in design, then moves to the comparative analyses of the case studies, and concludes with an in-depth analysis of the model utilisation and the improved designs proposed.

Chapter 8: This chapter highlights the contributions of this research to knowledge and the implications for future systems. It refers back to the original research gaps and questions, and how this research has attempted to bridge these gaps. It concludes with the implications the solutions proffered would have on future LNGC designs.

Chapter 9: Presents general conclusions of the research work carried out in this thesis with suggestions for future research.

1.4 Publications

The following conferences have been completed as part of the studies completed in this research:

* Ekanem Attah, E & Bucknall, R. Energy Use onboard LNG Steam Ships. *Low Carbon Shipping **Conference**, 2013, University College London*
* Ekanem Attah, E & Bucknall, R. Influence and Impact of the EEDI on the Design of LNG Carriers. *Influence of the EEDI on Ship Design **Conference**, 2014, Royal Institute of Naval Architects.*
* Ekanem Attah, E. & Bucknall, R. Energy Use onboard DFDE Steam Ships. *Shipping in Changing Climates **Conference**. 2015, Low Carbon Shipping Consortium.*
* Ekanem Attah, E. & Bucknall, R. The Use of Waste Heat Recovery System to improve the Efficiency of LNG DFDE vessels. *International **Conference** on the Design,*

Construction and Operation of LNG/LPG Vessels. 2017, Royal Institute of Naval Architects.

The following journal paper has been completed as part of the studies completed in this research:

* E. Ekanem Attah, R. Bucknall “An Analysis of the Energy Efficiency of LNG Ship Powering Options” ***Journal** of Ocean Engineering, Special Issue on Marine Emissions, 110, 62-74. 2015*

1.5 Research Segments

The main segments of this research work are summarised as follows:

Review of the propulsion systems in the LNG Shipping Industry

A comprehensive literature review of the propulsion systems has been conducted to understand the current status and expected future challenges in the design of future LNG carrier propulsion systems. The move from steam propulsion to diesel electric and diesel mechanical and its implications have been identified as key aspects in this research.

Development of models to characterise LNG propulsion systems

The governing principles of the different propulsion systems were studied and applied to calculate the performance of the vessels under specific conditions. Thermodynamic models of the different propulsion systems have been developed to characterise these systems, and these have been validated.

Utilisation of models to develop improvements in future designs

These validated thermodynamic models have now been used to characterise improvements in these individual systems. For the steam model, the focus has been on adding components that will increase the thermal efficiency of the system under steady state conditions. For the diesel technologies, the addition of modern components to achieve this has been explored.

Practical Demonstration of Design Improvements

Design improvements chosen are analysed in actual sea going conditions, results are collated, analysed and implications of the analysis of results are quantified, discussed, or detailed. These results are then used to project future scenarios and fuel consumption savings and emissions reduction values have been quantified on a fleet-wide basis.

Interrelation between efficiency and emissions peculiar to LNG carriers

The use of unconventional fuels within LNG shipping has presented both advantages and disadvantages. On the one hand, natural gas burns cleaner with fewer pollutants, while on the other, methane emissions are increased. This interrelation between this increased methane emissions on the present and future technologies is also further analysed.

Development of Innovative Software Characterizing Energy Flows

The research also involves the development of innovative software for ship energy systems that characterises energy flows in ships and is adaptable across ship types. No such software is publicly available in the LNGC industry and this research work would be of great interest to ship operating companies therefore it has the potential to be exploited globally.

2.

LITERATURE REVIEW

2.1 Introduction

To completely understand and identify the issues which need be taken forward for further research, a comprehensive review of the propulsion system options is required in order to fully appreciate the holistic system as well as identify likely problems so as to proffer solutions. The literature review is subdivided into four parts. 1) Literature describing the different types of systems. 2) Review of literature comparing the different systems in terms of propulsive efficiency, emissions, reliability & availability and economic valuation. 3) Literature on trends in design. 4) Literature review on future prospects for LNGCs. The overarching aim of this thesis is to analyse and characterise the different LNGCs propulsion options in terms of efficiency and emissions which in turn should help ensure optimal choices for future propulsion systems are identified. Therefore, the methods selected for carrying out this literature review are designed to provide a description, summary and critical evaluation of the works in relation to LNGCs propulsion efficiency and emissions.

To satisfy the review objectives, the four different literature groups are reviewed in this section. Each section is reviewed using different methods which are summarized below [7]:

- Literature describing the different types of systems: A theoretical review [8] is adopted for this section, as this helps identify the existing engineering theories behind the current LNGCs propulsion technologies, and to what degree those theories have been investigated so as to develop new hypotheses to be tested [7] [8].
- Literature comparing the different systems in terms of propulsive efficiency, emissions, reliability & availability and economic valuation: An Argumentative and Systematic review approach is adopted. The argumentative approach enables the examination of literature selectively so as to support or refute an argument, assumption or philosophical problem established within the literature comparing the LNGCs, as it relates to four separate individual aspects (efficiency, emissions,

reliability/availability, & economic valuation). The systematic review is required so as to identify and critically appraise relevant research, critically evaluate and summarize research about each of these for individual aspects [7] [9].

- Literature trends in Design: A historical review approach is adopted. The approach will be to focus on examining the trends in LNGCs designs and tracing its evolution over the period. The purpose is to place the research in a historical context so as to identify the key areas of future research [7] [10].
- Literature on Future Prospects for LNGCs: A Methodological approach is required as to focus on how the evaluated literature on LNGCs design trends draws its conclusions. Reviewing the methods used for appraising future designs provides a framework for understanding how other researchers draw on a wide variety of knowledge and provide considerations for parts of this research [7] [9].

2.2 Understanding the Types

2.2.1 Steam Turbine Propulsion System (STPS)

STPS technology is installed in 71 percent of the current LNG fleet [9]. This majority is due its domination over the past decades mainly due to the ease with which the technology manages the use of BOG, simple operation and intrinsic safety. When the cargo tank pressure is elevated, the steam boilers burn the BOG to produce high pressure steam which drives the turbines connected to the propeller. During periods where the propulsion load is not sufficient to fully utilise the BOG capacity, such as slow steaming or in port conditions, the excess steam that is generated is dumped in the main condenser. It is this simple philosophy that eliminates the need for a gas combustion unit (GCU) which is a requirement for the other two propulsion systems (DDD and DFDEs) [11].

The outline of the plant normally consists of two gas/HFO fuelled boilers supplying steam to a cross compounded double reduction geared steam turbine plant driving the propeller. This generated steam is also used to supply auxiliary services such as turbo generators which provide electricity, as well as other heating services [12]. The electrical capacity of the turbo generator is dictated by the total electrical load required during full rate cargo discharge using the electrical cargo pumps. For this reason, two turbo generators are usually installed and sized to meet the cargo discharge electrical requirements, which usually is usually the operating condition at which the electrical load on-board is at its maximum [11]. Older steam LNGCs have a 100% auxiliary diesel generator installed, having a capacity equal to one of the turbo generators, as a safety requirement to supply sufficient power during black outs or periods where the steam system is not available to power the turbo generators. Newer steam LNG ships however have two 50% capacity diesel generators to provide increased protection against single point failures that could lead to difficulty in recovering the plant after a black out. The outline of the plant described is similar on every steam LNG ship in service since the first steam LNGCs entered service in 1964 [12] [10]. Figure 4 outlines a conventional steam plant.

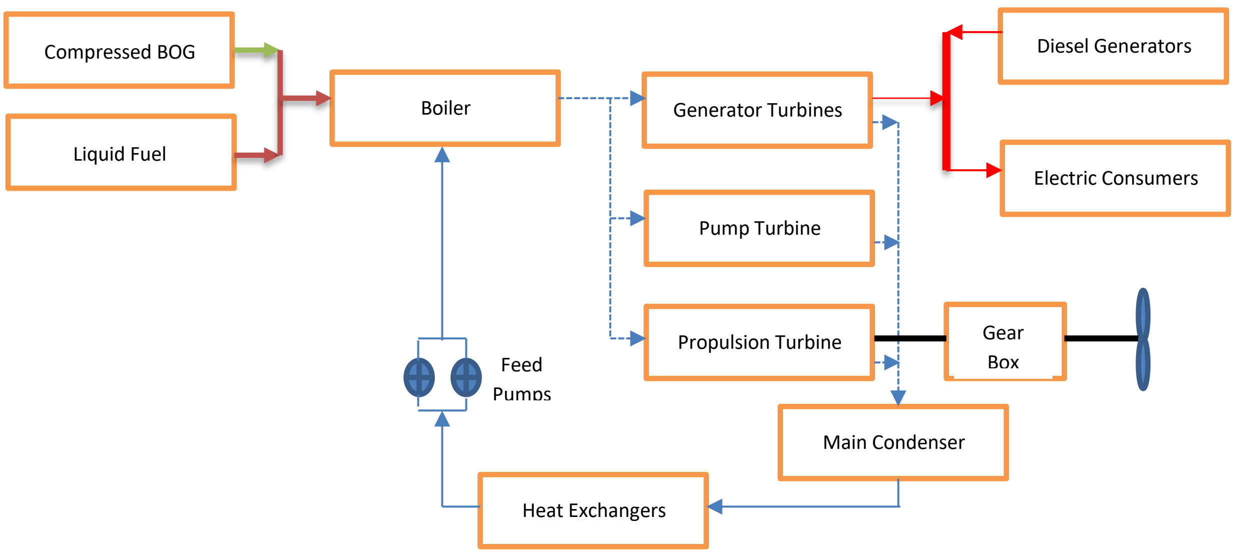


Figure 4: Schematic of the STPS showing energy usage Source: [11]

2.2.2 Slow Speed Diesel with Reliquefaction Plant (SSDR)

This is a single fuel diesel mechanical propulsion system with a re-liquefaction system where the BOG is liquefied and returned to the cargo tanks, instead of being used as a fuel. Diesel or Heavy Fuel oil is used for the engines. The slow speed diesel engines are usually used in the twin screw format with two slow speed diesels connected directly to two propeller shafts. Also in this format, clutches and shaft brakes are also installed so as to improve availability and maintainability requirements. This propulsion unit is also equipped with a GCU to dispose of the BOG in circumstances where the BOG capacity is larger than the capacity of the re-liquefaction plant [11] [13].

The BOG re-liquefaction concept is based on a closed nitrogen cycle extracting heat from the BOG. In this cycle, cargo boil off is evacuated from the LNG tanks by a low duty (LD) compressor, the vapour is then compressed to 5 bar and then cooled to -160 °C in a cryogenic heat exchanger. This ensures the condensation of the hydrocarbons in the gas back to LNG, while the nitrogen and other incondensable gases remain as gas bubbles in the LNG. These bubbles are removed in a liquid separator, where the LNG is separated and pumped back to the cargo tanks with the nitrogen rich incondensable gases being either discharged to the atmosphere or burnt in the GCU [13]. For current sized LNGCs this additional re-liquefaction system would require an additional load of between 3 to 4 MW. However, the current slow speed diesels have capacities between 216,000m3 and 260,000m^3 thus requiring between 4.5 and 5.5 MW extra electrical energy. Figure 5 shows a typical schematic of a 250,000m^3 SSDR LNGC [11] [12].

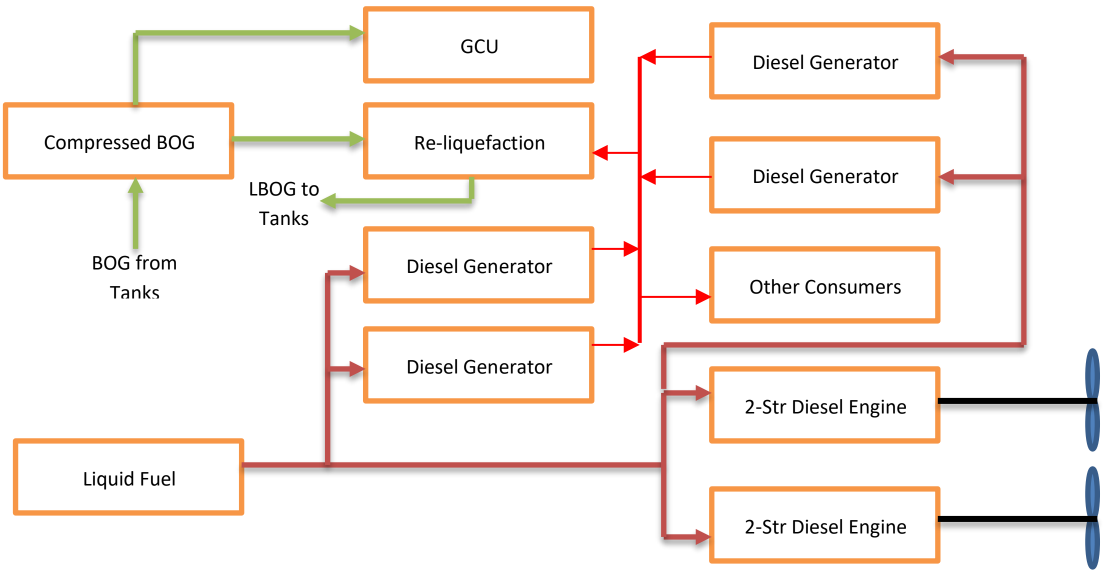


Figure 5: Schematic of the SSDR showing fuel energy usage Source: [22]

2.2.3 Dual Fuel Diesel Electric Propulsion (DFDE)

The DFDE propulsion system features modified diesel engines that have been designed to burn BOG as well as diesel fuel oil. This design employs multiple diesel generators, typically four, to provide all the vessel's power requirements which in this case also includes the main propulsion system on what has been termed a "power station principle" [12], as the dual fuel diesel engines are the prime movers for the provision of electrical power and electric motors tap from this electrical power supply to propel the ship. The engine, however, operates on gas with pilot fuel injection, or on liquid fuel, and cannot burn the two fuels at the same time, and as such mixtures of the gas and liquid fuel cannot be burnt simultaneously, which is a disadvantage when compared to the steam turbine propulsion system which can utilize both simultaneously.

The need to manage BOG in circumstances where the main propulsion system is not in use necessitates the presence of a GCU on this system, just as on the SSDR, and the capacity of the GCU installed on-board is usually equal to the total BOG rate on a typical laden journey. The provision of multiple diesel generator sets provides a degree of protection against loss of propulsive power even in the event of a plant upset such as a malfunction, as the most likely consequence of an unscheduled engine shut down is a relatively small loss of speed. Figure 6 shows a schematic of a typical DFDE system [12] [14].

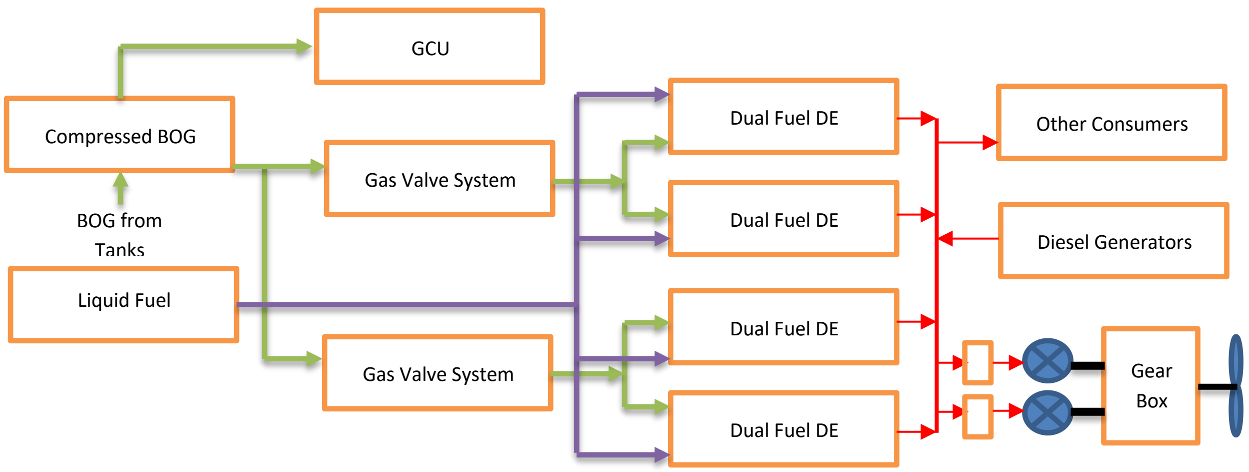


Figure 6: Schematic of the DFDE showing energy usage Source: [14]

2.2.4 Propulsion System Considerations

When it comes to propulsion selection for LNGCs, this choice is closely related to the utilisation of boil of gas and electrical power generation [11]. The reason for this is while the steam turbine propulsion system (STPS) utilises BOG as fuel for steam generation, which in turn is used to drive steam turbines for propulsion and electricity generation, the DFDEs use the BOG as fuel to generate electric power to drive electric motors connected to the propeller shaft. The SSDR recovers the BOG while consuming large amounts of power for the re-liquefaction process. Therefore, any overview or comparison of these three propulsion systems would need to take into account the BOG, the electrical power generation and the main propulsion system.

It is also important to consider the twin screw issue when considering propulsion options. While the reliability of the single screw steam turbine LNG ships has been accepted throughout the industry, primarily due to the fact that they require very little regular maintenance which can only be conducted with the propulsion system immobilized. Diesel machinery on the other hand requires more immobilization for maintenance by nature, when compared to the STPS. As the normal industry practice is to not permit complete shutdown of the propulsion machinery when a vessel is alongside in port, therefore with a twin engine, shutdown of one propulsion diesel engine is considered acceptable with the proviso that the second propulsion diesel engine is available and on standby to power the vessel if deemed necessary [12] [14].

Another reason for the adoption of twin configurations is due to the increasing sizes of LNG Carriers, as the larger carriers (over 200,000 m^3) are designed for relatively shallow draft for the propulsion power required. To attain such a design with a single screw may not be achievable since the propeller loading may be too high, which could result in high vibration levels induced into the hull structure as well as propeller cavitation [12]. The physical constraints of the steam turbine prevent their installation in twin screw configurations. Also on the larger LNGCs, the propulsion power requirement is larger than that which current steam turbines can offer, the largest of which being about 30MW - 33MW, due to its gear torque capacity [12] [14].

2.3 Comparison of LNGC Propulsion Systems

2.3.1 Outline

The comparison of LNG propulsion systems has not, to date, been of general academic interest. There have however been many commercial comparisons of propulsion systems on-board LNGCs. These are usually initiated by product manufacturers who may or may not be impartial regarding the benefits and shortcomings of their products. The reason for this comparison is primarily because the original standard design, the steam turbine, has a poor thermal efficiency, and improvements in diesel engine technologies, as well as development of on-board re-liquefaction technologies, have made the shortcomings of the steam turbine even more apparent. In some of the literature reviewed [15], [16], [17], the chart in Figure 7 is used to indicate the differences in efficiency of the different propulsion systems. Most commercial proponents highlight the fact that the steam turbine is bottom on the chart and fuel savings, usually in terms of millions of dollars, can be achieved by a change of propulsion to any of the other alternatives. As fuel consumption is usually proportional to CO_2 emitted, the carbon footprint is another point that is often highlighted.

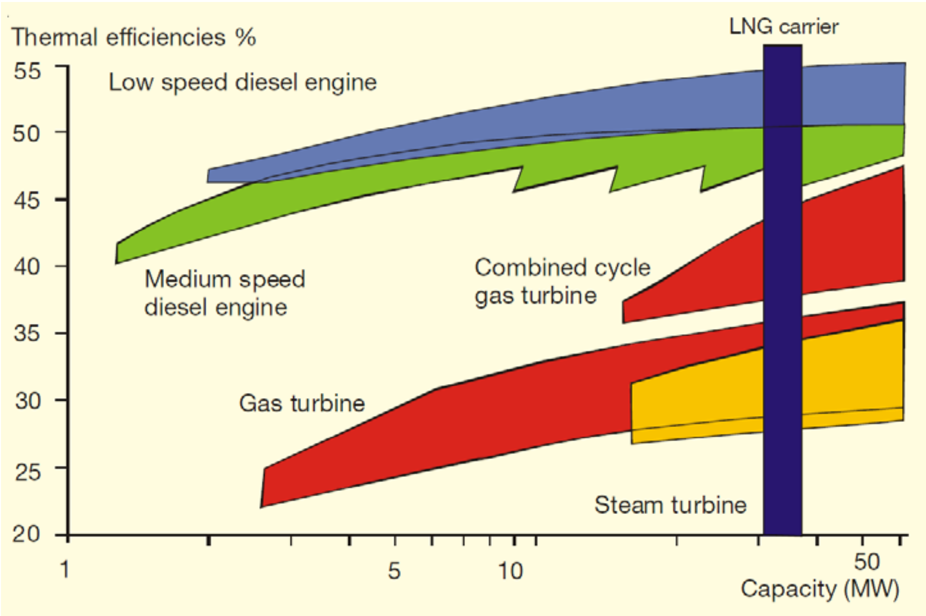


Figure 7: Graph showing the efficiencies of different propulsion systems Source: [13]

Most LNGC literature is focused on propulsive efficiency and emissions, while other literature sources focus on qualitative comparisons, safety and reliability. For the purpose of this review, all propulsion comparison literature is grouped into 4 sections;

- Propulsive Efficiency
- Emissions
- Reliability & Availability
- Economic valuation

2.3.2 Propulsive Efficiency

As explained earlier, Figure 7 provides an indication of the different thermal efficiencies of the different propulsion systems. As can be seen from the diagram, the steam turbine is at the bottom of the efficiency scale with a range from 27% - 33%, while the other two propulsion systems, DFDEs and SSDRs have efficiency ranges of 42% - 48%, and 48% - 53% respectively. Konstantinos [15], however offered a deeper comparison of efficiencies related to prime movers and auxiliary engines of LNGCs by analysing data from Wartsila [16] and Tractebel Engineering GmbH & Dorchester Maritime ltd [17]. In his analysis, the efficiencies for each propulsion system were classed as;

- For the steam turbine the fuel, which in this case includes boil off gas, is fed through the boilers, it comes out with a 89% efficiency. This goes through the steam cycle, which itself has a 35% efficiency, then to the shafting system, which is about 99% efficient, giving an overall efficiency of approximately 30%
- For the DFDE the fuel, which in this case also includes BOG, is fed to dual fuel medium speed diesel engines, which are 48% efficient. The energy goes through a mechanical/electrical conversion which has 98% efficiency. It then goes through an electrical/mechanical conversion for the propulsive motors, which is 98% efficient. The gear box and shafting transmission both have efficiencies of 98% and 99% respectively. This brings the total propulsive power efficiency to approximately 43%.
- For the SSDR the fuel, in this case just HFO, is fed to slow speed diesel engines which are 49% efficient. The shafting transmission system is about 98% efficient. This results in an overall efficiency of about 48%

A similar analysis was carried out on the auxiliary power for the STPS, DFDE, and SSDR with the electrical power efficiencies being 26%, 47% and 43% respectively [15]. The full results are summarized in Table 1[15].

Table 1: Comparing the efficiencies of different propulsion systems. Source: [15]

<table>
<tr><td>Prime Mover</td><td colspan="2">STPS</td><td colspan="2">DFDE</td><td colspan="2">SSDR</td></tr>
<tr><td>Configuration</td><td colspan="2">Two Boilers;
HP & LP Turbines- 2 Cylinder impulse/reaction turbines</td><td colspan="2">4 Gas/MDO Diesel Engines (some might be upgraded to burn HFO)</td><td colspan="2">2 Slow Speed Diesel Engines (MAN B&W or Sulzer RT Series)</td></tr>
<tr><td>Fuel used for Prime Mover</td><td colspan="2">Gas/HFO/MDO</td><td colspan="2">Gas/HFO</td><td colspan="2">HFO</td></tr>
<tr><td>Fuel Treatment</td><td colspan="2">HFO preheating, BOG Compressing</td><td colspan="2">BOG Compressing</td><td colspan="2">HFO Purifiers</td></tr>
<tr><td>BOG Handling</td><td colspan="2">Burn in boilers, Steam Dumping</td><td colspan="2">Burning in DF Engines, Gas Combustion Unit.</td><td colspan="2">2 100% Reliquefaction Plants</td></tr>
<tr><td>Transmission</td><td colspan="2">Mechanical Drive with Reduction Gear</td><td colspan="2">Electric Drive with 2 Slow/High Speed Propulsion Motors</td><td colspan="2">Direct Drive</td></tr>
<tr><td>Electric Power</td><td colspan="2">2 Steam Turbine Generators</td><td colspan="2">Available from Main Generator Engines</td><td colspan="2">3 or 4 Diesel MDO Generator Sets</td></tr>
<tr><td>Additional Equipment</td><td colspan="2">Boiler Exhaust Economizer</td><td colspan="2">Exhaust gas Auxiliary Boiler</td><td colspan="2">Exhaust gas auxiliary Boiler</td></tr>
<tr><td>Propulsion Unit</td><td colspan="2">FPP; Bow and stern thrusters</td><td colspan="2">1 or 2 FPP/CPP with 2 Bow Thrusters</td><td colspan="2">2 FPP; 2 Bow/Stern Thrusters.</td></tr>
<tr><td rowspan="17">Plant Efficiencies;</td><td>Fuel/BOG</td><td>100%</td><td>Fuel/BOG</td><td>100%</td><td>Fuel</td><td>100%</td></tr>
<tr><td>Boilers</td><td>89%</td><td>DF Engines</td><td>48%</td><td>Engines</td><td>49%</td></tr>
<tr><td>Steam Cycle</td><td>35%</td><td>Conversion</td><td>98%</td><td>Shafting</td><td>98%</td></tr>
<tr><td>Shafting</td><td>99%</td><td>Motors</td><td>98%</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Gearbox</td><td>98%</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Shafting</td><td>99%</td><td></td><td></td></tr>
<tr><td colspan="2">Propulsion Efficiency: 30%</td><td colspan="2">Propulsion Efficiency: 43%</td><td colspan="2">Propulsion Efficiency: 48%</td></tr>
<tr><td>Fuel BOG</td><td>100%</td><td>Fuel/BOG</td><td>100%</td><td>Fuel</td><td>100%</td></tr>
<tr><td>Boilers</td><td>89%</td><td>DF Engines</td><td>48%</td><td>Aux Engines</td><td>45%</td></tr>
<tr><td>Steam Cycle</td><td>30%</td><td>Alternators</td><td>97%</td><td>Conversion</td><td>96%</td></tr>
<tr><td>Conversion</td><td>96%</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Electric Power Efficiency: 26%</td><td colspan="2">Electric Power Efficiency: 47%</td><td colspan="2">Electric Power Efficiency: 43%</td></tr>
</table>

It is however important to note that most of the studies carried out by Konstantinos[15] on the propulsion systems were done purely on design characteristics of the prime mover, since at the time these efficiency studies were carried out, there were not any propulsion systems in service other than the STPS.

2.3.3 Emissions

Regulation and legislation pertaining to maritime emissions is gaining increasing attention and as such is evolving both regionally and globally. International regulation for air quality from ships is mandated by the International Maritime Organisation (IMO) as well as several regional and state agencies most notably the US Environmental protection Agency (EPA) [18] [19]. The IMO have legislated the limits of the allowable amount of SO_x and NO_x emissions from marine fuels while the US EPA as well as the European Union have mandated stringent limits on SO_x and NO_x within their respective regions [20]. More recently, the IMO has developed the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP), which are aimed at reducing the amount of CO_2 ships emit from the design and operational standpoints respectively. When it comes to LNG shipping, as a result of there being three different propulsive technologies available, as well as the different fuels used (HFO, MDO and BOG), there has been a considerable amount of literature on LNG shipping emissions. Even with the complexity provided by the different fuels and different propulsion systems, the emissions of Nitrogen Oxides, Sulphur Oxides, Carbon dioxide and methane in the exhaust gases need to be considered [12] [18] [19].

Sulphur Oxides: These emissions are a by-product of the sulphur content of the fuel being used. When BOG is being used, SO_x emissions are practically non-existent and are significantly high when HFO is used. When marine diesel oil is used the SO_x emissions are considerably less than when HFO is used. The SSDR will emit more SO_x when compared to duel fuel systems as its primary fuel is HFO. STPS will emit more SO_x than SSDR when in HFO mode and would reduce to zero when in BOG mode. DFDE SO_x emission is a function of how much pilot fuel is consumed when in gas only mode and how much MDO is consumed when in diesel mode [12] [19]. Figure 8, 9, and 10 show graphical representations of the emissions of the different propulsion systems.

Nitrogen Oxides: Nitrogen oxide emissions are directly related to the combustion process itself and are a factor of the peak temperature achieved during combustion and the duration at which the combustion gases are at that peak temperature [16]. NOx is also formed from the reaction of the fuel-bound nitrogen compounds with oxygen. Due to the characteristically low combined nitrogen content of BOG compared to HFO/Diesel Fuels, there is less NO_x emitted when BOG is used as the fuel when compared to HFO. Therefore the SSDR generates more NOx than the other options for the same power output, with the DFDE producing lower NOx emissions when it operates in diesel mode only. The STPS generally emits the lowest relative volume of NO_x due to its different mode of combustion i.e. due to its lower boiler combustion pressure [12] [20], although there are not significant amounts of literature in this regard.

Carbon dioxide: Carbon dioxide production is a function of the amount of fuel being consumed as well as the type of fuel. BOG has a lower carbon content than HFO therefore when BOG is used as a fuel less CO_2 will be emitted, as BOG generates more energy per kg of CO_2 emitted (20MJ/kgCO_2) when compared to HFO (13.48MJ/kgCO_2) or Diesel Oil (14.04MJ/kgCO_2). As the efficiency of the plant will have a major role in the quantity of CO_2 emitted quite expectedly the steam turbine has the worst CO_2 emissions profile, whether in BOG or HFO mode. The SSDR has a higher propulsive efficiency than the DFDE, however the DFDE's ability to burn the lower carbon BOG means it would emit lower levels of CO_2. Additional the SSDR requires large amounts of auxiliary power to liquefy the BOG which also increases its fuel consumption and hence CO_2 emissions [12] [18] [19].

Methane: Methane emissions are a by-product of gas burning diesel engines. The severity of methane emissions is emphasized by the fact that it has a Global Warming Potential (GWP) of 72 times that of CO_2 over a 20 year life cycle [19]. The DFDE is the worst of the propulsion options regarding methane emissions as 2% - 4% of the BOG used as fuel is discharged up the funnel. In comparison the STPS emissions when using BOG are less than 0.1% [18]. The SSDR, despite the fact it does not utilize BOG as fuel and instead liquefies it, still suffers some methane emissions as part of the re-liquefaction process, as there is a need to vent non-condensable gases from the re-liquefaction plant. The main component that is vented is usually nitrogen, but it also entrains methane which is discharged to the atmosphere. This methane emission is however a function of the cargo handling system and not the propulsion system, and as such when transiting without LNG cargo there are no methane emissions [12].

As a consequence of the majority of the literature reviewed being from product designers, and the different propulsion systems emit different compositions of the gases and combustion products listed above, there has been a noticeable and consistent trend by the authors to highlight certain emissions of other propulsion systems while downplaying the emissions of the products being marketed when comparing emissions or disproportionately using the BOG/ HFO mix to their own advantage. For example, Wartsila, the makers of the DFDE, when comparing the emissions of the DFDE to that of the STPS showed that there was a savings in terms of CO_2 emissions in the order of 30% - 40% [21], while failing to stress the much higher GWP methane emissions or the NO_x emissions inherent to DFDEs [12] [20].

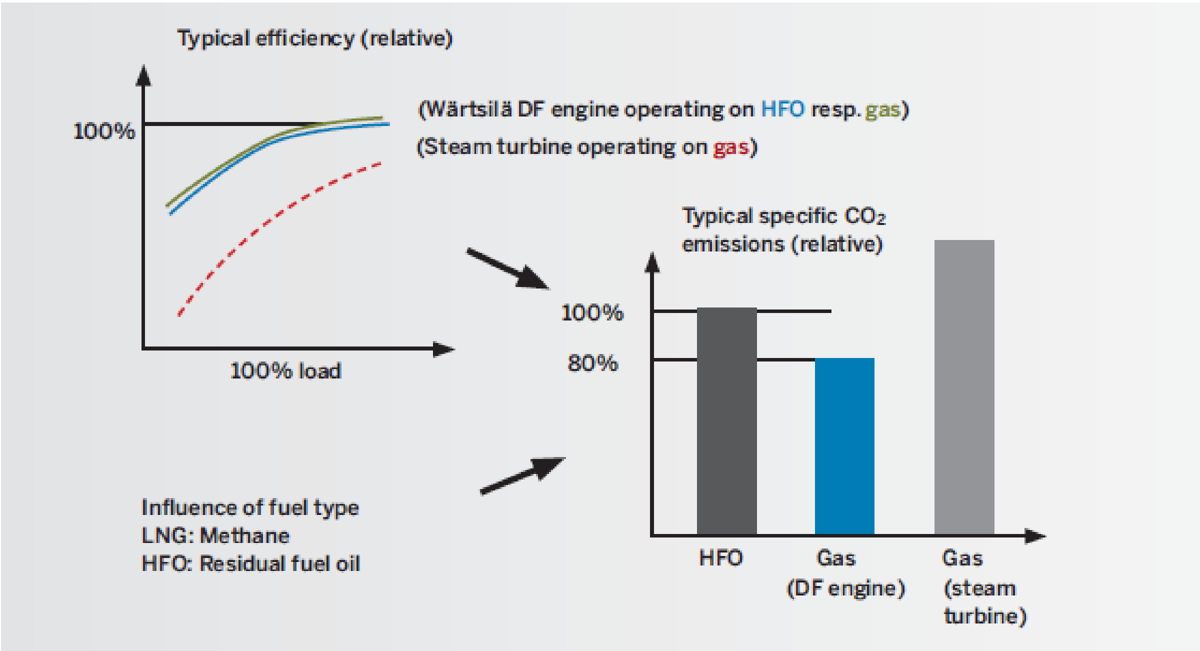
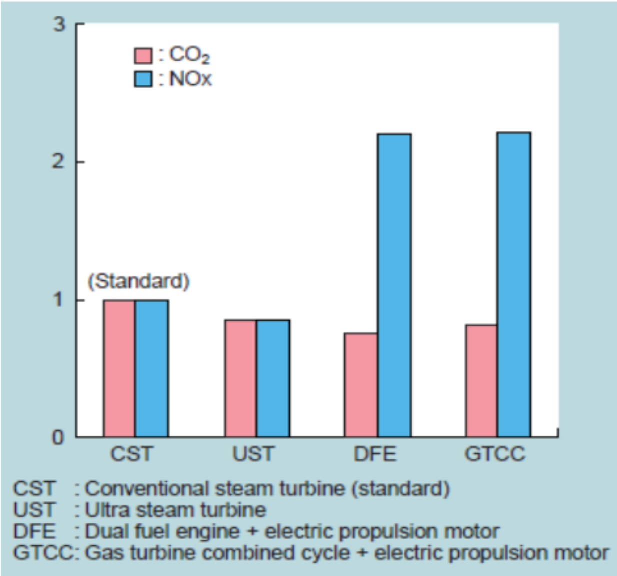


Figure 8: CO_2 emissions comparison DFDE/STPS Source: [21]

Mitsubishi Heavy Industries (MHI), the makers of the STPS, when comparing the emissions between the STPS and the DFDEs highlighted the higher NO_x emissions of the DFDEs during navigation on gas only mode but ignored the higher SO_x emissions when using HFO/MDO mode, but were quick to also highlight the higher NO_x and SO_x in port where the DFDEs are restricted to MDO mode only and the STPS can burn both HFO and Gas thereby emitting much less NO_x and SO_x [23].



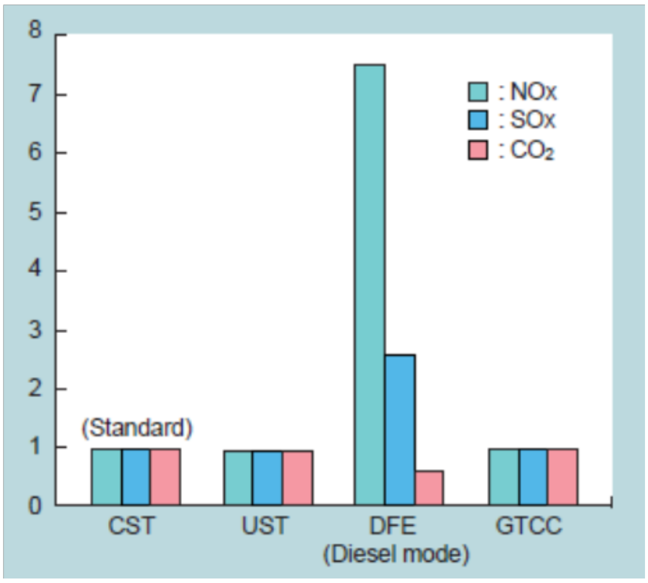


Figure 9a: Emissions comparison DFDE/STPS during passage. Source: [23]

Figure 9b. Emissions comparison DFDE/STPS during port. Source: [23]

Similar selective comparison was carried out by DFDEs proponents ABB when comparing the emissions of the DFDE to those of the STPS and SSDR, highlighting the increased CO_2 NO_x and SO_x emissions from the STPS and SSDR while failing to highlight the higher GWP methane emissions from the DFDE. In addition, the comparison was based on comparing a gas only DFDE with dual fuel STPS, which quite expectedly would deliver higher emissions, whereas a more balanced comparison would have been to a gas only steam plant. The emissions from port conditions were also excluded in the comparisons and the DFDEs do emit more NO_x and SO_x than the other two propulsion systems under port conditions [24].

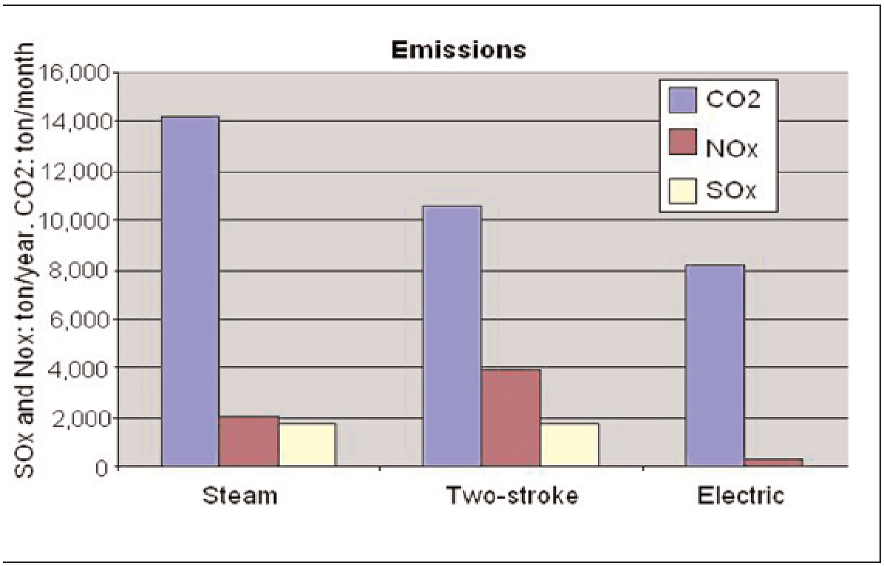


Figure 10: Emissions comparison STPS/SSDR/DFDE Source: [24]

MAN B&W, the manufacturers of the prime movers on SSDRs, when comparing the SSDR/STPS emissions did however admit the higher NO_x emissions of the SSDR but offered solutions to mitigate these higher NOx emissions. They did not however mention the methane emissions derived from the re-liquefaction system, although as mentioned previously, this methane emission is a function of the cargo handling system and not the propulsion system [13].

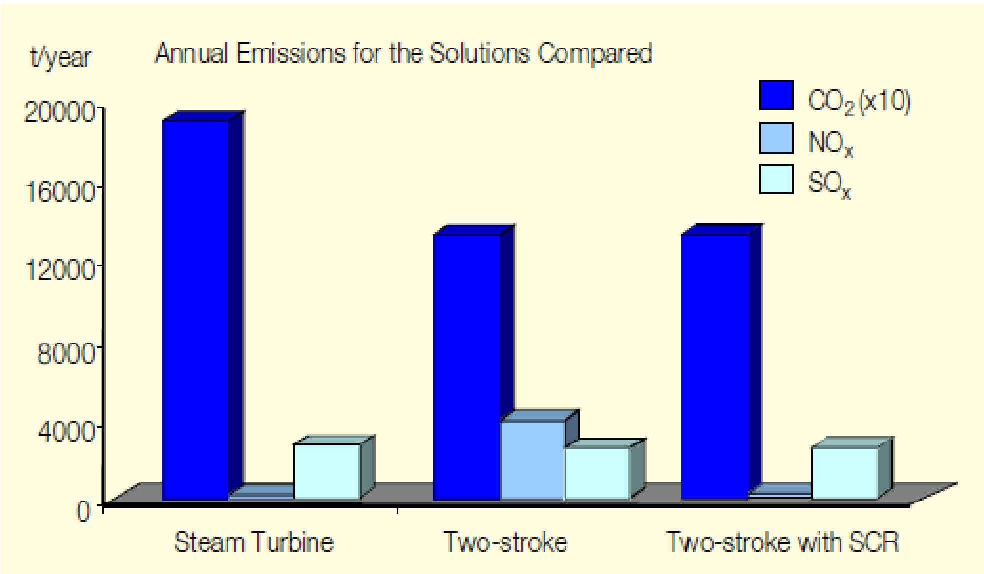


Figure 11: Annual Emissions comparison STPS/SSDR Source: [13]

Despite the fact that there has been some commercial bias and lack of impartiality in the literature when it comes to comparing emissions, there have however been other balanced arguments in this regard. Shell Shipping Technology estimated the emissions from the different prime movers, taking into account a larger variety of factors, including the emissions from the re-liquefaction plants, even though they failed to take account of methane emissions from DFDEs. Their results are summarized in Table 2 [12];

Table 2a: Emissions comparison STPS/SSDR/DFDE. Source [12]

	NOx (g/kWh)	SOx (g/kWh)	CO_2 (g/kWh × 100)	Particulates (g/kWh)
2 Stroke Diesel (Low Speed)	17	12.9	5.8	0.5
4 Stroke Diesel (Medium Speed)	12	13.6	6.12	0.4
Dual Fuel Diesel Electric	1.3	0.05	4.2	0.05
Dual Fuel Diesel (Slow Speed)	14.5	0.2	4.1	0.1
Steam Turbine	1	11.0	8.5	2.5
Gas Turbine	2.5	0	4.8	0.01

2.3.4 Reliability and Availability

It has been generally accepted that for LNG carriers the main objective is to deliver the cargo to the terminal at the scheduled time. According to Clarkson's dataset, 90% of LNGCs are owned by either the LNG supplier or the LNG buyer so this delivery requirement is engrained into the LNG shipping trade. A major reason for this is there is limited storage capacity at terminals so the whole LNG supply system is based on scheduled arrival of the LNGCs. It is also for the same reason that most LNG vessels are chartered on a long term basis, usually for between 20 to 30 years [24]. Taking these factors into consideration, the propulsion system chosen needs to be reliable to ensure the vessel will not arrive late at the terminal [24]. While the assuredly reliability and availability of the STPS is renowned throughout the LNG industry given its history, as well as its high safety record over the last 40 odd years, it is important that the newer propulsion systems i.e. the SSDR and DFDE should offer a similar or higher degree and level of safety, reliability and availability.

The Literature in this regard is scarce with only Chang et al from Hyundai Heavy Industries (HHI) knowingly conducting research in this field [14]. In their assessment they categorized reliability as key to the commercialization of different propulsion systems, defining reliability as the failure free probability under a given condition for a fixed period of time. Chang also defined availability as the asymptotic ratio of operating time to the total time while taking maintenance into account. Using availability as the preferred parameter for comparing the different propulsion options, they sub-classed availability into three sets of conditions;

- The probability that the propulsion system is able to generate the power output to match the design propulsion load,
- The probability that the propulsion system will be able to deliver the power output required to satisfy the required propulsion load in the event of failure of the prime mover.
- BOG utilization; a measure of the ability to use BOG as fuel or recover it to liquid state.

They listed all the major components of the different propulsion systems and estimated their failure rates and repair times, as shown in Table 2b, and then constructed reliability block diagrams to estimate the various availabilities.

Table 2b: Failure rate & Active repair time STPS/SSDR/DFDE major components. Source: [14]

Equipment	Failure rate, per 10^6 h	Active repair time, h
Steam turbine	40.0	16.0
Boiler	82.2	2.8
Gas turbine	756.8	23.7
Diesel engine	324.7	78.8
Electric generator	48.9	18.0
Screw compressor	47.4	22.8
Centrifugal compressor	256.4	25.7
Oil-processing pump	98.5	14.6
Electric motor	94.5	9.5
Process control valve	3.9	22.9

From the results, STPS exhibited the highest availability of the propulsion design options due as a result of the relatively low failure rate of the steam turbine, while DFDE displayed the lowest availability due to its four diesel engine configuration as availability is inversely proportional to the number of components given the same failure rate for all components.

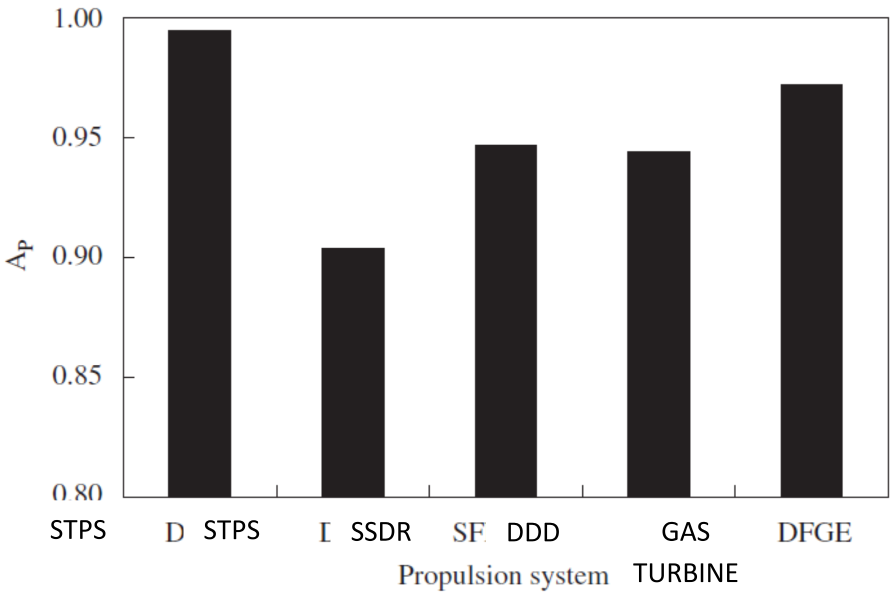


Figure 12: Availability of Propulsion Function. Source: [14]

In terms of availability of emergency propulsion, the SSDR offered the highest availability with the STPS offering the lowest although they noted that since the chances of requirement for an emergency voyage is very low, then the availability of emergency propulsion is not as significant.

The availability of the BOG utilization was determined to be roughly proportional to the demand of the propulsion load, as the availability of the BOG utilisation is a function of both the availability of the BOG compression system (supply) and the propulsion system (consumer). The result is the availability of the BOG propulsion function matches the demand of the propulsion function with STPS having the closest correlation, and DFDE the least with the SSDR holding an intermediate position.

Their analysis also made an attempt to quantify the risk and hazard analysis of the different propulsion systems, although this was not as detailed as the availability analysis. Here it was seen that the DFDE and SSDR introduce additional hazards due to the need for comparatively higher pressure for the natural gas fuel supply typically three times that required for the STPS system. The DFDE requires higher gas pressures to enable it run in gas mode, while the SSDR requires higher pressures for the re-liquefaction system. They note that any leakage from this higher pressure gas supply system increases the risk of fire or an explosion, especially if it happens in the engine room. Under such circumstances, this will severely limit the availability of the propulsion system in systems where high pressure BOG is used as a fuel. There are however safeguards implemented to militate against these risks and hazards, as ESD protection is acceptable where inherently safe machinery rooms are not guaranteed in vessels with multiple prime movers.

It would seem, based on the literature review of the availability and reliability comparison of the different propulsion systems by Chang et al, that there might be some degree of bias towards by the STPS as it performed reliably in their studies coming out as the best option in availability of propulsion and BOG utilisation. The availability of the emergency function, where the STPS rated lower than the other two systems, can be considered to be of minimal overall impact based on the extremely low historically incidence for utilising emergency propulsion. Any concern regarding neutrality of the research is not helped by the fact that the authors are with HHI, whose proclivities lie towards the STPS. However, the reliability of the steam turbine is without question, as the numbers show. There have been roughly 25 serious accidents between 1965 to 2005, a period completely dominated by the steam turbine propulsion system. One accident resulted in 6 fatalities with only four of the accidents being attributed to failure of the propulsion system [12] [14]. This is considered lower than the rest of the shipping industry which utilises different propulsion systems [14].

2.3.5. Economic Evaluation

The subject of economic evaluation of the different propulsion options has been, comparatively, the most abundant as regards literature sources. The general consensus has been that the STPS is so inefficient that if converted to either of the other two propulsion systems; either the DFDE or the SSDR, there could be potential savings in of millions of dollars per year. The typical figure being quoted is usually between $3M and $5M, but it must be noted that these figures are usually provided by proponents of either SSDR or DFDE. While the inefficiencies of the STPS and the associated fuel savings of the other propulsion systems are without question, a biased comparison could be misleading and end up being a lot more expensive. A typical example of this was the MAN study in 2005 [13], which asserted that by using the SSDR, savings of about $3M per year could be realised due to the fuel savings from the cost of high STPS consumption of the LNG even though the cost of LNG was, at the time, lower than the oil price. But by 2011, the price of oil had risen from its then price of $156 per ton to a record high of $650 per ton, while advancement in technologies to access more gas deposits led to a fall in gas prices. This meant that the SSDR was much more costly to run than the STPS despite its higher efficiency, as not only did the SSDR not have the option of burning the cheaper LNG for propulsion it also had to burn the more expensive HFO to generate large amounts of power to re-liquefy the cheaper natural gas cargo. This led to NAKILAT, who had 45 carrier with SSDR acquired after the post 2005 study, to announce plans for an ambitious $1 billion re-engine of the carriers [25].

With such major potential implications, any study with regards to economic valuation must at the very least, be robust, thorough and devoid of bias since, as it is seen with the case of NAKILAT, a projected $3M savings per year per ship could quite easily turn out to be $10M to $20M more expense per year per ship, and in the NAKILAT case with 45 ships it could quite easily top a billion dollars per year more expenditure when compared to the STPS. So, while the economic indicator is usually the unit freight rate expressed as $/MMBtu for the round voyage, all costs related to that round voyage, including financing capital expenditure (CAPEX) and operating expenditure (OPEX) divided by the numbers of MMBtu delivered, should be considered [12]. While the costs associated with CAPEX are quite easy to determine, for OPEX the key issue is the value ascribed to the BOG and vaporized LNG, if used as a fuel for the vessel, and how this compares with the current and varied HFO price.

Konstantinos [15] attempted a CAPEX comparison of the different propulsion systems. In his study he modelled a 150,000m^3 LNG tanker utilising the different propulsion options and found that the initial investment costs of the STPS, DFDE and SSDR propulsion systems only amounted to $20M, $21.65M and $20.8M respectively, with the total cost of the LNGC being $180M, $182M and $184 respectively. While his methodology is slightly unrealistic when considering the fact that all SSDRs built so far are above the 200,000m^3 capacity, for the reasons previously explained above, a look at the actual prices of LNGCs delivered in 2007, a year after his work was published, shows the average prices for LNGCs delivered that year were $175M for a 150,000m^3 STPS carrier, an $185M for a 155,000m^3 DFDE carrier and $215M for a 210,000m^3 SSDR carrier. The prices have increased gradually and in 2011 a 160,500m^3 STPS LNGC would cost approximately 213M, while a 171,800m^3 LNGC was 230M, and the 210,000m^3 SSDR was 240M. The summary is that an assessment of the literature suggests that, in terms of capital expenditure, the STPS least costly, with the SSDR being the costliest with the DFDE coming in between. However, in terms of $/m^3 capacity, the difference amongst the three CAPEX values of the propulsion systems are not substantial.

It is however important to note that while considering the CAPEX of LNGCs, a futuristic look at the total life cycle cost should be considered simultaneously i.e. CAPEX + OPEX. A lifecycle cost comparison study carried out by Chang et al [11] showed quite bluntly the insignificance of the CAPEX in terms of life cycle cost (LCC) as only approximately 5% of the LCC could be attributed to the CAPEX with the rest attributed to OPEX [11] [14]. The study was carried out over 20 year life cycles of the different propulsion systems, which included the current three (STPS, SSDR and DFDE) as well as other proposed alternatives still at the concept stage. In their results it was shown that within the OPEX costs the fuel cost component, which included the natural boil of gas, accounted for the major share while the portions of delivery loss cost due to maintenance and propulsion availability showed a significant variation across propulsion options, while the cost of lubricants and operation of the GCU were considered negligible [11][15].

Given that the majority of the cost comes from the fuel consumption within the OPEX, there was little explanation from the Chang paper in terms of profit from the use of different HFO/BOG mixes in relation to the propulsion technology utilized. A paper by MAN B&W however addressed this by developing a mathematical equation to calculate the profit from using either a DFDE or a SSDR for a 200,000m^3 LNGC [26]. The equation and graph are shown in Figure 13 and Figure 14 respectively. Full explanation is found in Appendix 5.

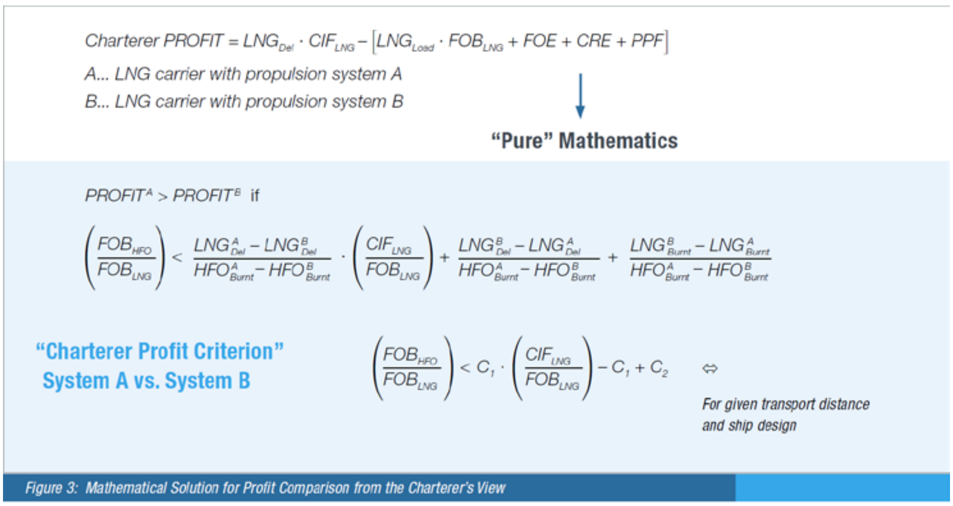


Figure 13: Mathematical Solution to calculating profit of 2 propulsion systems [26]

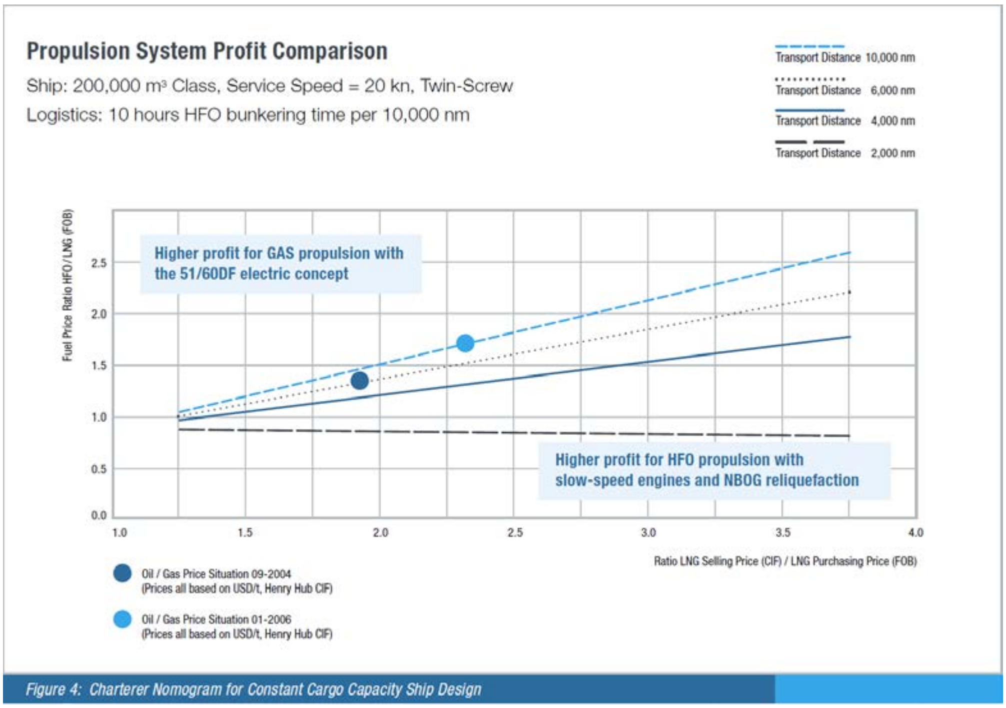


Figure 14: Charterer graph for constant capacity ship design Source: [26]

Although the methodology has the limitation that it was restricted to just the DFDE and SSDR concepts, the results however indicated that there was a tendency towards the DFDEs for short/medium transport distances, high HFO/LNG price ratios, and low LNG selling to purchasing price ratios while there was a tendency towards SSDR for long to very long transport distances, low HFO/LNG price ratios, high LNG selling to purchasing price ratios.

2.4 Trends in Design

2.4.1 Steam Reheat Turbine

With the development of the DFDE and SSDR, and both offering higher efficiencies, there has been quite a noticeable paradigm shift from the old design standard the STPS. While the STPS has good operational reliability, maintainability and quite an impressive operational safety track record, economic drivers have triggered this shift in propulsion technology. To this end the two remaining designers and suppliers of the STPS propulsion Kawasaki and Mitsubishi Heavy Industries; have developed the reheat cycle plant where steam pressure and temperature are raised. It is claimed to have improved efficiency by more than 13% [27]. The idea is that the plant operates in a regenerative cycle with steam tapped from the high pressure turbine and fed to a reheater in the boiler before supply to the intermediate pressure turbine. The efficiency gain is derived from a higher steam pressure condition (6MPa increased to 10 MPa), higher steam temperature condition (510ºC to 560ºC) and improved turbine operating efficiency [28], while retaining the advantageous features of the STPS. A schematic of the steam reheat turbine is shown in Figure 15 [29].

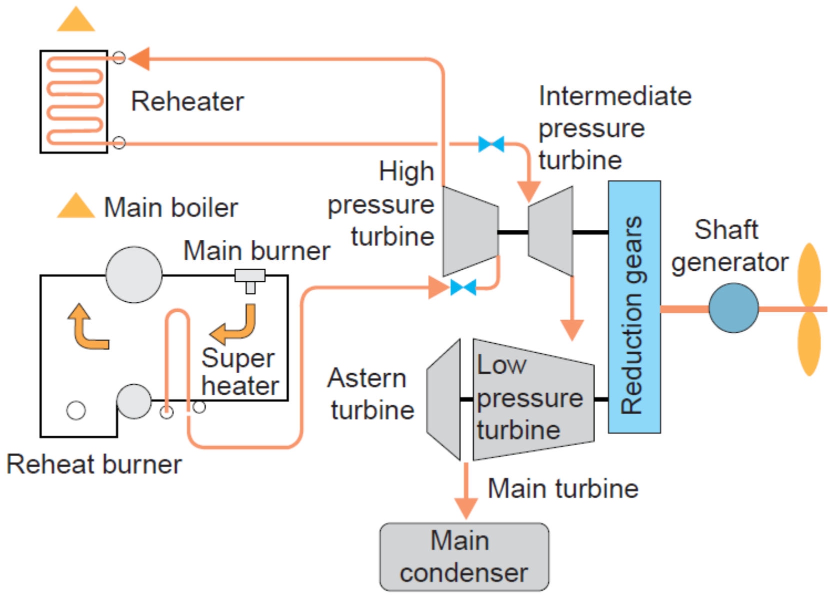


Figure 15: Steam Reheat Turbine Design Source: [29]

While it is expected that the CAPEX of the STPS is expected to rise with this enhancement to the propulsion system, it should easily be offset by the reduction in OPEX costs due to the improved efficiency. It also offers a proportionate reduction in emissions which are usually a function of the fuel consumption.

2.4.2 ME-GI propulsion system (High Pressure):

Despite having the highest thermal efficiency of all three propulsion types, the SSDR is less dominant in the LNG shipping industry due to its capabilities in handling boil off gas. Although all the slow speed diesel engine LNGCs have re-liquefaction plants that handle this boil off, initial reliability issues with these re-liquefaction plants, as well as new emission requirements, has made it seem counter intuitive to have an LNG carrier not utilising the cleaner boil of gas as fuel and while using large amounts of power to re-liquefy the LNG before returning it to the cargo tanks.

The new ME-GI propulsion systems which are two-stroke engines capable of burning gas have been introduced by MAN B&W as a proffered solution to this conundrum. The concept of the ME-GI system is based on the high pressure gas injection principle with pilot fuel ignition, ensuring the same high thermal efficiency of the diesel combustion process for heavy fuel oil burning can be achieved. MAN B&W claims that this would have an advantage over the carburetted premixed Otto cycle gas process currently being used by the DFDEs. The reason for this is the gas is not charged to the cylinder before or during the compression stroke thereby eliminating the risk of knocking. Thus high compression/expansion ratios can be utilized offering higher energy efficiency and lower gas emissions [30]. The schematic is shown in Figure 16 [14].

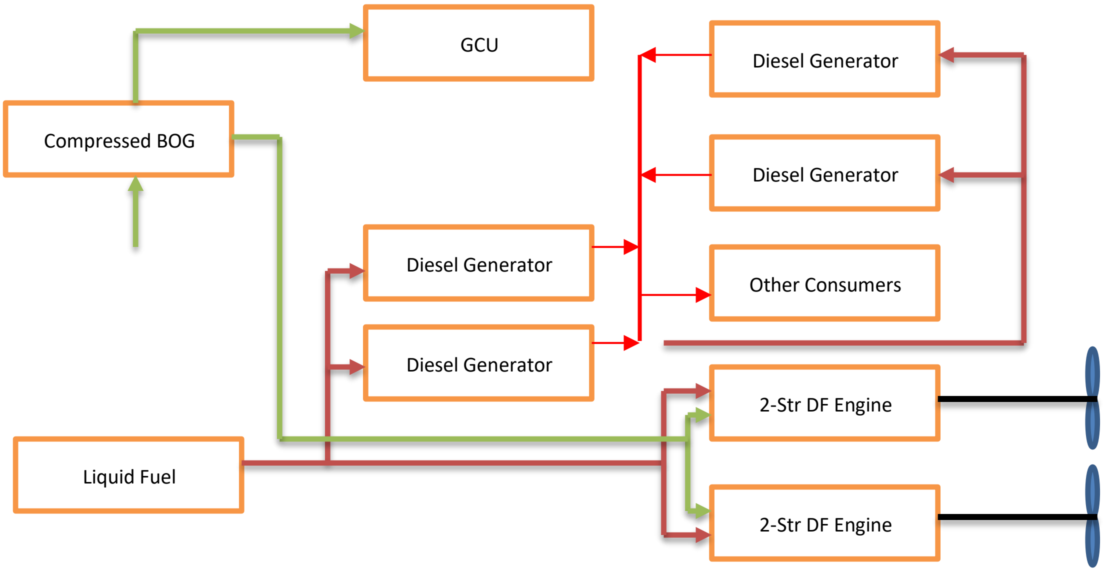


Figure 16: Schematic of the ME-GI Propulsion System Source: [14]

The point of biggest concern for the ME-GI propulsion system is the gas fuel would have to be compressed to a pressure of 250 bar before it can be injected and such a high gas pressure has never before been utilised in the LNG shipping industry, and the understandable worry is that such a high pressure might cause problems during actual operation. The energy required for compression would also reduce the efficiency gains of using the higher efficiency diesel engine when compared to the STPS, as well as the power that would otherwise have been consumed by the re-liquefaction plant. This option is however an improvement on the DFDEs in terms of flexibility of fuel choice, as it can burn varied levels of the HFO/BOG mix. In terms of emissions for the ME-GI propulsion system, the engine still emits a high level of NO_x although it is reported as being 15% better than its HFO only burning variant [30]. The SO_x and CO_2 emitted are reduced and are lower than the DFDEs or steam turbine due to its higher overall efficiency, while particulate emissions are also reduced due to the use of cleaner burning methane. Methane emissions however have been reduced drastically when compared to the DFDEs which emit between 2% to 4% with the ME-GI reported to emit less than 0.2%, which is similar to the STPS [30] [31].

2.4.3 X-DF Propulsion System (Low Pressure)

This basically extends the DFDE Lean burn Otto cycle on the two-stroke engine technology, in which fuel and air are mixed and burned at a relatively high air to fuel ratio [86]. This piston is usually at about the middle of the compression stroke when gas admission into the cylinder occurs ensuring that the gas is injected at a low pressure ranging from 5bar-16bar. Figure 17 provides an illustration of the low-pressure X-DF Configuration [84].

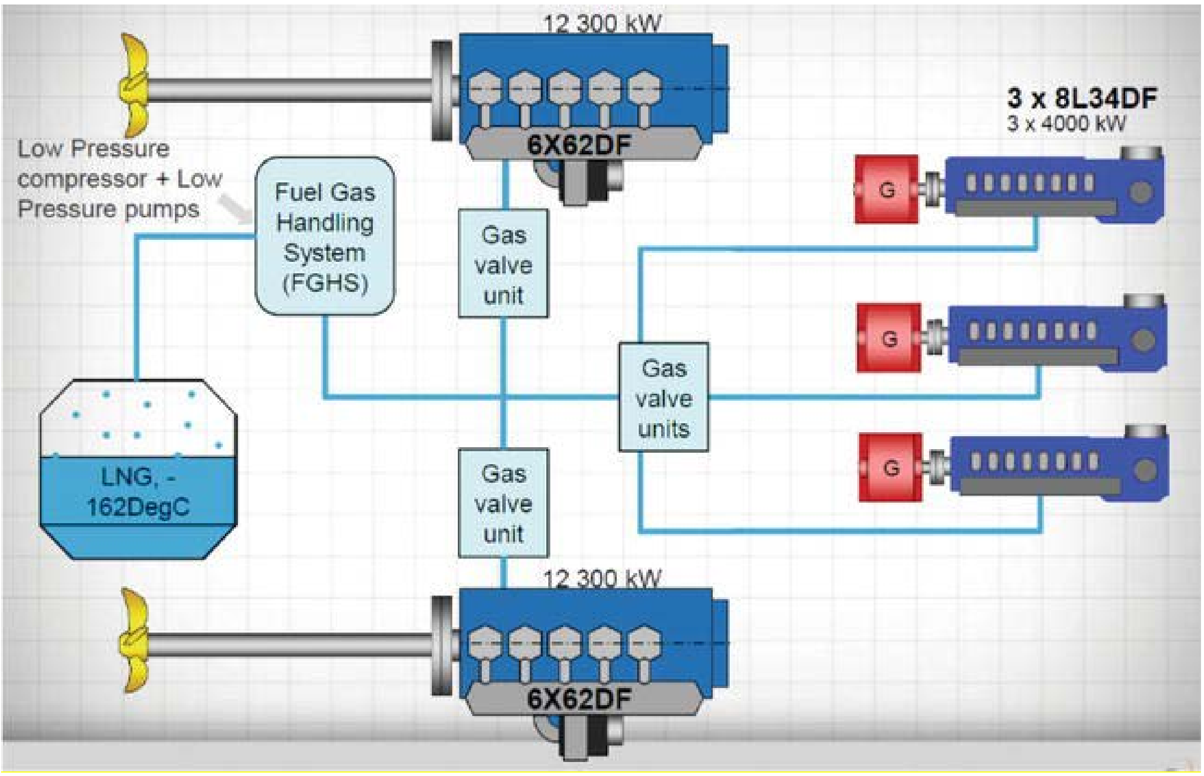


Figure 17 Schematic of the X-DF Propulsion System [84]

2.4.4 Comparisons of the ME-GI and the XDF Propulsion Options

These concepts are driven by the two main manufacturers; MAN Diesel & Turbo utilise the High Pressure- ME-GI concept, while Wartsila focuses on the low-pressure X-DF concept. Initial LNGC interest was focussed on the ME-GI options, however the X-DF option has undergone substantial development and is being favoured by LNGC shipowners [87]. As both the X-DF and ME-GI are technically different, each option has its particular merits and demerits in terms of power performance, emission and economy. These are summarized in Table 3 [88]:

Table 3: Comparison of the X-DF and ME-GI options [88]

	Low pressure (WinGD X-DF)	High pressure (MAN ME-GI)
Power performance	BMEP: 17.3 bar Output: approx. 17% lower than the diesel engine counterpart Dynamic response: poorer than diesel engine	BMEP 21 bar Output: comparable with the diesel engine counterpart Dynamic response: comparable with diesel engine
Thermal efficiency	Approx. 47%	Approx. 50%
NOx emission	IMO Tier III	IMO Tier II
CH4 slip	3 g/kWh	0.2 g/kWh
Methane Number (MN)	MN ≥ 65 (DCC technology)	Adapt to various MN
Gas consumption	140–142 g/kWh @100%MCR	136–138 g/kWh @100%MCR
Pilot fuel consumption	0.8 g/kWh@100%MCR 2.7 g/kWh@30%MCR	5 g/kWh@100%MCR 12 g/kWh@30%MCR
Fuel gas supply system	LNG pump: centrifugal pump, with simple structure and low maintenance requirement Low pressure gas compressor: a large variety of products, small size and weight, low energy consumption Low pressure vaporizer: low cost and mature technology	Low pressure vaporizer: low cost and mature technology High pressure gas compressor: few products, large size and heavy weight, high energy consumption
CAPEX	For LNG fuelled vessels, the CAPEX of high pressure fuel and gas supply system is approx. 15% higher. For LNG carriers, the CAPEX of high pressure fuel and gas supply system is approx. 40% higher.	
OPEX	The two options are comparable	

2.4.5 Steam Turbine and Gas Engine (STaGE) Propulsion

The STaGE propulsion system is essentially a hybrid between the STPS and the DFDE. This configuration consist of an ultra-steam turbine on the port side and a dual fuel diesel electric configuration on the starboard side [84]. The exhaust gases from the dual fuel engine is recovered to heat the feed water in the steam turbine system as a means of improving efficiency. There is no need for a turbine generator as with convention STPS plants as the dual fuel engine supplies both power to the propulsion motor and auxiliary power required for the vessel. Figure 18 illustrates a typical STaGE configuration [85].

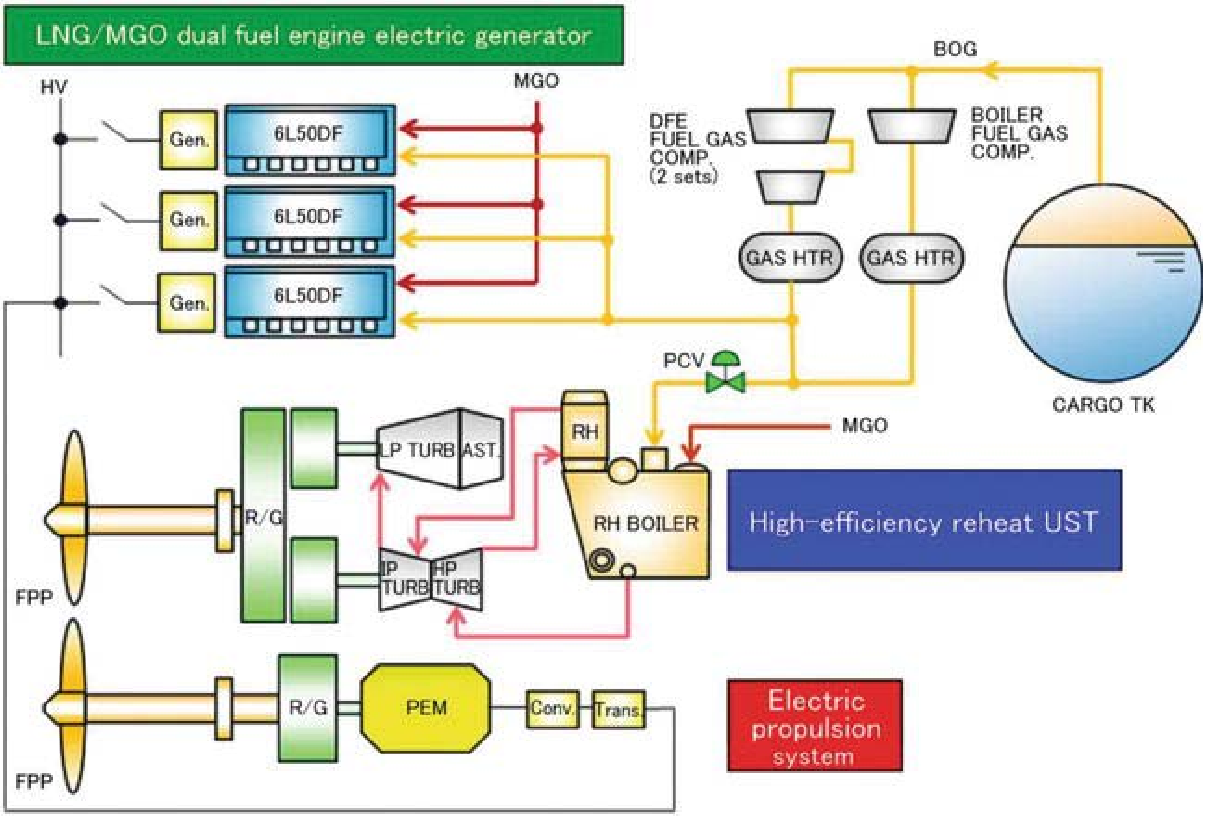


Figure 18: Schematic of the STaGE Propulsion System Source: [84]

The STaGE plant combines the reliability of the steam plant and the high efficiency of the DFDE to improve the redundancy of both the port and starboard sides.

2.5 Prospects for the Future

While it is important to note that some other propulsion options are still not past the concept stage, the four propulsion systems mentioned above, namely the steam reheat turbine, ME-GI, the STaGE and the Low-Pressure Gas Diesel Engines (X-DF) are already in service. The ME-GI propulsion system is already installed in LNG carriers due for delivery from 2016 onwards from Daewoo Heavy Industries in Korea [32]. The steam reheat turbine is already in service and it's expected to be the new standard for future orders of STPS. Other propulsion options have however been encouraged by the recent entry of the STaGE and XDF into the LNG shipping market. Fuel cells have been proposed as a future alternative as they can run on LNG but, as they have comparatively lower specific power and power densities than conventional diesel engines thus are not well suited to LNG vessels for the foreseeable future due to the vessels' substantial power requirement.

Another proposed option is the gas turbine cycle. Today the efficiency of a simple cycle gas turbine is getting closer to 40% and is beginning to show an increased advantage when compared to other propulsion systems as, historically, it has a higher reliability than diesel propulsion applications. The efficiency can be further improved by the addition of a combined cycle arrangement, where a heat recovery steam generator (HRSG) is added to the system which utilises the hot exhaust gases from the gas turbine to generate steam which will drive a steam turbine to generate electrical power. The proposal also includes fitting the HRSG with burners for auxiliary firing with either BOG or HFO. An auxiliary gas turbine is also fitted to adapt to low load demands as well as to perform propulsion redundancies as required. The addition of the HRSG as well as the auxiliary gas turbines increases both the CAPEX and the complexity of the plant, but the LCC would be expected to be lower since the CAPEX cost is usually a fraction of the LCC. The gas turbine requires about 40 bar BOG pressures which is also new to the LNG shipping industry [14]. In terms of emissions, it will offer a reduction in NO_x levels to lower than those from SSDRs but slightly higher than emissions from DFDEs and STPSs. SO_x levels should be the lowest due to the quality of fuel required by gas turbines, while CO_2 emissions are expected to be higher than the STPS but slightly lower than any of the diesel options as they have higher efficiencies. Particulate emissions would be virtually zero, again due to the quality of fuel being used, with methane emissions being in the 2% to 4% range. The schematic in Figure 19 is a typical gas turbine LNGC concept:

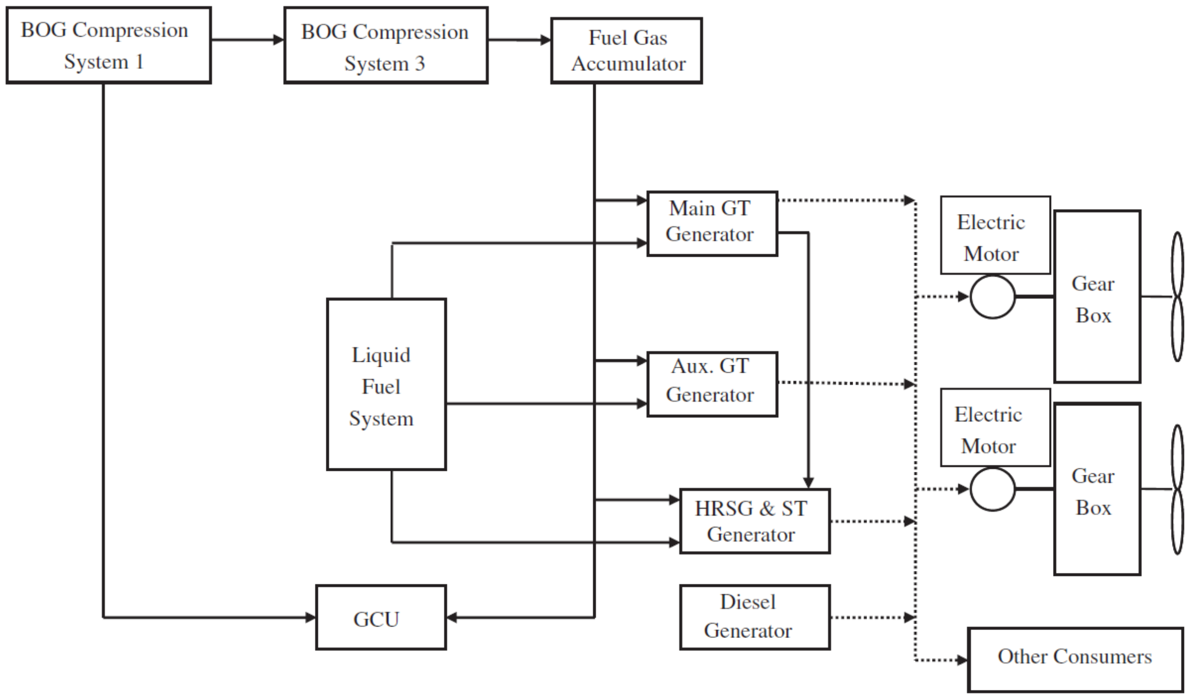


Figure 19: Schematic of the Gas Turbine LNGC Propulsion System. Source: [14]

One additional point worth considering is the interrelation between the LNGCs and the wider shipping industry. While the global shipping industry is growing at a rate averaging 2% per annum [33], the LNG Shipping industry is growing at a rate of 7% [6], showing in the next 50-100 years, the LNG Shipping industry will be quite a significant proportion of the global average. Also worth considering is the choice of fuel being used by LNGCs. Due to the nature of the boil off of cargo, as explained in chapter one, LNGCs have considerable experience of using natural gas as fuel. Other vessels in the global fleet have traditionally used liquid fuel for their daily operations. With newer emissions regulations coming into force, such as the global sulphur cap by 2020 [34], and the EEDI/EEOI requirements, there is greater demand for new vessels to start utilising natural gas as fuel [35]. This in turn will ensure that the results of this study can be expanded beyond its current scope for LNGCs, and be used for the wider shipping industry that adopt NG as a fuel.

2.6 Literature Review Summary

This chapter presented a review of the available literature on the propulsion systems for LNG carriers. First, it reviewed studies into the different propulsion types and their associated configurations, then research on comparative analysis of these different systems in terms of efficiency, emissions, availability/reliability, and economics. It then concluded with an analysis of trends in modern designs as well as future prospects. The key findings from the literature review are summarized in the points below:

- It was seen that LNG carrier propulsion is dominated by three main configurations; Steam (STPS), Diesel Electric (DFDE) and Direct Drive Diesel (DDD/SSDR). The literature showed that STPS has dominated the LNG industry since inception, due to its unique capability in utilising BOG, an inevitable by-product of the marine transportation of LNG, as the generated gas is burnt in marine boilers to produce steam for the turbines which are used for propulsion and electricity generation.

- Recent development in BOG handling technologies has moved the industry towards diesel propulsion. The SSDR utilises a conventional 2-stroke diesel engine for propulsion, with the BOG being liquefied by an on-board re-liquefaction plant, and sent back to the cargo tanks, while the DFDEs utilize BOG in gas burning 4 Stroke diesel engines to generate electrical power which is then supplied to propulsive motors for propulsion and auxiliary electrical power generation. The result of this is a mix of different technologies within the current LNG shipping fleet, with the STPS installed on 56% of the current fleet with the DFDE and DDD 31% and 13% respectively. For future orders however, the figure stands at 56% DDD, 39% for DFDE and 6% STPS.

- This marked change in propulsion preference has triggered a closer look at the particular peculiarities of each propulsion system to ascertain what this change means to the outlook of the LNG shipping industry and this was highlighted in the literature analysis. The studies showed that while the reliability and/or availability of the STPS is very good and without question throughout the LNG shipping industry, the main trigger for the change was purely economic. The STPS, with an efficiency of approximately 30%, has higher fuel consumption characteristics than the DFDEs and SSDRs, each with approximate efficiencies of 43% and 48% respectively.

- While the diesels are clearly the propulsion of choice in terms of fuel efficiency, the literature suggests a tendency towards the DFDEs for short/medium transport distances, high HFO/LNG price ratios, and low LNG selling to purchasing price ratios while there was a tendency towards SSDR for long to very long transport distances, low HFO/LNG price ratios, high LNG selling to purchasing price ratios.

- The propulsion change also brings about a change in the emissions profile of the LNG shipping industry. While the change towards the more efficient diesel engines will reduce CO_2 emissions, the SSDR introduces higher NOx emissions as well as higher SOx emissions due to its non-use of BOG for propulsion. The DFDEs, despite having low NOx, SOx and CO_2 characteristics, emit methane, which has a Global Warming Potential that is a lot higher than that of CO_2.

- The literature also highlights there are newer propulsion systems starting to enter and compete in the market. The new ME-GI propulsion combines the higher efficient 2 stroke engines of the SSDR, with the gas burning capabilities of the DFDE, while reducing the methane emissions profile drastically to become a strong alternative for future propulsion systems. The gas turbine system is also a viable option, combining its STPS like reliability with a much higher efficiency. In addition, the STPS has been developed into the reheat turbine, where the pressures and temperatures are elevated, resulting in a 13%-15% increase in system efficiencies, while still keeping the proven reliability of the STPS

However, despite the research that has been covered in this literature review, certain research gaps still exist. The overarching aim of this research, as stated in Chapter 1, was to characterise LNGC propulsion options in terms of efficiency and emissions so as to ensure optimal choices for future propulsion systems are identified. The available literature has not covered this research topic in sufficient depth to ensure the aims of this research are achieved. The research gaps not covered are:

- **The influence and Impact of EEDI on LNG carriers.** There is a noticeable scarcity of EEDI literature as it relates to LNG vessels. This has been attributed to the fact that LNG carriers have non-conventional propulsion systems and the EEDI is a relatively new concept. However, the impact of the EEDI on LNGCs is a key component of characterizing LNGCs in terms of emissions and efficiency. Additionally, as the EEDI is a regulation upon which new vessels would be constructed, an EEDI analysis of the LNGCs propulsion options will ensure optimal choices for future systems are identified.
- **Lack of case studies of the actual operation of LNGCs in regular sea going conditions**. Most of the literature reviewed [14][15][22][26][29][30], considered the different propulsions systems from a design standpoint, with voyage analysis carried out using theoretical values. This can be attributed to vessel management companies not presenting such figures in the public domain and access to such information is usually restricted. However, when attempting to characterise the propulsion systems in terms of efficiency and emissions, case studies of the actual operation of these vessels are required to characterize the LNGCs properly using actual operational figures so as to improve the validity of conclusions.
- **The use of validated models to design improvements of LNGC propulsion systems**. While the modelling techniques have been explored in designing improvement in vessel power plant design, no literature reviewed actually utilized data from the actual operating conditions of the LNG vessels in modelling design improvements. This can again be attributed to a lack of data in the public domain from shipping companies. Nonetheless, the use live data from actual sea going operations will improve the validity of the modelling techniques and ensure optimal choices for future propulsion systems are highlighted.
- **Impact of improvement technologies on EEDI of future LNGCs.** There is a lack of literature in this regard, again this can be attributed to EEDI being a relatively new concept, as well as LNGCs having non-conventional propulsion systems. This is

relevant, as current design improvement options, including those covered by the modelling process, can be utilized to determine optimal propulsion choices in future.

3.

DEVELOPING THE RESEARCH QUESTION AND APPROACH

3.1 Introduction

This chapter defines the research question and approach by focussing on the research opportunities identified in the literature review. It starts with determining questions the answers to which would satisfy any identified gaps. It then proposes methods to answer these questions and through such mechanisms contribute to subject knowledge.

3.2 Research Question Outline

The key research question would focus on how the propulsion change coupled with the rapid increase in NG demand would affect energy and emissions performance within the LNG shipping industry and options proposed to improve it. This can then be broadly subdivided into two key areas:

- Energy Efficiency in Design: How does the transport efficiency of the current LNG shipping industry relate with regards to emissions performance and how this is expected to change with the current propulsion shift?
- Improving Energy Efficiency in Design: What technological improvements could be made to existing configurations as well as future orders so as to improve transport efficiencies and reduce emissions?

It is expected that the answer to these research questions would ultimately add to the valuable academic knowledge on the topic of LNG Carriers propulsion technologies in areas where it is currently lacking. This study will focus on the STPS and the DFDE configurations as these collectively make up 87% of the current fleet. The direct drive diesel technologies will also be analysed but not in as much detail as these two other configurations primarily because the current SSDR configuration is no longer being constructed while its replacement, the ME-GI configuration, is only entering into operation. Therefore, the ability to conduct a robust analysis of the direct drive diesel technology at this time, given the limitations highlighted, has been taken into consideration.

3.3 Research Methods and Approach

In order to answer these research questions four empirical and analytical methods are explored; qualitative descriptive studies, theoretical analysis, case studies, and engineering modelling & simulation [45]. These methods are data centred ensuring that by staying in close proximity to the data, genuine experiences are captured as part of the research process. The data collection and analysis process is not linear or straightforward but iterative as the data would be collected and analysed simultaneously. The data collection process could be collective- as in the case of the descriptive studies, or specific- as in the case of the case studies or even more generic when it comes to the modelling & simulation. The important factor is that sufficient detail of LNGCs propulsion representation is covered in order to improve the veracity of the results.

The qualitative description study has been covered in most of the literature review. It is a comprehensive summary of the state of the LNGC propulsion system using descriptions and observable facts. The current LNGC propulsion systems have been described, and the different efficiencies and the future outlook have also been studied.

The next stage of analysis is a theoretical analysis, where the research moves on from substantive to formal theory. Here established efficiency theories, and present/future emissions regulations are tested using data from current LNGCs population. Proposed future technologies are also examined using critical analysis on plant design. The third stage is the case study, where a detailed investigation of the LNGC propulsion is carried out to capture the reality in greater detail [46]. Here the focus is on an individual case and not the larger population seeking an in-depth holistic understanding of the propulsion technology in its natural setting. The engineering modelling and simulation would bring together data and results from the qualitative descriptive study, the theoretical analysis, and the case studies in order to develop innovative solutions to improve LNGC transport efficiencies and reduce emissions. This analytical process ensures that final models created would include configuration of the surrounding parameters of the operational application field observed during each case study. Figure 20 summarizes the research process.

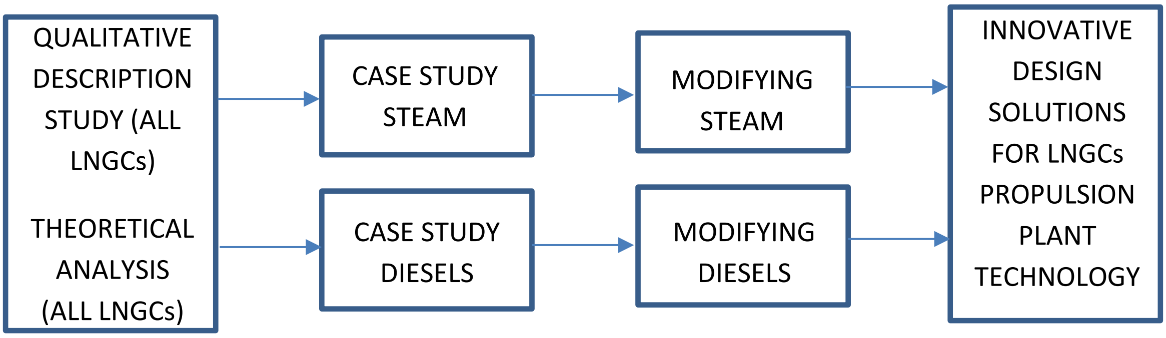


Figure 18: Full Research Pathway

The IMO's mandated Energy Efficiency Design Index (EEDI) is used to carry out a theoretical analysis of current and future LNG vessels. The EEDI is a mathematical measure of the mass of CO_2 emitted per unit of transport work for a particular ship design in grams of CO_2 per tonne nautical mile. The EEDI, which is mandatory for all LNG vessels above 400gt, aims to promote the use of more efficient engines and ships by defining a reference EEDI baseline value which new vessels would be required to adhere to. This baseline value is then tightened incrementally every five years thereby continuously stimulating the design of more efficient ships.

In the case of this research, the EEDI analysis would be used to compare the design efficiencies of the three different propulsion systems within the current LNG fleet against the current IMO mandated EEDI baseline value. In terms of emissions, the focus would be primarily on CO_2 gas because, in terms of quantity and global warming potential (GWP), CO_2 is the most significant greenhouse gas emitted from vessels [17]. The case studies will involve real time analysis of typical operating conditions of individual LNGCs and how they relate to the theoretical design values and assumptions. The IMO mandated Energy Efficiency Operational Indicator (EEOI) would be used as a benchmark for this analysis.

For the Engineering modelling and simulation, comprehensive models of the prevalent steam propulsion and the newer diesel electric (DFDE) are proposed. These comprehensive models will be able to analyse and compare the different propulsion systems at different speed/load conditions with their respective outputs. This would then allow for the analysis of the energy savings due to the addition of innovative technologies to the different propulsion types, while constantly monitoring their emissions profiles. This modelling step would focus on the STPS primarily because this technology has been fully defined as opposed to the SSDR/DDD propulsion systems where different configurations already exist and more are still under development. The DFDE systems are not modelled, but a practical approach to efficiency improvements was adopted by using experimental technology on actual vessel operations. It is important to note that the steam turbine propulsion and DFDE propulsion collectively make up 87% of the current fleet hence the relevance of concentrating on those two should not be diminished.

It is also important to emphasize the rationale behind the level of detail in the STPS as it is widely perceived to be a diminishing propulsion option. Upcoming regulations such as the Energy Efficiency Ship Index (EEXI) and Carbon Intensity Indicator (CII) [89] will require existing ship to improve upon their propulsion efficiency in a similar pattern as the EEDI from 2023 [89]. This will require technological improvements on existing steam vessels to be able to continue trading without having a speed cap on the vessel operations. As sizeable percentage- over 50% of current LNGCs are STPS, the modelling of design improvement carried out in this research would be of interest to STPS operators who are seeking improvements to current propulsion efficiency so as to be able to catch up with upcoming regulations.

Whilst it might be beneficial to utilise modelling and simulation to improve the propulsion efficiency of the STPS so as to catch up with upcoming regulation, the same does not necessarily apply to the DFDE. As the literature review has shown, the efficiency of the DFDEs are about 50% higher than those of the STPS, therefore it is unlikely that the upcoming EEXI regulation will have the same impact on the DFDE as with the STPS as this regulation is industry specific and not technology specific. Consequently, a practical approach is adopted for the DFDE as the objectives of DFDE vessel operators isn't to catch up with upcoming regulations per se, but to compete with the higher efficient gas burning two stroke options that are currently being adopted in the LNG industry. The higher exhaust temperatures of the DFDE present an opportunity for waste heat recovery systems over the gas-injection two stroke options.

3.4 Research Approach Summary

The key research questions and research approach are summarized according to the following points:

Research Question 1: How the cargo transport efficiency of the current LNG shipping industry relates with respect to emissions performance and how this is expected to change with the current propulsion shift? This research question will be answered by a combination of literature review, case studies of individual systems, as well as analytical study using the EEDI.

Research Question 2: What technological improvements could be made to existing configurations as well as future orders so as to improve transport efficiencies and reduce emissions? This research question will be answered by engineering modelling and simulation so as to bring together data and results from the qualitative descriptive study, theoretical analysis and the case studies in order to develop innovative solutions to improve LNGC transport efficiencies and reduce emissions

4.

STEAM TURBINE PROPULSION SYSTEM (STPS)

4.1 Introduction

Having completed a literature review and established a research pathway in the previous chapters, this chapter provides a comprehensive analysis of the steam turbine propulsion system option as used in LNG Carriers. To achieve the research objectives, this chapter is subdivided into four parts. 1) An analytical study of the design of steam propelled vessels using the EEDI. 2) Case study analysis of steam propelled vessels in actual operation. 3) Development and validation of thermodynamic models to characterise these systems. 4) Utilisation of the validated models to characterise system improvements in the STPS.

4.2 An Analysis using the EEDI

The main purpose of the EEDI is to quantify CO_2 emissions from ships in relation to the projected work performance and hence define baselines for new ship designs, thereby instigating more efficient ship designs. EEDI regulations were adopted for many new diesel driven ship designs such as oil tankers, bulkers and container ships from January 2013. LNG carriers were excluded from these regulations due to initial complexities in calculating the EEDI values of steam turbine and diesel electric propulsion systems, which are collectively installed in over 90% of the current LNG fleet and as specified in the future order book. With LNG shipping design transitioning through a propulsion option preference change from steam propulsion to diesel propulsion in future designs, the industry has limited knowledge and an insufficiency of the statistical data required to develop a reliably representative EEDI reference curve [36]. However, after a comprehensive review, the IMO approved amendments to MARPOL Annex VI to extend the application of the EEDI to LNG carriers and this was adopted in April 2014, with implementation carried out in September 2015 [37]. The adopted baseline for LNGCs is shown in the equation below with the phased implementation timetable shown in Table 4a;

$$Baseline\ Value = 2253.7 \times Deadweight^{-0.474}$$

Table 4a: EEDI Baseline for LNGCs. Source: [37]

Ship Type	Size	Phase 0	Phase 1 Sept 2015 – Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 – Onwards
LNG Carrier	>10,000 DWT	n/a	10% reduction	20% reduction	30% reduction

4.2.1 EEDI Analysis of the Current Steam Fleet:

In order to effectively predict the impact of the LNGC EEDI baseline on the design of future LNGCs a statistical analysis of the current fleet of LNGCs has been carried out. Data pertaining to the existing fleet is obtained from Clarkson's World Fleet Register and only ships built in 2000 or later have been taken into account. A close estimate for these ships has been calculated using the EEDI formula which takes into account only main and auxiliary engine power (P_{ME}, P_{AE}), standardised specific fuel consumptions (based in MEPC 65 [38]), with capacity in tons deadweight and the speed of the ship, both obtained from the Clarkson's World Fleet Register and verified on the respective classification society fleet registers [39], [40]. For the different propulsion systems, the estimated EEDI formulas are summarized in the Table 4b; [37, 38].

Table 4b- EEDI Formulas for LNGCs. Source: [37, 38]

	Direct Drive Diesel	Dual Fuel Diesel Electric	Steam Turbine
Margin	Engine: 10% Sea: 20%	Engine: - Sea: 20%	Engine: - Sea: 20%
Design Margin	$M\arg in = \frac{0.9}{1.2}$ $M\arg in = 75\%$	$M\arg in = \frac{1}{1.2}$ $M\arg in = 83\%$	$M\arg in = \frac{1}{1.2}$ $M\arg in = 83\%$
P_{ME}	$P_{ME} = 0.75 \times MCR_{ME}$	$P_{ME} = 0.83 \times \frac{MPP}{\eta_{Electrical}}$	$P_{ME} = 0.83 \times MCR_{ME}$
SFC_{ME} (g/kwh)	190 (HFO)	175 (FBO)	285 (FBO)
P_{AE}	$P_{AE} = (0.025 \times MCR_{ME}) + 250 + (Capacity \times BOR \times COP_{reliq} \times R_{reliq})$	$P_{AE} = (0.025 + 0.02) \times P_{ME} + 250$	$P_{AE} = 0$
EEDI	$3.1144 \times \frac{(190 \times P_{ME}) + 215 \times P_{AE}}{Capacity \times V_{ref}}$	$2.75 \times \frac{(175 \times P_{ME}) + 175 \times P_{AE}}{Capacity \times V_{ref}}$	$2.75 \times \frac{285 \times P_{ME}}{Capacity \times V_{ref}}$

For the steam turbine propulsion system, the following assertions and assumptions were made;

- The SFC_{ME} takes into account the total energy input to the boilers for supply to the steam turbines, and as the electrical power is primarily supplied by the turbine generator, which is integrated to these boiler supply systems, the P_{AE} is taken to be zero.

The baseline equation was applied and combined with the equations in Table 4, while taking into account the percentage reductions in EEDI to be implemented in the phases mandated by the IMO up to 2025.

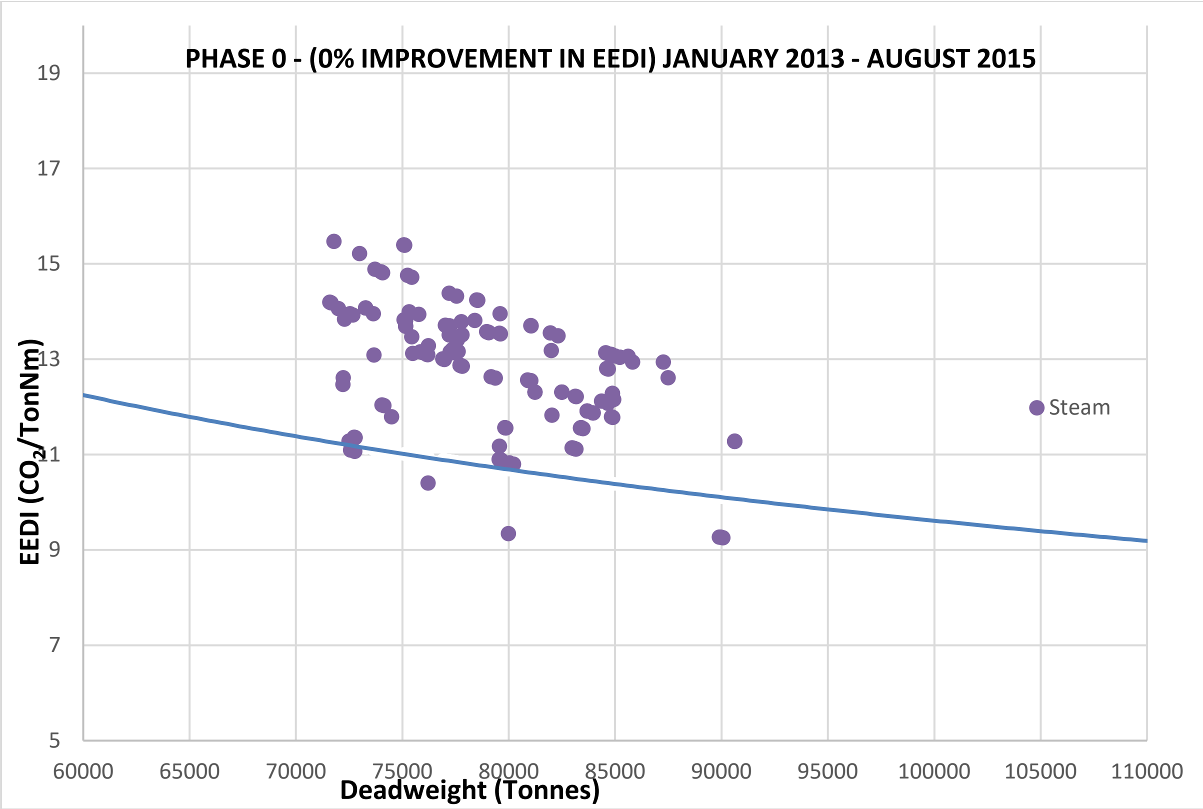


Figure 21- Phase 0 (0% Improvement in EEDI) January 2013 – August 2015

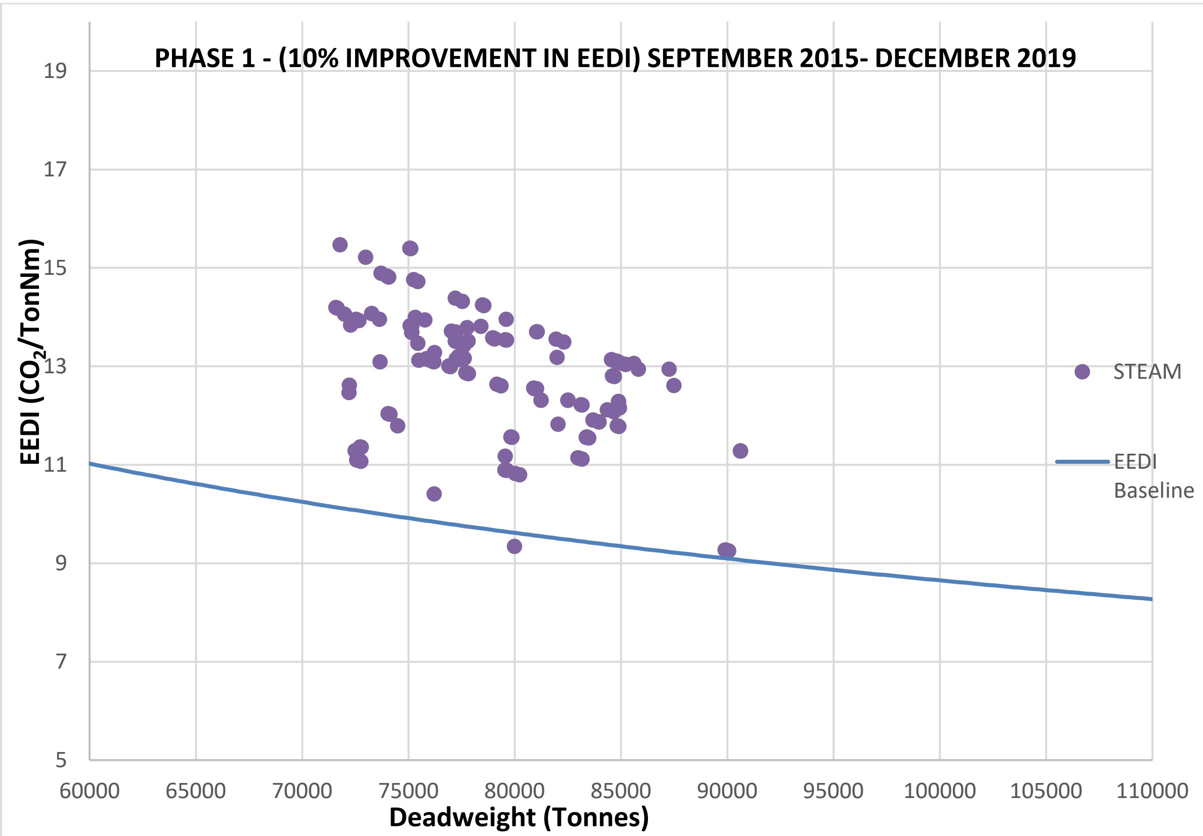


Figure 22- Phase 1 (10% Improvement in EEDI) September 2015 – December 2019

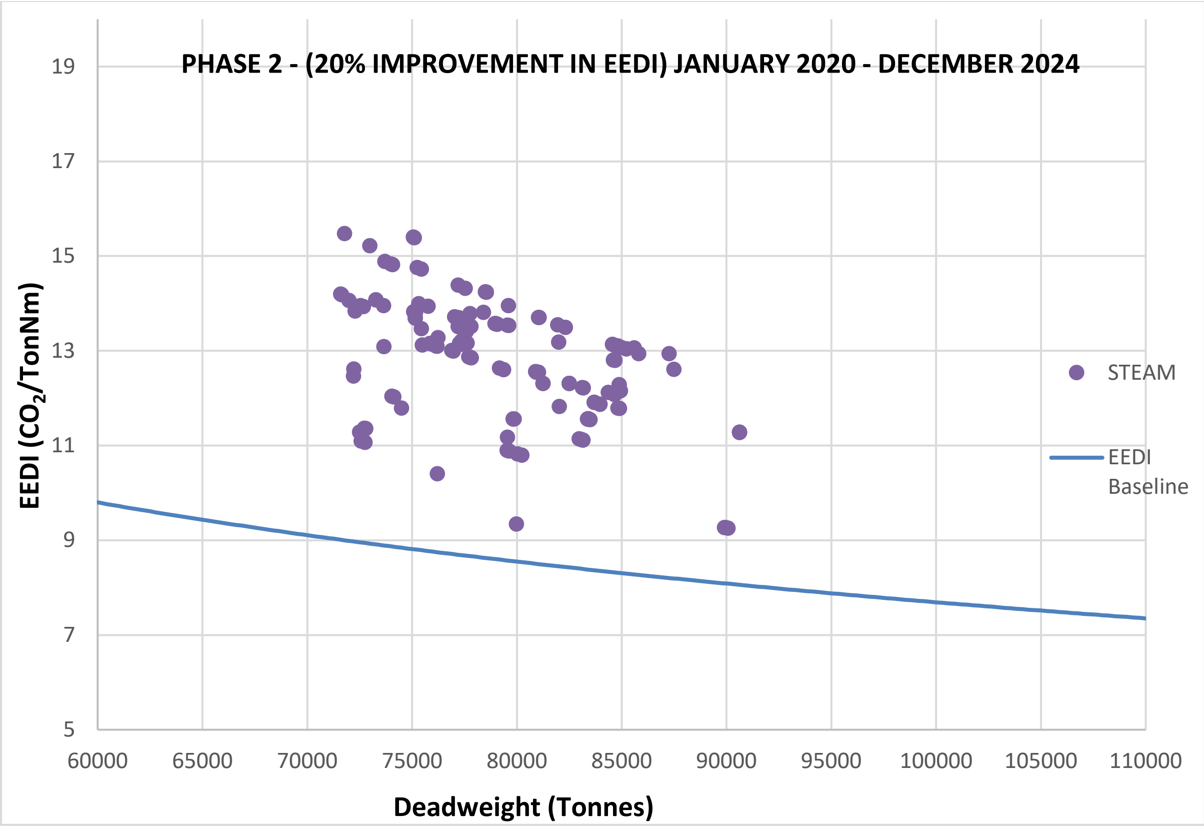


Figure 23- Phase 2 (20% Improvement in EEDI) January 2020 – December 2024

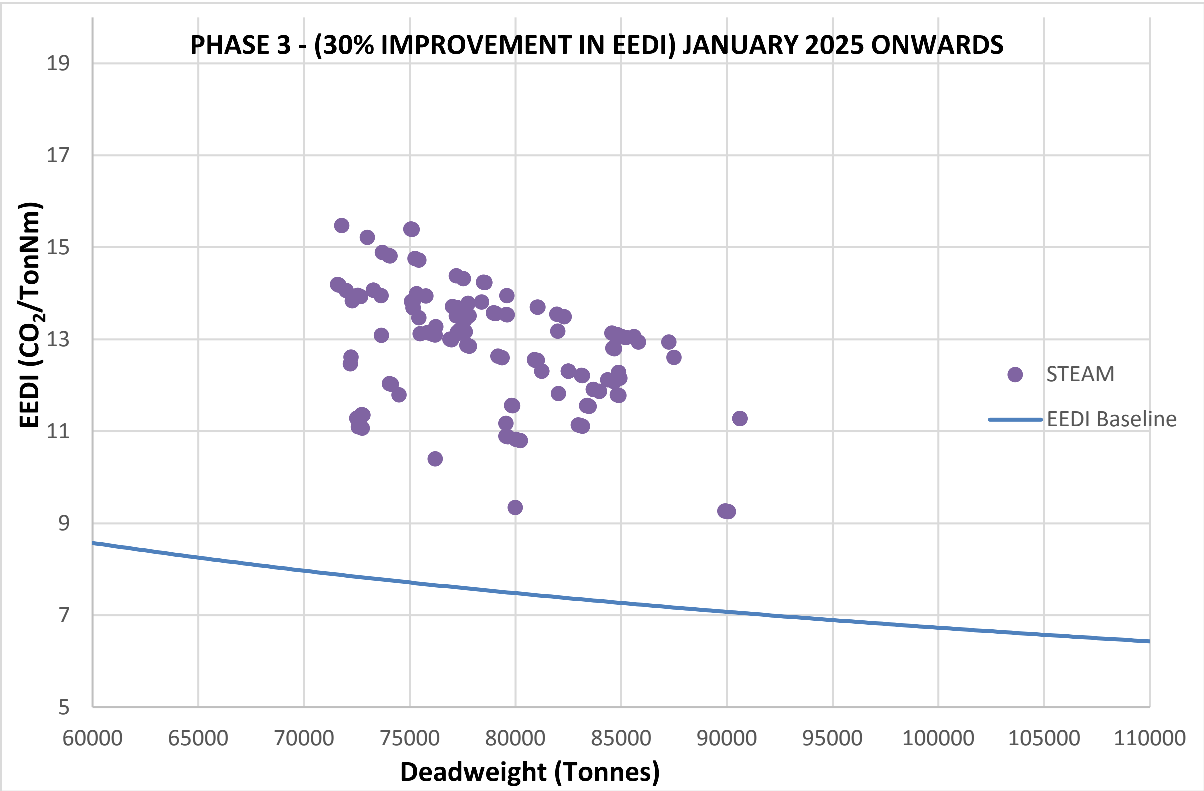


Figure 24- Phase 3 (30% Improvement in EEDI) January 2025 onwards

Table 4c summarises the results from the EEDI study of the steam fleet.

Table 4c EEDI Analysis of the steam fleet

Propulsion Type (Nos)	Phase 0 Compliant	Phase 1 Compliant Sept 2015 – Dec 2019	Phase 2 Compliant 2 1 Jan 2020 – 31 Dec 2024	Phase 3 Compliant 1 Jan 2025 – Onwards
Steam Turbine(159)	7- (6%)	1- (0.6%)	0- (0%)	0- (0%)

The full dataset with associated calculations and results are presented in Appendix 1.

4.3 Case Study

As can be seen from Figure 2, steam ships still dominate the fleet numerically and these ships are likely to still be around for at least another 20 years. In order to analyse the energy efficiency of these ships, a case study was devised. The choice for the case study is a ship built between 2000 and 2010, a period within which the number of steam ships delivered comprised 43% of the total LNG fleet [2]. The choice of ships for this case study also has particular merits. Nearly all steam propulsion LNG ships, regardless of age, are similar in system configuration and operation as they all have boilers,; turbo-alternators; steam feed pumps; main condensers; intermediate heaters and utilise cargo boil off/heavy fuel oil (HFO)/marine gas oil (MGO) in their fuel mixes, with steam dumping being utilised at low loads. In addition, all steam LNG ships built from 1994 have near identical plant configurations as the case study with minor variations. This translates to 78% of the current steam powered fleet [2].

The process was to analyse the design characteristics as well as the actual operational performance and undertake a comparison between the two to indicate how efficiently the LNG carrier is being operated. A ship with the characteristics summarised in Table 5.

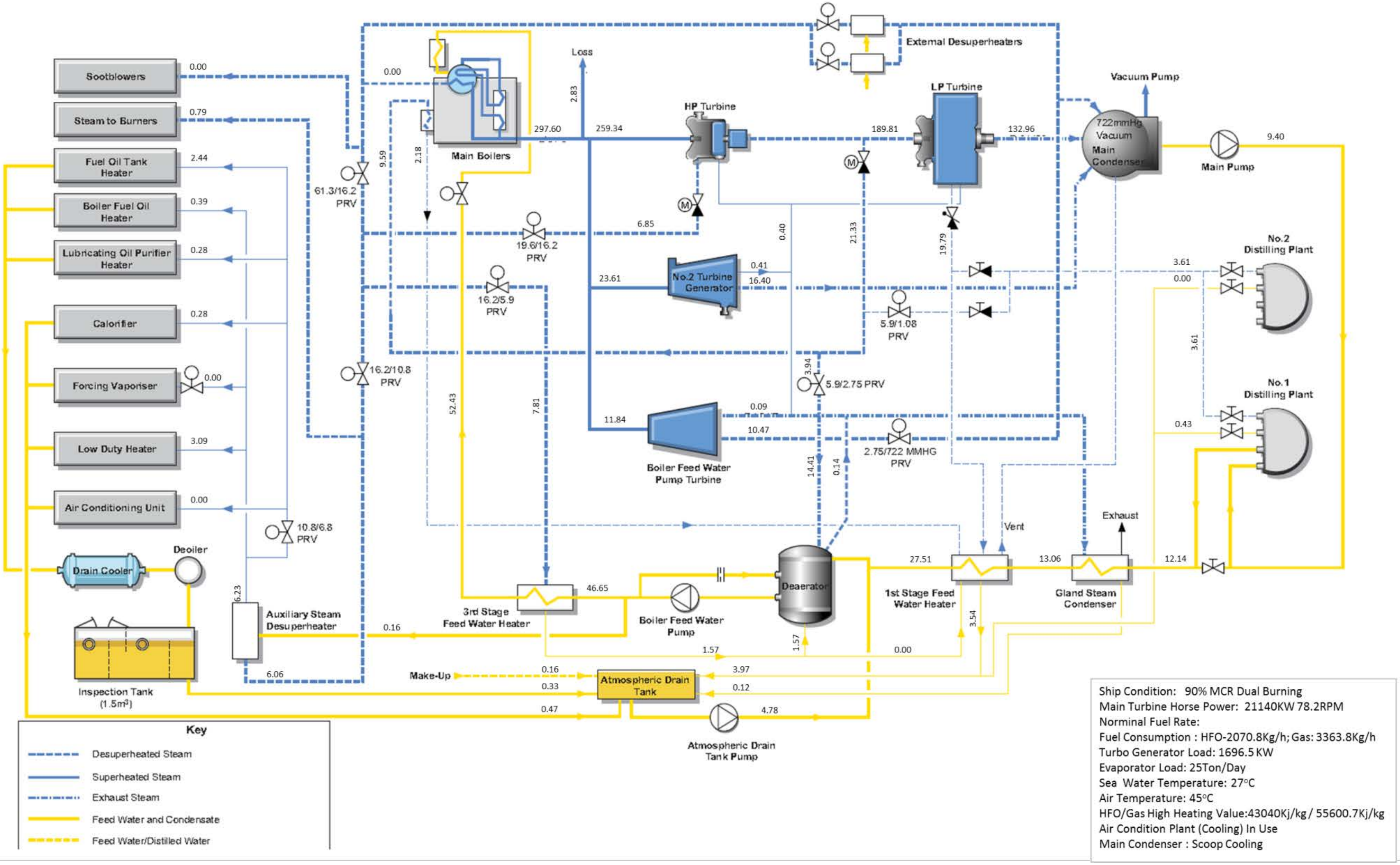
Table 5: Case Study Ship Principal Characteristics.

Ship Principal Characteristics		
Characteristics	Value	Comments
Ship Type	LNG Carrier	
Date of Delivery	2006	
Summer Draught	12.32 m	
Draught, Ballast	9.78 m (Normal & Heavy Weather)	
Cargo Tank Capacity	141,052 m^3	At 100%
Deadweight, Summer Draught	79,541 t	
Displacement, Summer Draught	113,567 t	
Service Speed	19.25 knots	Design Draught 11.25 m
Propulsion Engine		
Descriptive Notes: Steam Turbine Driven Shaft Via Gearbox		
Make and Model	Mitsubishi MS 36-2 Steam Turbine	
Rating (Turbine)	23,500 kW	HP Turbine: 5,685 rpm LP Turbine: 3,351 rpm Propeller: 81 rpm
Specific Fuel Consumption at rated power		
Propeller	5 Bladed 8.6 m diameter	Fixed Pitch
Generators and Boilers		
Turbo Generators: Two Steam Turbo Generators		
Make and Model (Turbine)	HHI RG92-2	8145rpm
Generator	4062.5 kVA at 1800 rpm	
Specific Fuel Consumption at rated Power	13.65 t/h	Steam
Diesel Generators: Two 6-Cylinder Direct injection Diesel Engines		
Engine Make and Model	Hyundai MAN- B&W 8L28/32H	2 x 1,600 kW at 720 rpm
Generator	2,000 kVA at 720 rpm	
Fuel	LSDO	
Boilers: Two Top Fired Water Tube		
Make and Model	HHI 2 X MB-3E	
Rating	47 t/h 515^{O}C at 60 Bar	Maximum 55 t/h
Rated Fuel Consumption	4001 kg/h	Maximum Burner Capacity
Fuel	HFO/Methane/MGO	

In this study, assumptions were kept at an absolute minimum, with typical values being obtained onboard or calculated based on actual operating conditions for all modes of operation (ballast, loaded, loading, discharging, manoeuvring, Off Port Limit operations) over a 12 month period.

4.3.1 Design versus actual Energy Flow Analysis and Results

The first step was conducting an energy flow analysis showing how all the fuel derived energy is used. To do this, design heat balance and flow diagrams [41] were utilized to develop energy flow diagrams (EFD). These energy flow diagrams are essential in detailing how much fuel the plant should consume at different modes of operation respectively. The EFD was used to quantify the 'design specification'. To obtain recorded data for actual scenarios, the Kyma Steam Plant Analyser [42] was used which monitored the engine and plant performance during actual operations during a 12 month period. This was supplemented by back up information obtained from plant logs, electronic archive sheets and noon reports over the same 12 month period. The different modes of operation analysed included 100% Maximum Continuous Rating (MCR) Dual Burning, 90% MCR Dual Burning, 70% MCR Dual/HFO Burning, 50% MCR Dual/HFO Burning, 30% MCR Dual/HFO Burning, in Port Loading, in Port Discharging, and hotel load (anchor) conditions. Based on these conditions, the EFDs were utilized to provide better visualisation of the results, samples of which are shown in Figure 25 and Table 6 respectively.



Ship Condition: 90% MCR Dual Burning
Main Turbine Horse Power: 21140KW 78.2RPM
Norminal Fuel Rate:
Fuel Consumption : HFO-2070.8Kg/h; Gas: 3363.8Kg/h
Turbo Generator Load: 1696.5 KW
Evaporator Load: 25Ton/Day
Sea Water Temperature: 27°C
Air Temperature: 45°C
HFO/Gas High Heating Value:43040Kj/kg / 55600.7Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Scoop Cooling

Figure 25: 90% MCR Dual Burning Vessel EFD

Table 6: 90% MCR Design/Actual Summary Vessel Condition

Ship Condition (Design)	**90% MCR Dual Burning**		**Ship Condition (Actual)**	**90% MCR Dual Burning**	
Main Turbine Horsepower	21,140 kW 78.2 rpm		Main Turbine Horsepower	21,215 kW 77.6rpm	
Nominal Fuel Rate (F/G)	303.9 g/kWh	234.9 g/kWh	Nominal Fuel Rate (F/G)	372.2 g/kWh	293.9 g/KWh
Fuel Consumption	2,070.8 kg/h	3,363.8 kg/h	Fuel Consumption	851 kg/h	5,575 kg/h
Fuel Energy in	276.16 GJ/h		Fuel Energy in	341.15 Gj/h	
Turbo Generator Load	1,696.5 KW		Turbo Generator Load	1595 Kw	
Evaporator Load	25 t/day		Evaporator Load	24 t/day	
Sea Water Temperature	27°C		Sea Water Temperature	22°C	
Air Temperature	45°C		Air Temperature	35°C	
HFO/Gas Heating Value	43,040 kJ/kg	55,600.7 kJ/kg	HFO/Gas Heating Value	42,391 kJ/kg	43,040 kJ/kg
Air Condition Plant	Cooling (In Use)		Air Condition Plant	Cooling (In Use)	
Main Condenser	Scoop Cooling		Main Condenser	Scoop Cooling	

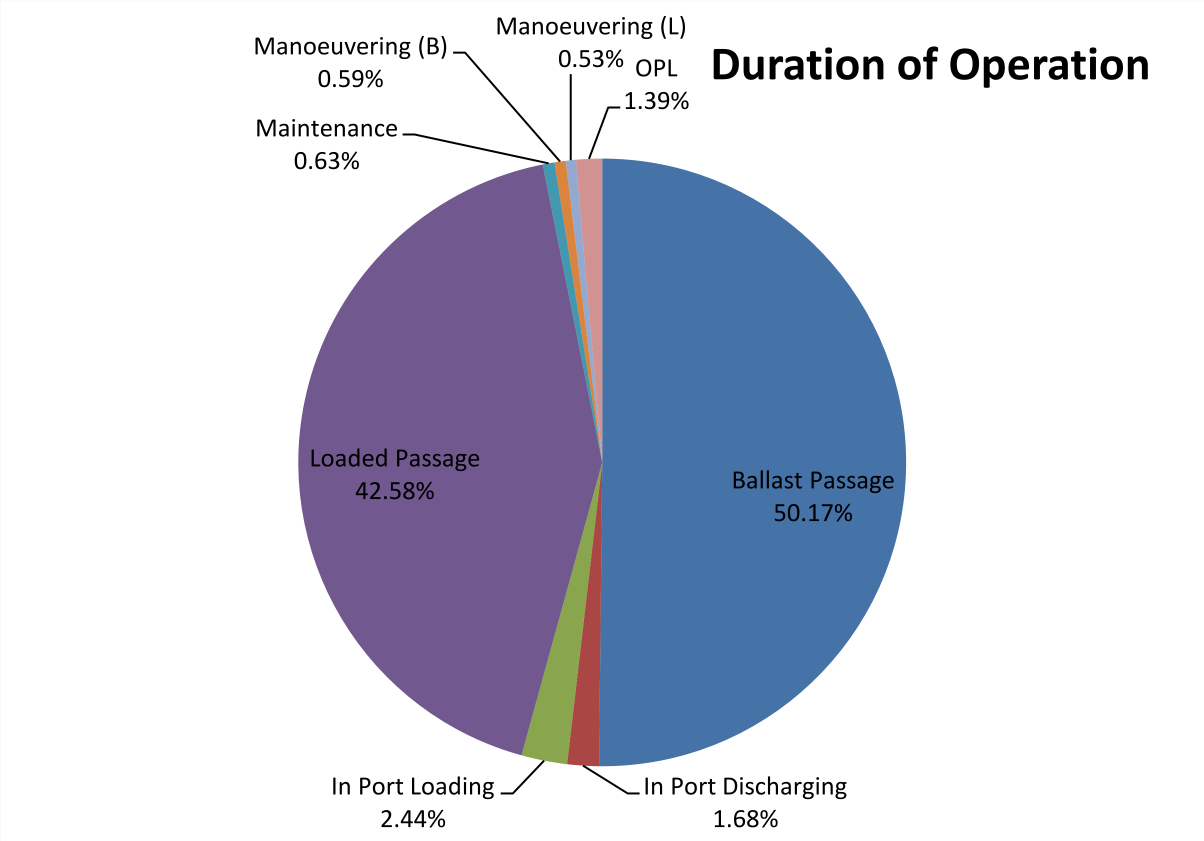


Figure 26: Vessel Duration of Operation for the Year

Table 7: Vessel Time of Operation Summary

Mode of Operation	Time (HH:MM:SS)	Percentage
Ballast Passage	4367:18:00	50.17%
Loaded Passage	3706:42:00	42.58%
In Port Loading/Discharging	358:15:00	4.12%
Off Port Limit (OPL) Operations	120:44:00	1.39%
Manoeuvring	97:57:00	1.12%
Maintenance Operations	54:36:00	0.63%
Total	8705:32:00 (363 Days)	100%

The Table 8a highlights the design condition of the vessel, as provided for by the vessel builders. As seen for the different operating conditions, there is a supply of fuel energy to the plant and this is then utilised by the vessel for its operation. The table essentially represents the utilisation of this fuel energy within the vessel at the different conditions, by the different systems.

Table 8a Vessel Design Energy Usage in GJ/hr

Design Energy Use In GJ/h	100% MCR	90% MCR	70% MCR	50% MCR	30% MCR	Loading	Discharging	OPL
Boiler Heat Loss	42.16	38.4	24.87	19.69	15.53	7.88	10.85	7.24
Propulsion	84.6	76.1	59.19	42.3	25.38	0	0	0
M/E Heat Loss	138.28	124.59	100.23	79.14	54.49	0	0	0
M/E Other Losses	10.78	10.27	7.81	6.41	4.75	0	0	0
T/A Hotel Load	6.18	6.18	5.53	5.38	6.42	14.04	19.99	5.19
T/A Heat Loss	15.61	15.37	13.99	13.58	15.8	33.41	50.34	12.23
T/A Other Losses	1.68	1.65	1.53	1.45	1.13	0.75	1.66	0.14
Feed P/P Heat Loss	0	0	0	0	0	0.56	0	4.54
Feed P/p other loss	1.35	1.28	1.15	1.11	0.95	0.84	0.84	0.93
Steam loss	2.99	2.83	2.45	2.17	1.85	1.38	1.54	1.13
Dump	0	0	0	0	0	0	0	0
Total Energy	**303.63**	**276.67**	**216.75**	**171.23**	**126.3**	**58.86**	**85.22**	**31.4**

Table 8b represents the same table in percentage utilisation terms. This is quite essential in clearly highlighting the largest energy consumers in the different modes of operation.

Table 8b Vessel Design Energy Usage in %

Design Energy Use In (%)	100% MCR	90% MCR	70% MCR	50% MCR	30% MCR	Loading	Discharging	OPL
Boiler Heat Loss	13.89%	13.88%	11.47%	11.50%	12.30%	13.39%	12.73%	23.06%
Propulsion	27.86%	27.51%	27.31%	24.70%	20.10%	0.00%	0.00%	0.00%
M/E Heat Loss	45.54%	45.03%	46.24%	46.22%	43.14%	0.00%	0.00%	0.00%
M/E Other Losses	3.55%	3.71%	3.60%	3.74%	3.76%	0.00%	0.00%	0.00%
T/A Hotel Load	2.04%	2.23%	2.55%	3.14%	5.08%	23.85%	23.46%	16.53%
T/A Heat Loss	5.14%	5.56%	6.45%	7.93%	12.51%	56.76%	59.07%	38.95%
T/A Other Losses	0.55%	0.60%	0.71%	0.85%	0.89%	1.27%	1.95%	0.45%
Feed P/P Heat Loss	0.00%	0.00%	0.00%	0.00%	0.00%	0.95%	0.00%	14.46%
Feed P/p other loss	0.44%	0.46%	0.53%	0.65%	0.75%	1.43%	0.99%	2.96%
Steam loss	0.98%	1.02%	1.13%	1.27%	1.46%	2.34%	1.81%	3.60%
Dump	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total Energy Used	**100.00**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

As highlighted in Table 8b, at 100% MCR, 45.54% of energy supplied is lost as heat from the M/E exhaust to the condenser. Other heat losses in the system are attributed to the boiler heat loss at 13.89% and the T/A heat loss at 5.4%. The useful energy at this condition 27.86% used for propulsion of the vessel and 2.04% by the T/A for hotel load- essentially electrical supply to the vessel auxiliary power consumers. The useful energy usage represents approximately 30% of the total energy supplied at this condition. This useful energy percentage reduces progressively to 25% at 30% MCR, and this is evidently due to the reduction in energy demand from the propulsion system. At Loading and Discharge conditions, the major consumer of energy is the T/A as the M/E is shut down and the useful energy usage at these conditions is approximately 24%, and drops to 16.53% at OPL conditions.

Table 8c represents the actual energy usage of the subject vessel at the different operating conditions. Ironically, during the period analysed, the vessel was not operated at 100% MCR with the maximum observed being 91% and this is highlighted in the table below.

Table 8c Vessel Actual Energy Usage in GJ/hr

Actual Energy Use In GJ/hr	91% MCR	90% MCR	70% MCR	50% MCR	30% MCR	Loading	Discharging	OPL
Boiler Heat Loss	47.97	56.04	41.71	37.79	25.65	16.7	13.88	16.52
Propulsion	77.05	76.37	57.636	43.11	24.88	0	0	0
M/E Heat Loss	174.37	170.84	139.97	126.27	103.89	0	0	0
M/E Other Losses	15.27	12.78	14.37	9.1	6.81	0	10.13	17.47
T/A Hotel Load	5.67	5.74	5.61	5.65	6.11	8.64	18.13	5.75
T/A Heat Loss	14.19	14.53	14.01	14.25	16.14	20.93	45.95	14.93
T/A Other Losses	1.59	1.45	1.61	1.48	1.73	5.13	6.02	4.75
Feed P/P Heat Loss	0	0	0	0	0	0	0	0
Feed P/p other loss	2.25	1.42	2.08	2.13	2.05	1.86	1.86	1.86
Steam loss	1.77	1.38	2.24	2.27	2.31	1.38	1.38	1.38
Dump	0	0	0	0	0	49.25	19.42	57.19
Total Energy Used	**340.13**	**340.55**	**279.236**	**242.05**	**189.57**	**103.89**	**116.77**	**119.85**

Table 8d represents Table 8c in percentage utilisation terms.

Actual Energy Use In (%)	91% MCR	90% MCR	70% MCR	50% MCR	30% MCR	Loading	Discharging	OPL
Boiler Heat Loss	14.10%	16.46%	14.94%	15.61%	13.53%	30.56%	14.26%	26.36%
Propulsion	22.65%	22.43%	20.64%	17.81%	13.12%	0.00%	0.00%	0.00%
M/E Heat Loss	51.27%	50.17%	50.13%	52.17%	54.80%	0.00%	0.00%	0.00%
M/E Other Losses	4.49%	3.75%	5.15%	3.76%	3.59%	0.00%	10.41%	27.88%
T/A Hotel Load	1.67%	1.69%	2.01%	2.33%	3.22%	15.81%	18.62%	9.18%
T/A Heat Loss	4.17%	4.27%	5.02%	5.89%	8.51%	38.31%	47.20%	23.83%
T/A Other Losses	0.47%	0.43%	0.58%	0.61%	0.91%	9.39%	6.18%	7.58%
Feed P/P Heat Loss	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Feed P/p other loss	0.66%	0.42%	0.74%	0.88%	1.08%	3.40%	1.91%	2.97%
Steam loss	0.52%	0.41%	0.80%	0.94%	1.22%	2.53%	1.42%	2.20%
Dump	0.00%	0.00%	0.00%	0.00%	0.00%	90.14%	19.95%	91.27%
Total Energy Used	**100.00**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

As highlighted in Table 8d, at 91% MCR, 51.27% of energy supplied is lost as heat from the M/E exhaust to the condenser. Other heat losses in the system are attributed to the boiler heat loss at 14.10% and the T/A heat loss at 4.17%. The useful energy at this condition 22.65% used for propulsion of the vessel and 1.67 by the T/A for hotel load- essentially electrical supply to the vessel auxiliary power consumers. The useful energy usage represents approximately 24% of the total energy supplied at this condition. This useful energy percentage reduces progressively to 16% at 30% MCR, and this is evidently due to the reduction in energy demand from the propulsion system. At Loading and Discharge conditions, the major consumer of energy is the T/A as the M/E is shut down and the useful energy usage at these conditions is between 16% and 19%, and drops to 9.18% at OPL conditions.

Table 8e highlights the difference between the design conditions and the actual operation conditions

Table 8e Difference between Actual and Design energy Usage

Actual-Design Energy Use (GJ/hr)	**90% MCR**	**70% MCR**	**50% MCR**	**30% MCR**	**Loading**	**Discharging**	**OPL**
Boiler Heat Loss	17.64	16.84	18.1	10.12	8.82	3.03	9.28
Propulsion	0.27	-1.554	0.81	-0.5	0	0	0
M/E Heat Loss	46.25	39.74	47.13	49.4	0	0	0
M/E Other Losses	2.51	6.56	2.69	2.06	0	10.13	17.47
T/A Hotel Load	-0.44	0.08	0.27	-0.31	-5.4	-1.86	0.56
T/A Heat Loss	-0.84	0.02	0.67	0.34	-12.48	-4.39	2.7
T/A Other Losses	-0.2	0.08	0.03	0.6	4.38	4.36	4.61
Feed P/P Heat Loss	0	0	0	0	-0.56	0	-4.54
Feed P/p other loss	0.14	0.93	1.02	1.1	1.02	1.02	0.93
Steam loss	-1.45	-0.21	0.1	0.46	0	-0.16	0.25
Dump	0	0	0	0	49.25	19.42	57.19
Total Extra Energy GJ/hr (in %)	**63.88 (23%)**	**62.486 (29%)**	**70.82 (41%)**	**63.27 (50%)**	**45.03 (77%)**	**31.55 (37%)**	**88.45 (281%)**

As seen from Table 8e, there is an extra energy requirement of between 63GJ/h and 71GH/hr, representing approximately 21% to 50% extra fuel requirements from the design conditions between the 90% and 30% MCR range. This increase in energy requirement is primarily due to additional energy required by the main engine. This invariably leads to high boiler heat losses due to the additional steam being generated, as well as larger M/E heat losses due to the additional steam demand to the M/E. This is fairly similar across the 90% MCR to 30% MCR range. For the conditions where the M/E is shut down, the extra energy requirements are 37%, 76%, and 281% for Discharging, Loading and OPL conditions. The bulk of this additional energy requirement is due to dump steam- this is normally used when the vessel is at very low loads to maintain the boiler load above a certain threshold to ensure plant stability. Additional causes of inefficiency are the T/A and the ME which consumes energy despite being shut down due to the practice of constantly warming through the engine to ensure the engines are ready to be restarted at short notice.

The full dataset, calculations and EFDs are shown in Appendix 2/3.

The next step involved using the Marine Environment Protection Committee (MEPC) mandated Energy Efficiency Operational Index (EEOI) to analyse the vessel's efficiency over the same period, using the same data from the case study. Throughout the case study, the EEOI is used as a representative value of the ship's efficiency over a period and represents the trading pattern of the vessel. It is the fuel consumption expressed in CO_2 emitted per unit of cargo nautical mile as expressed below:

$$EEOI = \frac{Fuel\ Consumption\ \times Carbon\ Factor}{Mass\ of\ Cargo\ \times Distance\ Covered} \tag{1}$$

The trading period covered is from 19/06/2012 to 26/05/2013 during which the vessel delivered six cargoes, all originating from Bonny, Nigeria. Two cargoes were each delivered to Japan and Korea, while one each to Spain and India. The results of the EEOI for these voyages are shown in Table 9; all input values for the calculation were obtained from on-board vessel records.

Table 9: Actual EEOI over Six Voyages

Voyage	Distance (nm)	LNG Delivered(t)	LSDO Consumed(t)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/t.nm)
1- NG-JPN	22,559.3	129,683	12	4,694	2,676	32.37
2- NG-IND	16,242.8	128,887	33	4,649	637	31.74
3- NG-SPA	7,179.5	134,445	39.2	2,039	247	29.65
4- NG-JPN	22,406.1	128,848	4	4,861	2,505	32.65
5- NG-SKR	22,289.7	128,596	14	5,261	2,438	34.35
6- NG-SKR	22,249.6	128,480	7	5,304	2,568	35.26

Additionally, comparisons between the actual EEOI and the design (i.e. best case) EEOI were carried out for each of these voyages. The EEOI was recalculated based on the design specifications of the plant to ascertain how efficiently these cargoes should have been delivered based on theoretical design parameters. To achieve this, all log records for the plant during the six voyages were analysed. Based on the fuel consumption design specifications at those conditions, equivalent fuel consumption for each specific voyage was obtained. The identical amounts of LNG and LSDO consumed during the actual voyages were replicated and used to calculate the design EEOI for each respective voyage. The results are displayed in Table 10:

Table 10: Calculated Design EEOI over the Six Voyages

Voyage	Distance (Nm)	LNG Delivered(t)	LSDO Consumed(t)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/tonNm)	Δ% from Actual
1- NG-JPN	22,559.3	129,683	12	4,694	1042	24.63	-31.4%
2- NG-IND	16,242.8	128,887	33	4,649	(539)	23.91	-32.8%
3- NG-SPA	7,179.5	134,445	39.2	2,039	(325)	21.53	-37.7%
4- NG-JPN	22,406.1	128,848	4	4,861	949	25.18	-29.7%
5- NG-SKR	22,289.7	128,596	14	5,261	341	24.20	-41.9%
6- NG-SKR	22,249.6	128,480	7	5,304	394	24.70	-42.8%

As can be seen from the design EEOI obtained above, the reduction in operational efficiency of the vessel when benchmarked against design specifications is between 29.7% and 42.8%.

4.3.2 Improving Energy Efficiency of Steam Propelled LNG Ships

In this research, improvement in energy efficiency will be examined from two different directions; the first will be from an operational perspective and the other from a design stand point. For operational measures, further analysis of the energy utilisation of the data presented in Table 6 was carried out to ascertain which individual components have efficiency losses and introduce options for reducing these losses.

From the energy usage analysis, three significant sources of inefficiencies are identified.

The first is in the steam consumption of the MT. Design specifications indicate that to achieve 100% MCR while dual firing, each boiler would be producing 47.5t/h steam. However, in actual conditions, both boilers are producing 52.5 t/h steam, but only achieving

91% MCR. A closer look at the EFDs, design and actual, indicate that an extra 10t of steam is going to the main propulsion turbine and the feed pump steam consumption also increases so as to supply the extra feed water required to produce the steam. This trend is quite common throughout the different modes of operation, as

- At 90% MCR the MT requires 18t/h more steam than design conditions;
- At 70% MCR 17t/h more;
- at 50% MCR 21t/h; and
- At 30% MCR 18t/h more steam is required.

The higher steam consumption invariably leads to an increased mass of exhaust steam, and a significant amount of this heat energy is lost in the Main Condenser. The higher steam consumption was traced back to a significant drop in hull and propeller performance. During the performance trial carried out immediately after dry docking during which extensive cleaning work had been carried out on the propeller and hull, the vessel achieved 98.6% MCR with the boilers producing 47.5t/h each and the MT steam consumption matched design specification. At 90%MCR, while the vessel was fully loaded, the steam consumption was only 3t/h higher than design conditions compared to the 18t/h recorded during the period analysed. The full set of results is displayed in Appendix 3.

The second source of inefficiency is heat energy lost in the main boilers. as a consequence of the higher fuel consumption resulting from the increased mass of steam required by the MT, the heat energy losses in the boiler increase and this, coupled with a slight reduction in boiler efficiency from post dry dock conditions, accounted for 17-26% of additional losses across the different modes of operation.

The third source of inefficiency is within actual standard operational procedures during periods when the MT is not in use or at very low load. Under these conditions, steam flow from both boilers is set at minimum obtainable that will match the minimum controllable automatic fuel input, but even at this minimum setting the output is greater than that required to satisfy the steam demand from the plant. In the case study, the minimum steam flow rate from both boilers was set at 40t/h for all conditions when the MT was shut down. This figure compares to the actual required steam flows of 20t/h for loading, 29t/h for discharging and 11t/h for OPL conditions. The excess steam would be dumped to the main condenser and this result in heat energy being wasted. The rationale for this is that there is a limitation on how low the output from a boiler can be set in terms of steam produced, based on a minimum flow of HFO/Gas fuel to the boilers. In addition, the superheated steam exit conditions are poor at very low boiler load.

By shutting down one of the two boilers, under the previously described low demand conditions, can mitigate against and reduce the boiler performance limitations, as the load is large enough when serviced by one boiler to accommodate the minimum gas/fuel requirement, as well as maintain the superheated steam at the desired quality. The firing rate of the boilers can also be manually reduced, regardless of the minimum HFO/Gas fuel requirement, beyond the automatic minimum due to advancements in fuel combustion control in marine boilers. Also, the HFO/Gas Fuel relationship should be noted, as Gas Fuel's higher calorific value and lower carbon factor will result in a significantly reduced amount of CO_2 is emitted per joule or per gram when there is gas burning in the boilers than when there is HFO burning. However, for the period considered during the case study, gas burning was not carried out in discharge ports, with either HFO or LSDO being utilised.

4.4 Improving Energy Efficiency in Design- Engineering Modelling

4.4.1 Defining the models

One of the principal aims of this research is to improve the efficiency while reducing the emissions from LNG carriers. This can be achieved by optimising the technology used for mechanical propulsion of these vessels. As explained in chapter one, there are three propulsion systems currently in use by LNGCs; STPS, DFDE and SSDR, with the gas-injection diesel propulsion system already being installed on a few LNGCs that have just entered into service [80]. The modelling process will focus on the STPS variant with the focus being the optimisation of the power generation cycle.

System Simulation Specification

In this system, "the best performance is realised when the energy output of the steam turbine in relation to the amount of fuel used in the boiler is optimised". The emissions relative to the output would also be expected to reduce with reduction in fuel demand, as most emissions are in proportions relative to the amount of fuel consumed. As the main aim of the model will be to maximize energy output while minimising energy input, the model will focus on one configuration of the most common STPS ship currently in operation. This system will then be characterized by introducing heat exchangers to the system, carefully varying design parameters, and optimising the flue gas heat exchanger usage.

The basic configuration of a closed steam turbine system consists of a boiler, steam turbine, condenser and feed pump all linked via a steam path as shown in the diagram in Figure 25. However, Figure 27 is a simplified representation of the STPS configuration shown in Figure 25, which is a more realistic representation of the configuration currently under examination.

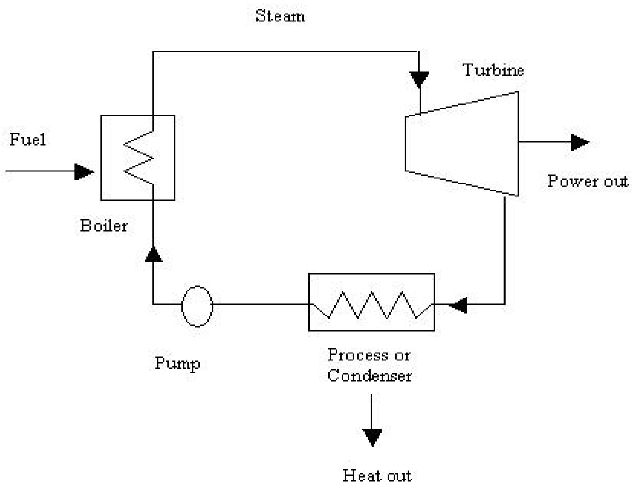


Figure 27: Basic Steam Cycle. Source: [43]

As seen from Figure 23, the components interact within a closed steam cycle with heat work being transferred in and out from the system. In this system, shaft power from both the HP and LP turbines would be converted to shaft power for the propeller which is not included within this model scope. In this system it is seen that each component defines a key aspect of operation that influences the behaviour of other components and the overall system.

In this system, feed water is pumped to the boiler at a given temperature and pressure, typically at 77 bar and 145^{o}C during full load steady state conditions. The boiler then produces steam at a pressure of 63 bar. The steam is then superheated to a temperature above its saturation temperature, essentially determining the temperature at which the steam enters the turbine.

The steam exiting the boiler is then fed to three different turbines; the main turbine, the turbo-generator and the turbo-feed pump. The main turbine comprises a High Pressure (HP) and Low Pressure (LP) turbine, both of which produce the shaft work that would provide propulsion for the ship. The steam expands in the turbine and through this thermodynamic process reduces in pressure and temperature. The exit pressure and temperature from the turbine is the input temperature and pressure to the condensing stage. The turbo-generator also expands the admitted steam to the pressure the main condenser only that in this case, the shaft power produced is then utilized for electricity generation. The exhaust from the steam used to power the turbines that drive the boiler feed pumps is not exhausted to the main condenser. This exit steam is at a higher pressure and temperature than that of the main condenser conditions and is then used for feed water heating.

In this cycle the condenser determines the pressure to which the steam will ultimately reduce. The condenser removes heat from the steam until all the steam condenses to water. This water is then sent to the feed pumps through a variety of feed heaters and from there to the boiler where the cycle then repeats.

Overall Model Goal

The model developed for this simulation will focus purely on the thermodynamic operation of the steam cycle. As such the physical aspects of the elements in the cycle, such as the boiler size, and type of materials utilized will not be considered. Also, the naval architecture aspects beyond the shaft power will not be considered. Since, the design parameters being investigated are all thermodynamic variables, rotational and heat energy system parameters do not need to be modelled beyond simplified assumptions. While steam turbines are variable speed machines and as such can operate at a range of output settings and conditions, they spend the majority of their operational time at steady state or near steady state conditions [44]. As a consequence, steam turbines of this type are designed to deliver optimum performance at a particular operational state or a set of clearly defined steady states. This model will therefore not simulate the transient operation of the system, but will instead attempt to characterize the effects of steady state design parameters on turbine output and performance.

The working fluid in a steam system is defined thermodynamically by two intensive variables and one extensive variable, and as long as these three variables are defined to within an acceptable degree of accuracy at every point of operation, the working fluid will itself be defined to an acceptably accurate degree. Each component used in this model ensures that any change in the water or steam enthalpy is accurately determined, with the mass flow rate of water and steam through the system being maintained, with any steam or water loss being replenished by an equal amount.

The Thermolib [81] toolbox in MATLAB is used for this simulation. Thermolib is used to model and simulate thermodynamic systems for a wide range of industries. Thermolib was used for this research because it contains a comprehensive set of Thermodynamic blocks that seamlessly integrate into the MATLAB environment. These Thermodynamic building blocks enables the design of the user defined components required for the development of this steam plant model. Thermolib also calculates real gas behaviour based on the Peng Robinson EOS [82], while also utilising the IAPWS-IF97 [83] formulation of thermodynamic properties for detailed calculations involving water and steam.

4.4.2 Overview of the major individual components

Boiler

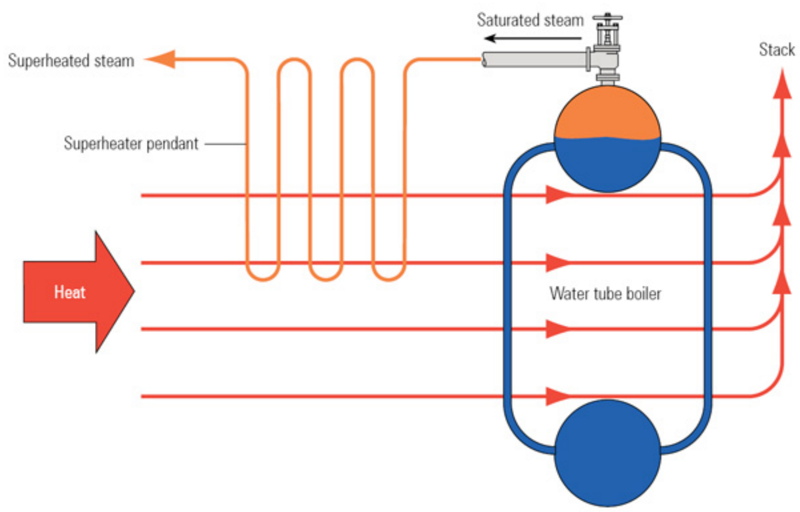


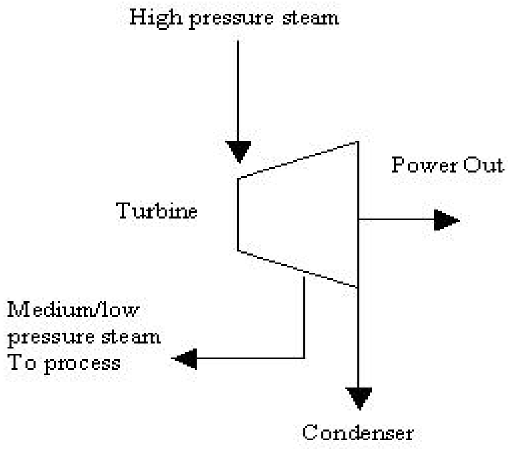
Figure 28: Boiler process overview. Source: [43]

Figure 28 shows a basic representation of the boiler operation in the steam cycle. The water enters the boiler from the top drum as a sub cooled liquid i.e. at a temperature well below its saturation temperature. It is then brought to saturation temperature, and then boiled in the pressure vessel at a controlled pressure determined by the boiler feed pump. The saturated steam is then sent through a heat exchanger called the super-heater where additional heat is added and it is then heated to the desired temperature. In practice, boilers normally experience pressure difference from the pressure of the sub-cooled liquid to the boiler pressure vessel and in the contours in the super-heater itself. Assumptions are kept at a minimum as every inlet/exit condition is sufficiently modelled based on manufacturers specifications with the heat input/heat transferred to the working fluid representative design conditions of the boiler being modelled. The feed air is modelled using a lambda burner which ensures that stoichiometric conditions are satisfied.

Turbines

Figure 25 represents the overall thermodynamic operation of the steam turbine system being modelled. As explained previously, steam from the boiler is fed separately to three turbines; the main propulsion turbine, the turbo generator and the feed pump turbine.

The main propulsion turbine consists of a high pressure stage and a low pressure stage, both of the extraction steam turbine class. Extraction steam turbines have openings in the casing for the extraction of a portion of steam at intermediate pressure as shown in Figure 29a. Steam from the boiler enters the high pressure (hp) stage of the turbine at specified temperature and enthalpy. After expanding to an intermediate pressure, the steam then passes through the low pressure (lp) turbine, and the steam expands through the turbine until it is exhausted to the condenser. While passing through the hp and lp turbines, steam at reduced pressure is “bled” off to be used for heating applications. The turbo generator is a condensing turbine, where there is no intermediate steam extraction, as this power-only utility turbine exhausts directly to the condenser which maintains low pressure conditions at the discharge end of the turbine. The feed pump turbine however is a non-condensing (back pressure) turbine, where it exhausts its entire steam flow into the intermediate feed heating services at conditions matching the process heating requirements as shown in Figure 29b.



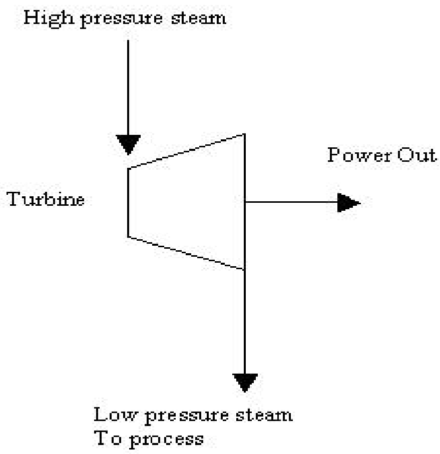


Figure 27a: Main turbine (Extracting Type). Source:[43]

Figure 27b Feed Pump Turbine (Non-Condensing). Source:[43]

The steam expands as it passes through the turbine stages that increase in physical volume as the steam pressure and density decrease to maintain the mass flow rate of the steam which is directed by a nozzle component to the blade components in each stage to produce rotary shaft power. The physical designs and dimensions of the turbines, such as the number of stages, blade angle length and shape, and the rotor diameter will determine the thermodynamic efficiency of this expansion process as a lower entropy generation rate and a greater amount of work extracted from the steam expansion translates to a higher thermodynamic efficiency.

The Thermolib library currently has examples of different steam turbine configurations that have been used to build this model. The turbine efficiency is a direct user input that can be adjusted by the user to replicate the practical steam turbine under consideration. The Thermolib steam turbine component is used to design the turbines in this model.

Condenser

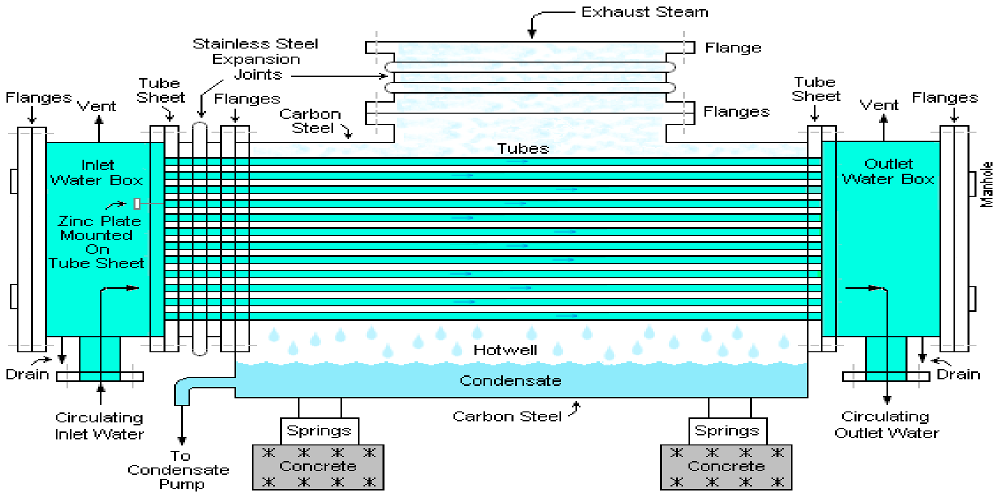


Figure 30: Condenser description. Source: [44]

Figure 30 gives a representation of the condenser in this steam system. These condensers usually operate under partial vacuum conditions, influenced largely by the temperature of the cooling water. Lower cooling water temperatures usually result in lower condenser pressures. The cooling water removes the heat from the steam exiting the turbines which is already at or just below the saturation temperature fully condensing the steam. The condensate is then drained using condensate pumps and sent to the feed system.

The Thermolib library has a condenser component that allows the user to directly specify the operating pressure. This setting therefore defines the pressure to which the steam coming from the steam turbines would as well as providing the heat energy removal necessary to fully condense this exhaust steam, while also defining the enthalpy at which the condensate leaves the condenser. Two assumptions are made;

- The exhaust pressure would be a steady state value for a given condenser design; and
- No pressure drop is observed to the feed system unless expressly stated.

Condensate Pumps

The condensate pump arrangement in a steam cycle is responsible for increasing the pressure of the condensate from condenser sump pressure to the pressure at the feed pump inlet. The Thermolib library has a pump component, where the discharge pressure can be explicitly defined rather than calculated for a specific pump design. Two further assumptions are:

- The pump discharge pressure is a value that has been directly defined by the user, not calculated by pump design characteristics.
- There is negligible heat or mass loss of the working fluid as a result of the pump operation.

Intermediate heaters

There are intermediate heaters installed on the system. These are primarily used to increase the enthalpy of the boiler feed water using heat exchangers fed with steam that has been bled of from the turbines. This bleed/heating steam is then condensed and sent back to the feed system for return to the boilers. The Thermolib library has heater components that have been upgraded to specifications for use in this model.

Feed Pump

The feed pump arrangement in a steam cycle is responsible for increasing the pressure of the condensate water from condensate pressure to boiler inlet pressure. The power to do this is obtained from the feed pump turbine and has the effect of raising the enthalpy of the feed water along with its pressure. The same pump components as for the condensate pumps on Thermolib are used for this input to the model. The same assumptions as the condensate pumps are employed which are:

- The pump discharge pressure is a value that has been directly defined by the user, not calculated by pump design characteristics.
- There is no heat or mass loss of the working fluid as a result of the pump operation.

4.4.3 Developing the Models

Figure 31 shows a screenshot of the Thermolib model used to develop this steam system simulation.

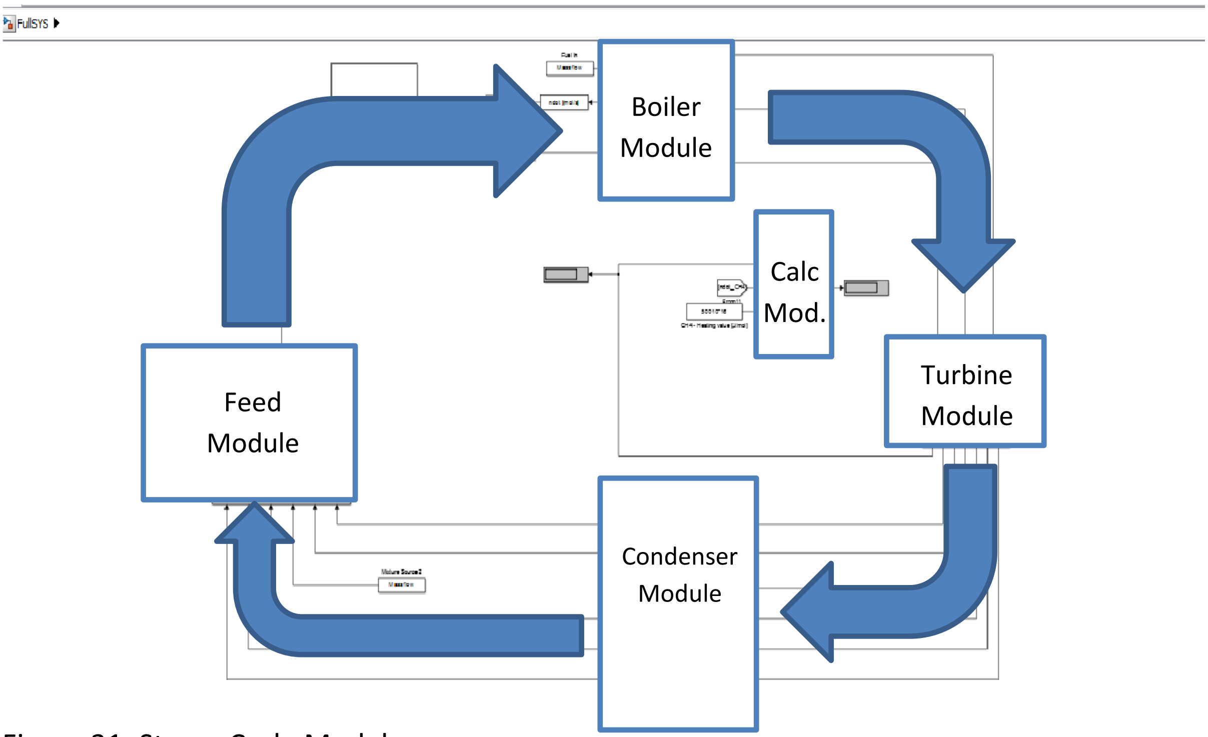


Figure 31: Steam Cycle Model

The model consists of four major subsystems; The Boiler, Turbines, condensate, and feed pump sub systems. Each consists of several components with blocks used to define the system and several constant input values. This section discusses each component individually, defining the inputs required and detailing the connections between components.

Boiler

Figure 32 is a screenshot of the Thermolib model used to perform calculations for the boiler in this steam cycle.

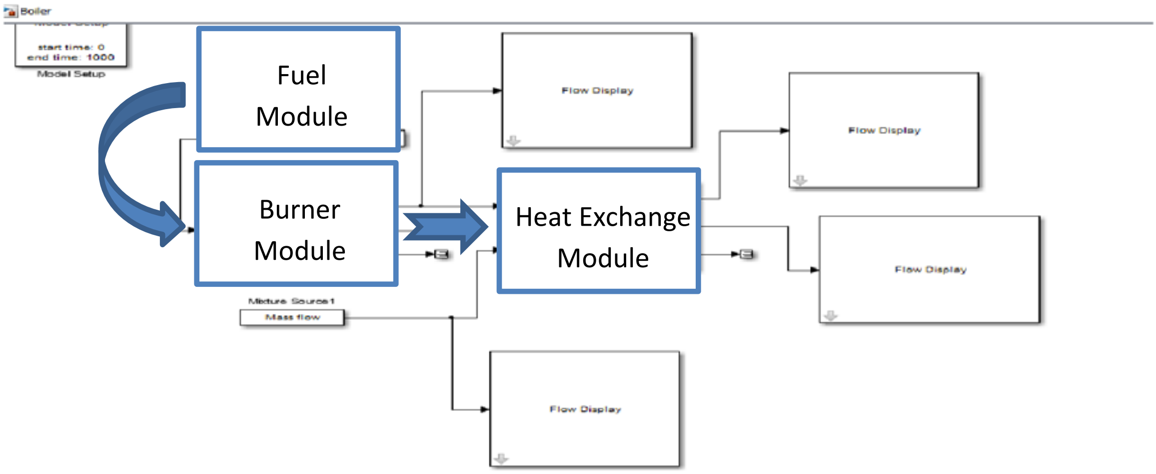


Figure 32: Boiler Model

The working fluid enters the model and undergoes a change in physical state from water to saturated steam via a thermodynamic process and then superheated steam with an increase in enthalpy. The increase in enthalpy is mainly due to heat input from the combustion of fuel where the flue gases due to this combustion transfer heat to the feed water. The working fluid in the form of superheated steam then exits the model at a thermodynamic state determined by the pressure drop and enthalpy rise defined by user inputs and modified by the model process. The boiler is treated as a black box that changes the thermodynamic properties of the working fluid.

Turbines

Figure 33 shows a screenshot of the Thermolib model used to perform calculations for the turbines used in this simulation.

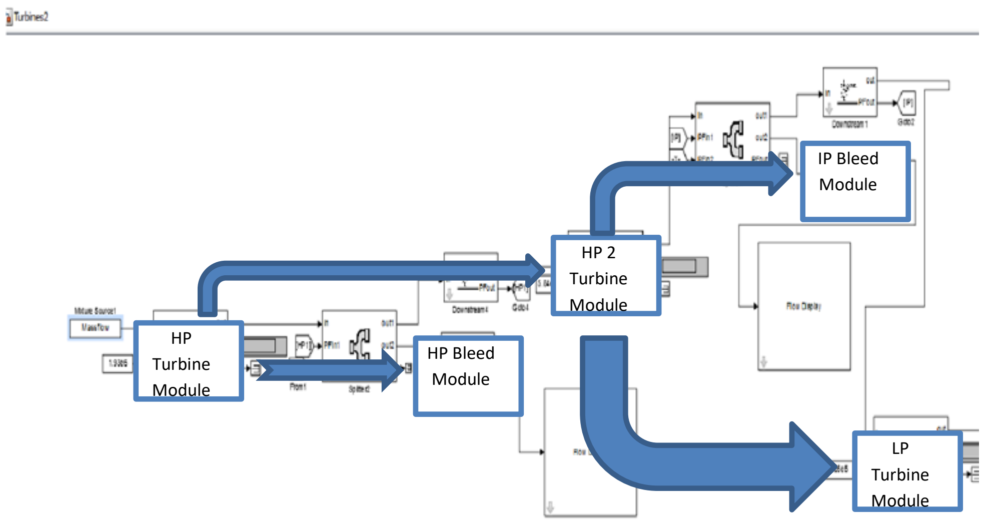


Figure 33: Turbine System Model

As explained previously, the steam cycle contains three turbine components. The main turbine component is more complex as it has connections that allow steam to be bled off from the intermediate stage of the hp turbine, the intermediate pressure (ip) connection and the intermediate stage of the lp turbine. This bleed steam is used for feed pre-heating purposes, while the rest of the steam then passes through the remaining turbine stage and into the condenser. The parameter inputs for the steam turbine components are a series of nominal flow rates and pressures at the inlet of the individual steam turbine sections, the condenser pressure, the mechanical efficiency, and isentropic efficiency of each section. These figures collectively define the power output of the turbines.

Condensate System

Figure 34 shows a screenshot of the Thermolib model used to perform calculations for the condenser in the steam cycle

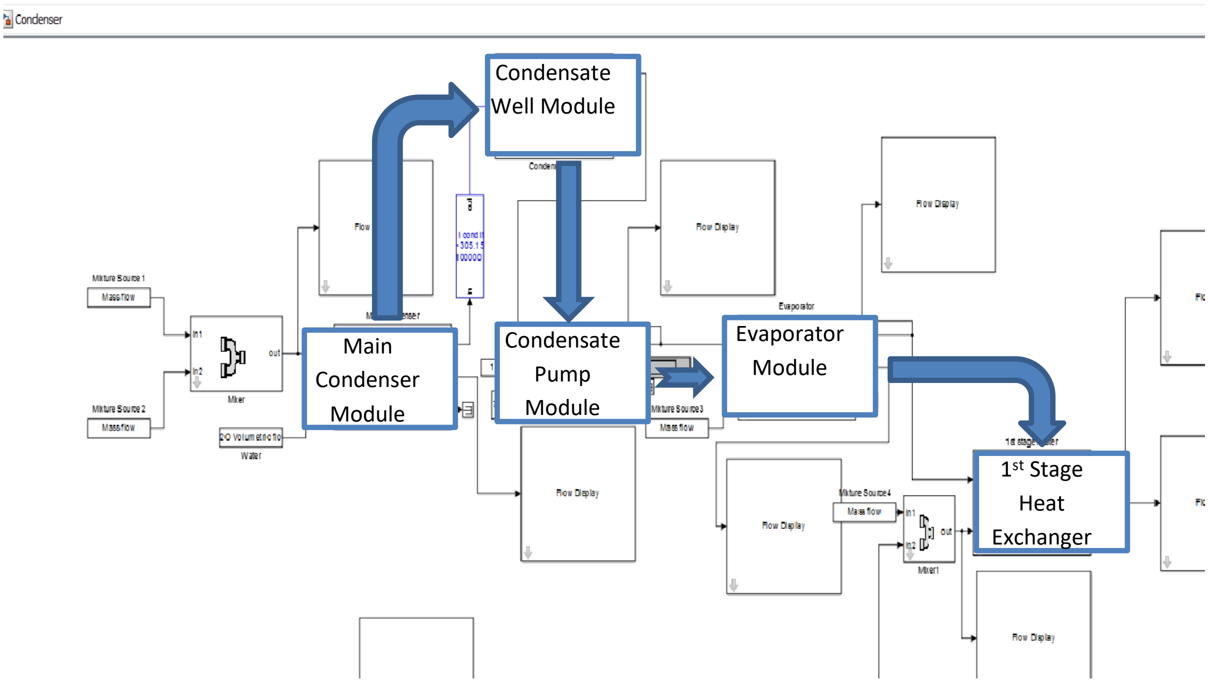


Figure 34: Condensate System Model

The condenser system consists of the main condenser, condensate pump, evaporator and 1st stage heat exchanger. The system starts with the main condenser, where the steam exiting the turbines would be condensed. The condenser is a heat exchanger component where heat is removed from the steam input using cooling water as the coolant fluid. This component has parameter inputs for condenser pressure, as well as input conditions for the cooling water flow. Since the condenser volume is not specified in this modelling process, the volumetric parameters are therefore irrelevant in this context. The exhaust steam enters from the upper fluid inlet connection and exits from the upper fluid outlet connection as a saturated liquid and the condenser components determine the amount of heat required to achieve this. From the condenser it is then taken by the condensate pump, which raises the pressure of the saturated liquid from the condenser pressure to the system/working pressure of the condensate system.

The pump model component used here is the pump component available in Thermolib library block. The pump model component used here allows the user to directly input the pressure increase across the pump. The pump model component has input parameters that facilitate the user in the design of steady state operation. These Input parameters include discharge pressure, pump efficiency, and pump flow rate. As the system is modelled in the steady state, the geometry of the pump is not considered. The pump model component characterises the discharge pressure and enthalpy of the water as well as calculates the power required to operate the pump.

From the pump the condensate goes through the evaporator and the first stage feed heater to complete the condensate system of this model. The evaporator is an item of equipment used for making fresh water, where 1) the bleed steam from the lp turbine is used to vaporise sea water to form steam, 2) the relatively cool condensate being supplied from the condenser is used to produce fresh water from the steam produced by distillation, thereby gaining heat in the process. The evaporator model component used in the system model is similar to the condenser model component in that the salient requirements are the heat exchange characteristics of the condensation process, with the heat exchange being between the incoming feed water and the evaporated steam from the sea water. The bleed steam condenses to a saturated liquid in the process of heating up the sea water. The first stage heater on the other hand used bleed steam to heat the condensate directly, with the bleed steam condensing to water.

Feed System

Figure 35 shows a screenshot of the Thermoib model used to perform calculation for the feed water system.

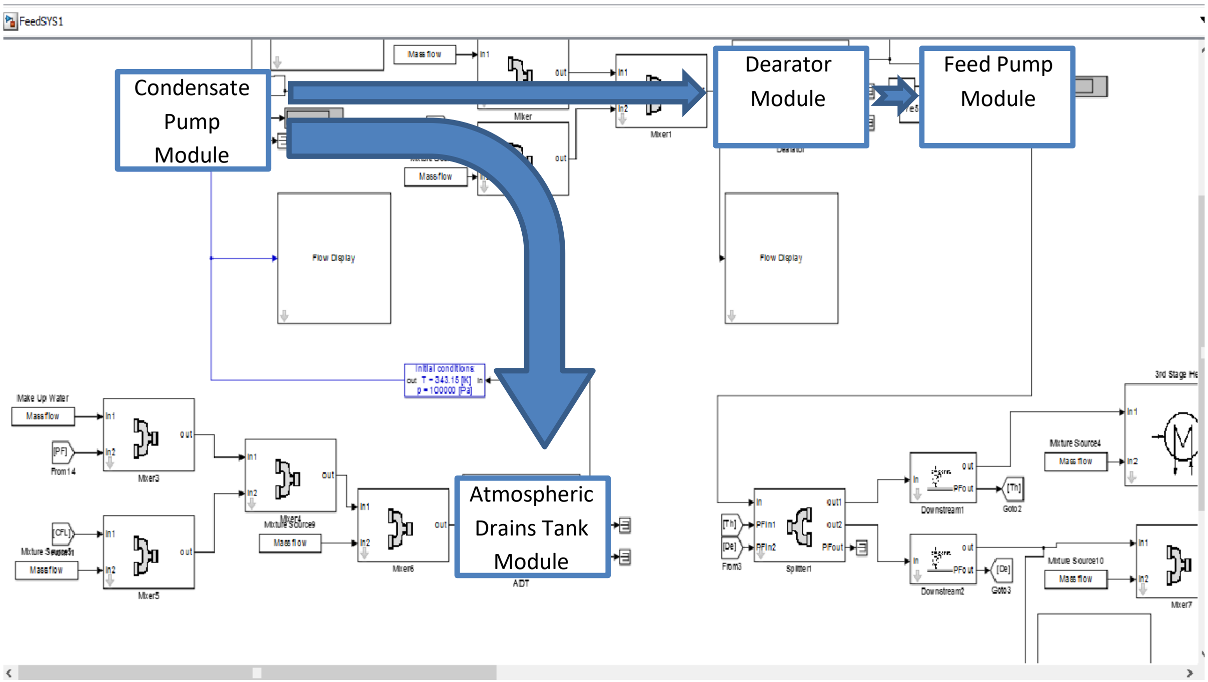


Figure 35: Feed System Model

The feed system basically takes the feed water and returns it to the boiler, where the cycle then repeats. The fluid from the condensate system then goes to a reservoir called a deaerator, where the fluid is mixed with bleed steam as well as condensate from other heat exchangers in the system. The other heat exchangers in the system include a calorifier- used for accommodation heating, lube oil purifier, natural gas vaporiser, natural gas heater, and fuel tank heating where auxiliary steam is used for services and then condensed to water which is then sent to a tank from where it is then pumped to the deaerator. The heat exchangers and the pump are of similar configuration to the equivalent components used previously in this model. The deaerator serves as a reservoir for the feed pump. The feed pump increases the water pressure and delivers it to the boiler where the cycle repeats. The feed pump model component is similar to the condensate pump model component detailed earlier in the system model where the only significant differences are in the pump flow rate and discharge pressure.

Full System Model Overview

Figure 36 shows the Boiler, Turbines, Condensate and Feed Subsystem all linked together to form the full steam cycle model.

To successfully carry out simulations, the system model requires a model set up block, which is used to set the thermodynamic properties of the working fluid and fuel used in the model, as well as the simulation start and stop time.

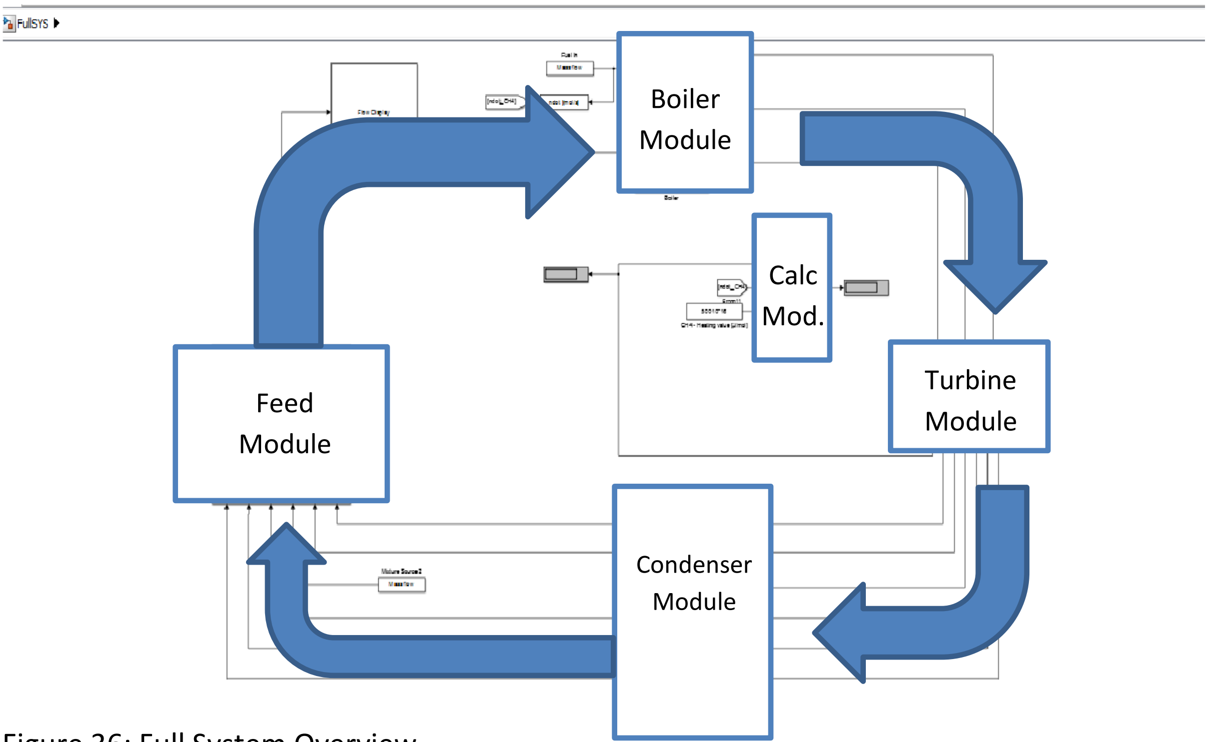


Figure 36: Full System Overview

The block description pages of the components have an array of initial values which provide the facility to define steady state operation. Since it is assumed that there are no working fluid mass losses in the system i.e. the system net mass flow rate is constant, the steam flow rate is set in the turbine. This, when combined with the pressure of the condenser and conditions in the pumps and heat exchangers, allows the full steam thermodynamic cycle to be fully defined.

Appendix 4 contains the Models and Subsystems general descriptions.

4.4.4 Verifying and Validating the Model

For temperature validation, a temperature range of ±10^{o}C was added for temperatures above 100^{o}C, and for temperatures below 100^{o}C, a temperature accuracy range of ±5^{o}C was utilised. The actual temperature difference was used to highlight temperature outside this accuracy range. For all other parameters besides temperature, no accuracy range was required as percentages used to highlight the difference between the model values and the design values.

Boiler model

To test the boiler model component, working fluid at a specified flow rate of (96005kg/h), pressure (77bar) and temperature (145^{o}C) is inputted to the model. The working fluid is then heated by the flue gases which are generated due to the combustion of a specific quantity of methane gas (5711kg/h). The heat exchange process occurs in the boiler, where the hot flue gases transfer some heat to the feed working fluid resulting in a change in thermodynamic properties of both the working fluid and flue gases. The quality of this heat exchange process is defined by the user so as to ensure, the thermodynamic conditions of the steam leaving the boiler are 61.5 bar and 515^{o}C . If the model is working correctly, the steam output would be at the specified higher enthalpy but at lower pressure than the boiler feed water input. Table 11 shows the results of the tests where the exit conditions are validated by the design conditions of a boiler of similar specification to that being modelled within this system model [41].

For the boiler model validation, a temperature range of ±10^{o}C was added for temperatures above 100^{o}C, and for temperatures below 100^{o}C, a temperature accuracy range of ±5^{o}C was utilised.

Table 11: Boiler Model Validation Results

Description	Design Values	Model Values	Error
Flue Gas outlet temperature ± 5^{o}C	180^{o}C	185 ^{0}C	0.0%
Superheated Steam Outlet Pressure	61.5bar	61.35 bar	0.2%
Superheated Steam Outlet Temperature	515^{o}C	515 ^{0}C	0.0%

The results are in agreement with the expected behaviour of the boiler being modelled: The enthalpy, temperature and pressure changes of the boiler model within the system model closely match those predicted by the actual boiler design data and specifications within acceptable error.

Turbines Model

The turbine model is tested in a similar way to the boiler model: the working fluid is sent through the turbine at specific thermodynamic conditions (61.3 bar, 510 ^{0}C), and this results in the turbines delivering output work and the output pressure is lower than the inlet pressure. This applies to all the three turbines; the main turbine, the generator turbine, and the feed pump turbine. When the model is run, the high pressure turbine generates 11.63 MW while the low pressure turbine generates 11.51 MW. For the turbo generator, the power generated is 1.45 MW, this power being converted to electrical energy. The feed pump turbine generates 0.37 MW shaft power which is used to power the prime mover for the feed pump. The turbine subsystem is running as expected as the temperature and enthalpy changes are within acceptable limits. Table 12 shows the validation data obtained from the turbines' components being modelled. As seen in Table 12, the differences between the design data and the simulation results vary from 0% to 14%. While differences on individual parameters are as high as 14%, the impact on overall model behaviour is considered acceptable as not only are these instances isolated, the overall model efficiency, and mechanical power generation are within acceptable ranges.

Table 12: Turbines Model Validation Results

Description	Design Values	Model Values	Difference (%)
HP Bleed Pressure (Bar)	19.3	19.3	0%
HP Bleed Temperature (^{O}C)	371	365	0.0%
HP Bleed Flow Rate (Kg/h)	3554.9	3554	0.0%
IP Bleed Pressure (Bar)	5.84	5.84	0.0%
IP Bleed Temperature (^{O}C)	212	238	Above- 14^{o}C
IP Bleed Flow rate (Kg/h)	8047.9	8046.92	0.0%
LP Bleed Pressure (Bar)	1.26	1.26	0%
LP Bleed Temperature (^{O}C)	127	109	Above- 8^{o}C
LP Turbine Outlet Temperature (^{O}C)	100	91	0.0%
Turbo Generator outlet Temperature (^{O}C)	117	119	0.0%
Turbo Generator outlet Pressure (mmHg)	720	719	0.1%
Turbo Feed Pump outlet temperature (^{O}C)	303	301	0.0%
Turbo Feed Pump outlet pressure (Bar)	2.8	2.8	0.0%
HP Turbine Total Power (KW)	11750	11633	0.9%
LP Turbine Total Power (KW)	11750	11513	2.0%
Turbo Generator Power (KW)	1786.5	1540	13%
Power Generation Efficiency (%)	31.9%	31.07%	2.6%

Condensate system Model

The condenser functions in the opposite manner to a boiler, therefore if this component runs properly the enthalpy of the working fluid at input should be greater than the enthalpy of the working fluid at output. Also, the cooling medium, in this case sea water, should have an enthalpy at output that is higher than at input, with the condensate pumps raising the pressure after condensation. During this test, it is seen that 71138 kg/h of steam at 100^{o}C at 720 mmHg (0.96bar) is sent to the condenser, and exits the condenser via the condensate pump at the same flow rate but as water at 27^{o}C and 7.5bar, with the cooling sea water increasing in temperature from 27^{o}C to 29.6^{o}C, indicating that the condenser model is functioning thermodynamically as expected. On exiting the condenser, the condensate passes through two functional heat exchangers where heat energy is added to the condensate from the bleed steam fed to the heat exchangers from the intermediate stage of the twin stage turbine. Table 13 details the thermodynamic changes which indicate that the model is working as required.

Table 13: Condensate System Model Validation Results

Description	Design Values	Model Values	Difference (%)
Condensate Pump Outlet Flow Rate (kg/h)	71188	71138	0.1%
Condensate Pump Outlet Temperature (^{O}C)	32.6	27	0.0%
Evaporator Feed Outlet Temperature (^{O}C)	39.7	36.7	0.0%
1st Stage Heater Feed Outlet Temp (^{O}C)	98.2	102.6	0.0%
Evaporator Heating Steam Outlet Temp (^{O}C)	76	64	Above- 6^{o}C
1st Stage Heating Steam Outlet Temp (^{O}C)	90	104	Above- 9^{o}C

Feed System Model

In the deaerator, the feed water from the condensate system mixes with the steam from the feed pump turbine exhaust as well as the condensate drains from the other heat exchangers. The mixing results in the outputs from the three feeds to the deaerator attaining the same resultant thermodynamic properties which are dependent on the quantity and thermodynamic conditions of the individual constituents. In this case, 71188kg/h water from the condensate system at 98 ^{0}C at 3 bar mixing with 4958kg/hr feed pump turbine exhaust steam at 281 ^{0}C and 2.8 bar, and 17533kg/h condensate drains at 98 ^{0}C and 9.5 bar resulting in a mixture of 96005kg/h saturated water at 4 bar 142 ^{0}C. Table 14 details the temperature and flow rates of the different fluids. From here it is taken by the feed pump, which then increases the pressure and temperature of the water to 77 bar and 145 ^{0}C respectively. Table 14 shows the data for the model against design specifications. While differences on individual parameters are as high as 11%, the impact on overall model behaviour are considered acceptable as not only are these instances isolated, the temperature variables are flexible hence the accuracy range is within specifications.

Table 14: Feed System Model Validation Results

Description	Design Values	Model Values	Difference (%)
Drains Pump Outlet Flow Rate (kg/h)	17533.7	17533.7	0.0%
Drains Pump Outlet Temperature (°C)	81.4	90.7	Above- 4°C
Deaerator Heating Steam in flow rate (kg/h)	4958.3	4958	0.0%
Dearator Heating Steam in Temperature (°C)	281	281	0.0%
Dearator Drains in flow rate (kg/h)	2979.1	2978.8	0.0%
Dearator Drains in Temperature (°C)	141	149	0.0%
Feed Pump Out to 3rd Stage Flow rate (kg/h)	96005	96045	0.0%
Feed Pump Out to 3rd Stage Flow rate (°C)	135	149.77	Above- 5°C
Feed water To De-sup Flow Rate (kg/h)	604.1	604.2	0.0%
De-superheater Outlet Flow Rate (kg/h)	4159	4158.6	0.0%
De-superheater Outlet Temperature (°C)	190	210	Above- 10°C
Gas Heating/Calorifier ADT in Flow Rate (kg/h)	3185	3188.6	0.1%
Gas Heating/Calorifier ADT in Temperature (°C)	100	102.51	2.5%
Fuel Heating ADT in Flow Rate (kg/h)	970	970	0.0%
Fuel Heating ADT in Temperature (°C)	70	66.3	0.0%
Feed Water to Boiler Flow Rate (kg/h)	96005	96045	0.0%
Feed Water to Boiler Temperature (°C)	145	150.7	0.0%

4.4.5 Model Utilisation

Defining and Developing Scenarios

As stated earlier, the goal is to optimize the power generation cycle by increasing the efficiency of the steam cycle. This would be achieved if the energy required to produce the steam is minimised while the proportion of useful energy exploited by the system is maximised. Energy enters this system from fuel, combustion air, make up water and pump work while energy leaves the system as exhaust gases from the boiler, steam and condensate losses i.e. working fluid losses through leakages and fuel atomizing steam, heat losses from the boiler, heat losses from steam/condensate components, heat loss in the main condenser and useful energy to the turbines. Efficiency can be improved by reducing losses or reducing the energy input for the same useful energy output or a combination of the two. Opportunities may exist for improving the efficiency using an inside-out approach which is classed into three groups:

- End Use: Improve the power generation capacity of the turbines, improve turbine efficiency, insulate hot surfaces and improve efficiencies of heat exchangers.
- Distribution: Improve insulation, reduce steam losses, optimise steam traps
- Conversion: Improve Efficiency of the heat exchange process in the boiler, reduce exhaust gas energy losses, optimize the combustion air inflow

From the three groups of approaches the following have been identified for further analysis, as they have a significant potential for improving the efficiency. They are:

- improve the power generation capacity of the turbines by reducing the condenser shell pressure;
- reduce boiler flue gas temperature; and
- Pre-heating the combustion air using the flue exhaust gases as opposed to steam pre- heating which is the current configuration.

The current boiler flue gas temperature of 170^{o}C - 180^{o}C is normally kept high to prevent cold end sulphuric corrosion, but with the use of natural gas fuel in this model, the temperature can be reduced further as there is negligible sulphur in the fuel. The same principle is applicable to the boiler combustion air heater, as the use of methane fuel negates the need for steam air heaters due to the fact the flue gases are clean products and as such fouling of the air heaters is not significant as would be the case with flue gas air heaters with HFO fuel. The use of flue gas heaters will optimise the system by removing the need for extra steam to be required for heaters. To run simulations with these modifications, the system would be characterized by making certain system adjustments:

- the condenser pressure/temperature,
- the boiler uptake temperature,
- and air heater optimisation.

These adjustments would help in optimising overall system efficiency by maximising work output efficiency while minimising energy input. Each of these adjustments would be assessed while holding the other parameters constant. The results of these parameter adjustment tests will be analysed then used to determine how best the modifications can be combined to optimise the performance of the propulsion system model. Table 15 details how the design configurations would be altered:

Table 15: Design Configuration Adjustments

	Trial 1	Trial 2
Condenser Pressure/Temperature	Reduce the condenser pressure to lowest theoretical value	Reduce the condenser pressure to lowest practical value
Boiler Uptake Temperature	Reduce the uptake temperature to lowest theoretical value	Reduce the condenser pressure to lowest practical value
Air Heater Optimisation	Basic Flue Gas Air heater	Highest Efficiency Flue Gas Air heater

The system then characterises the overall effect of the different adjustments based on the above trials by measuring the total power output of the turbines, and the total energy input required by the boiler with the efficiency determined by the ratio between the two values.

These results are expected based on the thermodynamic relationships of the system, and the sensitivity of the associated parameters will determine the effect on overall cycle efficiency. The following subchapter quantifies the effect of the above adjustments and uses these relationships to identify desired steam cycle conditions.

Scenario Results

The results obtained from the design alterations as summarized in Table 17.

Table 16: Scenario Results Summary

Description	Original Values	Trial 1	Trial 2
Boiler Input Fuel Energy	5711kg/h	5711kg/h	5621kg/h
Flue Gas Exhaust Temperature	185°C	162°C	145°C
Combustion Air Temperature	99°C	98°C	98°C
HP Turbine Power	11623KW	11652KW	11616KW
LP Turbine Power	11512KW	12923KW	14883KW
Turbo Generator Power	1449KW	1733KW	1869KW
Condenser Pressure	0.963bar	0.053bar	0.025bar

Table 17: Scenarios Efficiency Results and Calculations.

	Heat Input	Total Useful Power Output	Overall Efficiency
Original	79125KW	24650KW	31.07%
Trial 1	79121KW	26308KW	33.25%
Trial 2	77869KW	28368KW	36.43%

Scenario Results Discussion

The results indicate that there is a 7% increase in efficiency from the original model conditions in Trial 1 conditions due to a combination of combustion air heating using boiler flue gases and reduction in condenser steam inlet pressure to 0.053bar with a reduction in flue gas temperatures from 185°C to 162°C. The fuel energy input to the boiler is still constant, with the increase in energy attributed to 6.7% extra power generated by the turbines due to the reduction in condenser pressure. When the condenser pressure is further reduced to 0.025 bar in Trial 2, a 17.3% increase in efficiency is realised with the boiler exhaust temperature reduced to 145 ^{0}C. The fuel energy input requirement is also reduced by 1.5%, with the Main Turbine power output increased by 15%, with the combustion air temperature constant at 98 ^{0}C.

The results obtained are consistent with the initial expectations of the model trials and display an efficiency improvement of between 7 and 17 percent above the original conditions. The overall efficiencies of between 33.25 to 36.43 percent are still below the efficiencies of the DFDE and SSDR which have average efficiencies of 43 percent and 48 percent respectively. Other options exist to improve the efficiency of the system further. One such option is the introduction of reheat technology, as the literature review covered previously highlights, a 12 to 15 percent improvement in efficiency may be offered by this configuration [27] [28] [29]. It would be beneficial to combine parametric modifications determined from the scenario tests. The expectation would be that the efficiency would rise to approximately 40%, which is closer to the efficiencies of the existing diesel configurations.

The scenarios modelled thus far have only considered the full speed condition of the vessel, since during the field case study carried out the vessel spent majority of the one-year period at full speed conditions. Also, the majority of the fuel is consumed at full speed conditions, the majority of the energy savings that can be accrued would be under these operational conditions. However, energy savings can be realised at other speeds and the model developed can also be used for analysing and quantifying improvements that can be made at such speeds. The model is also adaptable for use with current designs as well as evaluating new designs of STPS propulsion, thus the two-pronged approach of energy efficiency in design and energy efficiency in operations can be covered within the modelling process.

4.5 Steam Turbine Propulsion System Summary

This chapter covered a comprehensive analysis of the Steam Turbine Propulsion System as a propulsion option for LNGCs. The first section covered an analytical study of the propulsion system using the EEDI. It was seen that the current designs do not satisfy the current EEDI benchmark and meeting future EEDI improvements could prove a challenge even with technological improvements. The second section covered case studies of Steam LNGCs in actual operation. It was seen that in actual sea going conditions, the operational profile did not match the design (manufacturer's) profile due to three key sources of inefficiency-

1) Higher amount of Steam Consumption due to higher power requirements to achieve design speed. This can be attributed to deterioration of vessel hull condition.

2) More Fuel consumed by the boiler due to higher steam requirements combined with lower boiler efficiency
3) Steam Dumping at lower loads resulting in high energy wastage when compared with the manufacturer's specifications.

The section also covered practical solutions to improve propulsive efficiencies which have been tested with quantifiable results. These include solutions such as regular hull monitoring after refit to ensure hull fouling is rectified promptly, usually through hull cleaning, although the preference will be to avoid hull cleaning by using a high performance coating for the hull. In addition, the shutdown of single boilers during periods of low or no propulsion utilisation will to reduce the impact of steam dumping. Also covered in the second section is the impact on these efficiencies on the EEOI of the vessel when benchmarked against the design recommended values. Here it was also seen that due to these inefficiencies, the drop in operational efficiency (EEOI) was calculated to be between 23% and 29%.

The final section covered the use of software based Engineering Models to analyse and quantify Design improvements to the steam turbine system. Here a thermodynamic model was created in Matlab/Simulink, validated using data obtained from manufacturers to an accuracy averaging about 95% across all the individual components modelled. This validated model was then used to model improvements to the steam turbine propulsion power plant using three methods: 1) Optimising the condenser pressures/temperature 2) Optimising the air heater configuration, 3) Utilisation of the boiler waste heat. It was seen that during the trial run of the scenarios created by the models, improvements in efficiency of between 7% and 17% were recorded, resulting in steam cycle efficiencies of 33.5% to 36.4%.

5.

DIESEL ELECTRIC PROPULSION SYSTEM

5.1 Introduction

In a similar manner to the detailed analysis carried out for the Steam Turbine Propulsion System in Chapter 4, this chapter covers a comprehensive analysis of the Dual Fuel Diesel Electric (DFDE) propulsion system option for LNG Carriers. To satisfy the aforementioned research objectives, this chapter is subdivided into four parts. 1) An analytical study of the design of DFDE propelled vessels using the EEDI. 2) Case study analysis of DFDE vessels in actual operation. 3) Development of design improvements to increase the efficiency of DFDE vessels. 4) Trial run and results analysis of the design improvements selected.

5.2 An Analysis of the DFDE fleet using the EEDI

Using the same methodology adopted for calculating the EEDI in the previous chapter and using the equations for the baseline and the index value found in Table 3 and Table 4 in Chapter 4.2, the EEDI analysis was carried out for the DFDE fleet. The following assumptions were made for this analysis [37, 38]:

- The $\eta_{electrical}$ is taken as 91.3% when considering generator, transmission, transformer and converter losses based on manufacturer's published data.
- It is assumed that the additional energy required to compress the BOG to supply the DFDE engine is approximately 2% of P_{ME} when compared to the energy required to compress BOG to supply the boilers in the steam turbine system. Hence the addition of the 0.02 factor.
- The pilot fuel requirement is less than 1% of the total energy requirement, and is considered negligible and will not be included in EEDI calculation.

The baseline equation was applied and combined with the equations in Table 4, while taking into account the percentage reductions in allowable emissions due to the implementation of the stricter EEDI phases up to 2025 Compliant vessels are shown below the baseline below the baseline curve, while non-compliant vessels appear above the baseline curve.

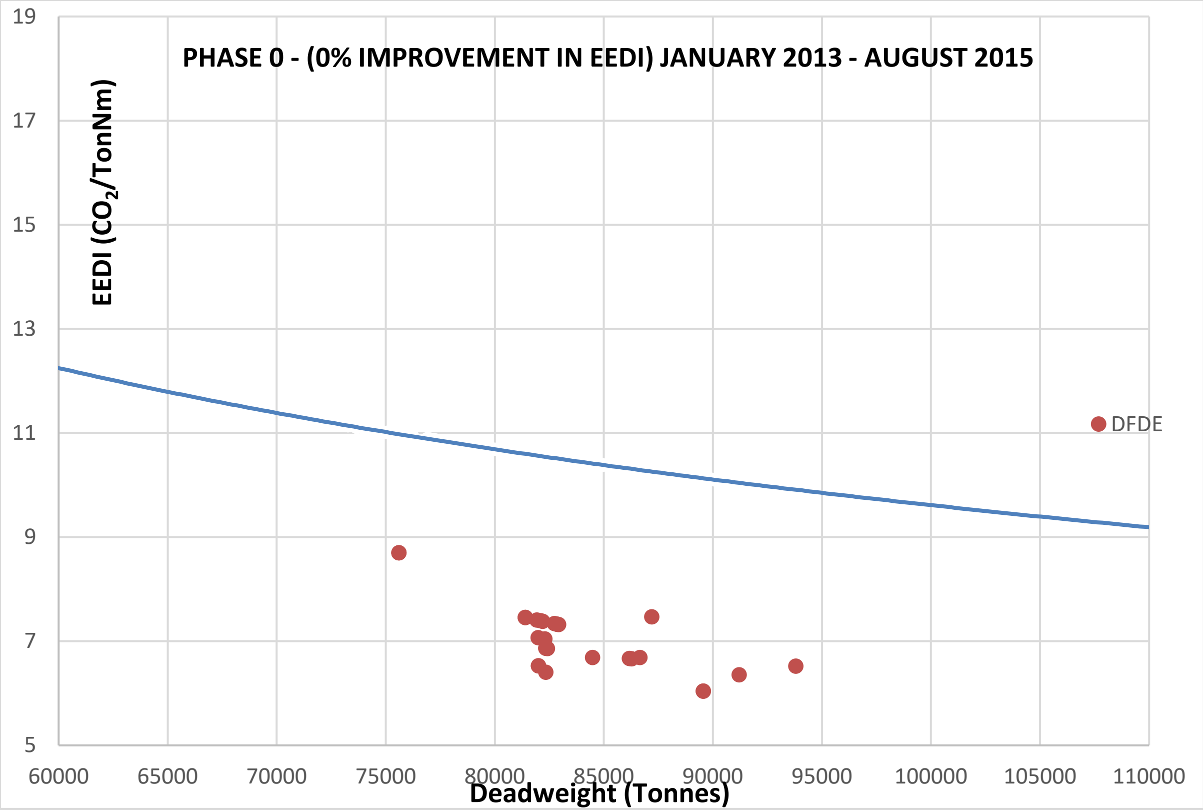


Figure 37- Phase 0 (0% Improvement in EEDI) January 2013 – August 2015

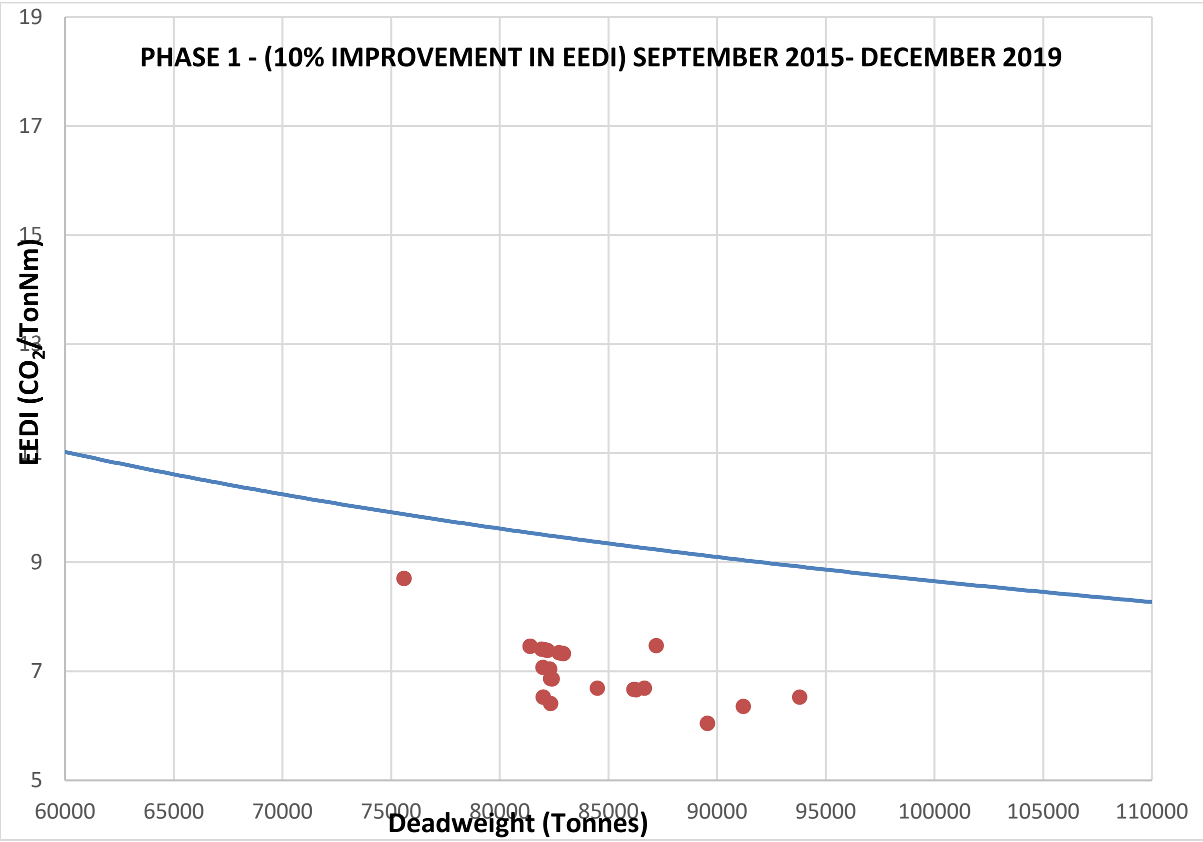


Figure 38- Phase 1 (10% Improvement in EEDI) September 2015 – December 2019

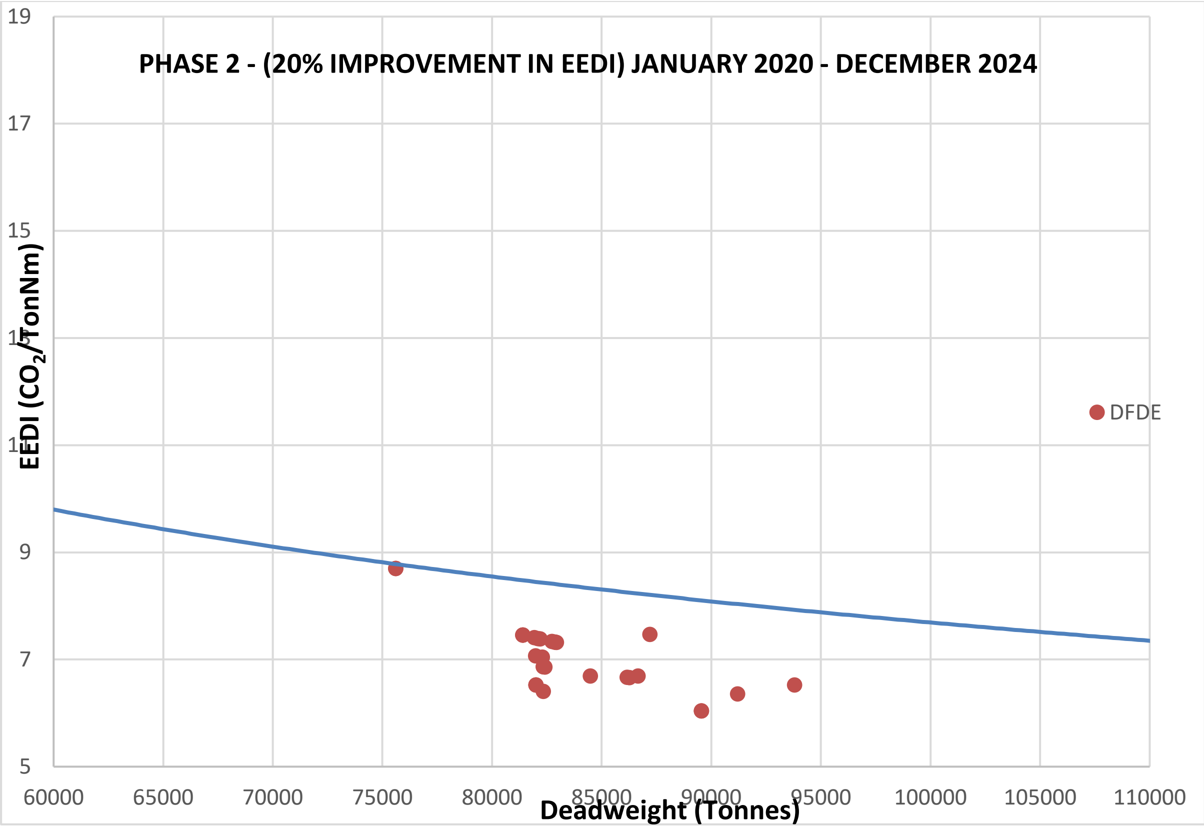


Figure 39- Phase 2 (20% Improvement) January 2020 – December 2024

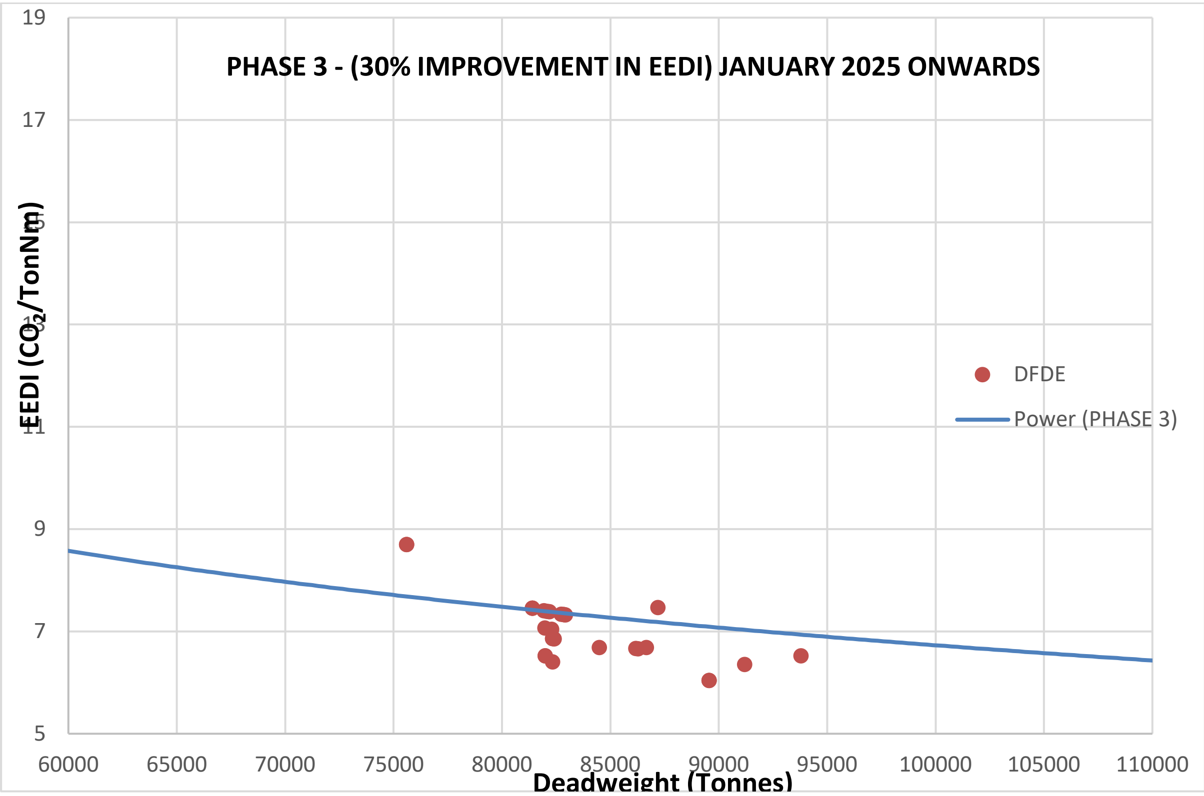


Figure 40- Phase 3 (30% Improvement) January 2025 onwards

The full dataset with associated calculations and results are presented in Appendix 1.

The following points can be ascertained from the EEDI analysis:

- The existing DFDE designs are compliant up to December 2024 as they all sit below the baseline value.
- The Phase 1 implementation also shows all current DFDE designs lie below the baseline value for the specified period and are compliant.
- Phase 2 implementation highlights that 97% of current DFDE vessels will still sit below the baseline value.
- After Phase 3 implementation, 56% of current DFDE designs will still be compliant and sit below the baseline.

Table 18 shows the results obtained from the EEDI analysis of the DFDE fleet.

Table 18: EEDI Analysis of the DFDE fleet.

Propulsion Type (Nos)	Phase 0 Compliant	Phase 1 Compliant Sept 2015 - Dec 2019	Phase 2 Compliant 2 1 Jan 2020 – 31 Dec 2024	Phase 3 Compliant 1 Jan 2025 – Onwards
Diesel Electric (32)	32- (100%)	32- (100%)	31- (97%)	18- (56%)

5.3 Case Studies

A qualitative research method involving the use of case studies is employed. This method is chosen because it provides an in-depth understanding of the DFDE technology during specific operational periods ensuring actual correlated data is captured. The focus will be on individual cases and not the larger population, to seek an in-depth holistic understanding of DFDE propulsion technology [45]. The data collection and analysis processes are carried out in real time as the data is collected and analysed simultaneously. Two case studies are devised for the analysis of the DFDE propulsion system:

Case Study A: The basis of this case study is the analysis of an existing DFDE vessel currently in service. It analyses the energy flows and usage during different modes of operation including ballast, laden, port (loading and discharging), off port limit operations (OPL), vessel manoeuvring, and maintenance. The analysis covers a 12 month period and includes voyages from Africa to Europe, Asia and South America. This analysis ascertains how energy is used, and how the vessel's operational profile impacts upon energy utilisation.

Case Study B: The basis of this case study is the performance analysis of a newly constructed DFDE LNG carrier during sea trials to determine ship performance in terms of speed, power and propeller revolutions, under specifically prescribed conditions, to verify the satisfactory attainment of the contractually stipulated performance [46]. The data from the sea trials will be used to define the standards/benchmarks against which the performance of the ship will be evaluated during its lifetime, and is used to provide guidance on planning future voyages, dockings, hull scrubs, etc. [47].

The results from the two case studies provide an opportunity to improve understanding of how the predicted idealised design operational conditions differ from actual operational conditions and also how this disparity affects the way in which DFDE LNGC efficiency is analysed over a ship's lifetime.

5.3.1 Case Study A

All the DFDE vessels in service have similar power and propulsion system design topologies and operational arrangements. They all utilise a multiple diesel-generator set configuration and can exploit a range of primary fuels such as MGO, HFO or BOG (with MGO as a pilot fuel). Additionally, they are fitted with an auxiliary boiler to produce low-pressure steam for the ship service's needs. The principal characteristics of the DFDE LNG carrier used for this case study are summarised in Table 19:

Table 19: Case Study A: Vessel Principal Characteristics

Ship Principal Characteristics		
Characteristics	Value	Comments
Ship Type	LNG Carrier	
Date of Delivery	2010	
Summer Draught	12.32 m	
Draught, Ballast	9.78 m (Normal & Heavy Weather)	
Cargo Tank Capacity	173,400 m^3	At 100%
Deadweight, Summer Draught	79,541 t	
Displacement, Summer Draught	113,567 t	
Service Speed	20.4 knots	@ Design Draught 11.95 m
Propulsion System		
Descriptive Notes: Electric Propulsion Driver Via Gearbox		
Make and Model	Converteam N3HXC 1120LL	
Output	32,400 kW	Shaft: 16,000KW x 83.3rpm each Motor: 16,500KW x 610 rpm each
Specific Fuel Consumption at rated power	191 g/kWh (MGO) 7410 kJ/kWh (Gas)	
Propeller (2 sets)	5 Bladed 8.6m diameter	Fixed Pitch
Generators		
Diesel Generators:		
Engine Make and Model	Wartsila 12V50DF x 3 Wartsila 9L46 x 1	
Generator	11400 kW at 514rpm 10395 kW at 514rpm	
Fuel	Methane/HFO/MGO	
Auxiliary boiler		
Make and Model	Kangrim PA0403P38	
Rating	6500 kg/h at 7 Bar saturated steam	Max pressure 10 bar
Rated Fuel Consumption	491 kg/h	
Fuel	HFO/MGO	

The Energy Efficiency Operational Indicator (EEOI) is used in this paper to analyse vessel efficiency. The EEOI provides a representative value of a ship's efficiency measured over a given period or voyage and can be used to investigate trading patterns of the vessel. The EEOI describes transport efficiency expressed in terms of CO_2 emitted per unit of cargo and nautical mile for a specified voyage. The formula is expressed below [48]:

$$EEOI = \frac{Fuel\ Consumption\ \times Carbon\ Factor}{Mass\ of\ Cargo\ \times Distance\ Covered} \tag{2}$$

The operating period of the DFDE LNG carrier investigated in this paper is between 16 May 2012 and 26 May 2013, during which time the vessel delivered ten cargoes, all originating from Nigeria. Three of these cargoes were delivered to France, two cargoes were delivered each to Brazil, Korea and Portugal and one cargo was delivered to Japan. The calculated EEOI for each of these voyages are shown in Table 21. All input values for the calculation were obtained from the vessel's on-board records. These routes are typical trading routes for vessels loading LNG from Nigeria with the vessels operating at service speed for the majority of the time.

5.3.2 Case Study B

The speed trials of a new LNG carrier are carried out to determine the relationship between the vessel's speed and the different loading conditions with fuel consumption also being recorded. The speed tests are carried out at power settings of 30%, 50%, 75%, 90% and 100% with a minimum of two runs per test. The first test run is with the ship heading in one direction and the second run with the vessel heading in the opposite direction. The ship's speeds, which are measured three times with a one-mile interval between measurements, and a minimum of ten minutes per run, are recorded and the average of the three values per run is calculated. In accordance with ISO 15016, [49] some corrections for wind, wave and swell beyond acceptable sea trial conditions are applied if and as required. For the new LNG DFDE carrier specified in Table 20a, the following were recorded [50]:

- Sea-state and depth
- Atmospheric pressure and temperature
- Time of test and course
- Relative wind direction and velocity
- Wave height and relative direction
- Swell height, relative direction
- Mean rudder angle movement
- Mean drift angle
- Ship's speed, power and shaft rpm
- Fuel consumption.

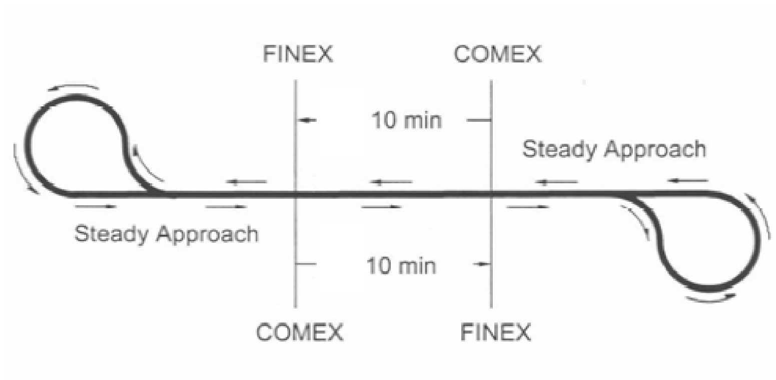
Table 20a: Case Study B- Vessel Principal Characteristics.

Ship Principal Characteristics		
Characteristics	Value	Comments
Ship Type	LNG Carrier	
Date of Delivery	2015	
Summer Draught	11.65 m	
Draught, Ballast	9.78 m (Normal & Heavy Weather)	
Cargo Tank Capacity	175,000 m^3	At 100%
Deadweight, Summer Draught	87,000 t	
Displacement, Summer Draught	113,567 t	
Service Speed	19.75 knots	Design Draught 11.65 m
Propulsion System		
Descriptive Notes: Electric Propulsion Driver Via Gearbox		
Make and Model	Converteam N3HXC 1120LL	
Output	24000 kW x 77.8 rpm	
Specific Fuel Consumption at rated power	189 g/kWh	To be determined during sea trials
Propeller (2 sets)	4 Bladed 8.2 m / 8.37 m	Fixed Pitch
Generators		
Diesel Generators:		
Engine Make and Model	Wartsila 8L50DF x 5	
Generator	7800kW at 514 rpm	
Fuel	Methane/HFO/MGO	
Auxiliary boiler		
Make and Model	Kangrim PA0403P38	
Rating	5000 kg/h at 10Bar saturated steam	Max pressure 10 bar
Rated Fuel Consumption	491 kg/h	
Fuel	HFO/MGO	

Table 20b: Case Study B- Speed Trial results

Principal Diamensions LBP x Bmld x Dmld : 280 m x 47.8 m x 26.2 m					
Place			Off Goeje Island		
Beaufort Number			4		
Anemometer Position (Above W.L)					
Projected Area (m^2)		Long	6368.1		
		Trans	1637.6		
Distance From Shore			14 NM		
Ship Conditn.	Max. Ballast	Sea and Weather			
Draft Ext. (m)	dF	9.60 m	Weather		Fine
	dM	9.50 m	Sea Water	Temperature	25°C
	dA	9.60 m		S. Gravity	1.020
	dcorr	9.52 m	Atmosphere	Temperature	24.2°C
Trim by stern		0.0 m		Pressure	1020 mbar
Displacement		97636.2 MT	Sea Depth		125 m

Path of Ship during Double Run



Load	Run	Dir (deg)	Time	Dur. (NM)	Speed	RPM (Port)	KW (Port)	RPM (stbd)	KW (stbd)	Rudd. Angle	Drift Angle	Rel. Wind		Wave		Swell		Fuel Flow	SFC (Test)	SFC (ISO)
												Dir.()	m/s	Dir.	H.(m)	Dir.	H.(m)			
30%		200	00:00	3	11.75	50.5	3669	50.4	3991	0.4	1.4	P62	21.24	S180	1.0	P150	0.3	4826	219	204
50%	1	20	03:45	3	15.49	58.7	6303	58.7	6141	0.25	2.0	P18	14.55	P135	0.8	S165	0.4			
	2	200	07:25	3	14.61	58.8	6064	60.0	6423	0.20	1.4	P129	1.99	S180	0.6	P170	0.4			
	Mean				15.05	58.8	6184	59.4	6282									6865	207	197
75%	1	20	10:25	3	17.54	68.3	9696	68.4	9393	0.7	2.0	S17	22.20	S25	2.5	S10	0.3			
	2	200	13:45	3	18.05	69.4	9465	69.4	8922	0.4	0.5	P68	2.12	S180	2.0	P170	0.4			
	Mean				17.79	69.9	9431	68.9	9158									9341	203	189
90%	1	20	20:40	3	20.33	73.6	11423	73.6	11181	0.9	0.9	S20	19.50	S5.1	1.5	P9.9	0.4			
	2	200	23:05	3	18.78	73.6	10877	73.6	10539	0.4	0.3	P38	8.14	P175	1.5	S180	0.4			
	Mean				19.56	73.6	11150	73.6	10860									10644	202	189
100%	1	20	06:00	3	21.05	76.0	12346	76.3	12193	0.7	0.1	S16	22.60	P0.2	1.5	P165	0.4			
	2	200	11:15	3	20.75	77.2	12266	77.1	11953	0.5	0.3	P25	4.27	P175	1.0	S14.8	0.4			
	3	200	18:15	3	20.11	77.8	12550	78.1	12345	0.7	1	P28	11.18	P175	1.0	S170	0.4			
	4	20	22:10	3	20.88	76.3	12523	76.4	12245	0.7	1	S19	24.02	S10.0	1.0	P5.0	0.4			
	Mean				20.69	76.8	12421	77.0	12184									12246	202	189

5.3.3 Analyses of Case Study Results

The majority of the voyages return similar EEOI results except those to Brazil and one of the voyages to France. The voyages to Portugal returned comparatively lower EEOI results. The reasons for these disparities are due to several factors usually related to the average distance travelled or specific operational practices

Table 21: Calculated EEOI for case DFDE Vessel

Voyage	Distance (nm)	LNG Delivered(m^3)	LSDO Consumed(t)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/t.nm)
1- NG-FRA	7,960	140,683	18	2,666	44	29.7
2- NG-SKR	19,050	146,480	33.7	5314	103.3	23.9
3- NG-SKR	19,050	145,579	49.8	5100	61.2	23.0
4- NG-PGL	7,306	163,959	18.3	1635	21.1	17.0
5- NG-FRA	7,960	161,999	32.3	2173	30.7	21.2
6- NG-FRA	7,960	161,947	29.7	2233	22.7	21.6
7- NG-JPN	25,260	153,939	64	6425	50.8	20.5
8- NG-PGL	7,306	162,612	24	1833	20.8	19.3
9- NG-BRA	6,784	160,734	32.7	2992	16.6	34.0
10- NG-BRA	6,784	159,323	34.3	3408	40.7	39.3

It is important to note is that whilst the voyages to Brazil are the shortest in terms of distance travelled, they had the most inefficient voyages. It is seen that the source of these inefficiencies was due to the relatively high amount of LNG utilized during the voyage. These high values are due to the peculiarities of the discharge operations that were undertaken in Brazil as the discharge terminal is a Floating Storage and re-gasification unit (FSRU), and quite large amounts of natural gas are consumed during discharge operations for tank stabilisation needs. Another issue of note is the disparity between the voyages to France, with one of the voyages being considerably (40%) higher than the other two when the EEOI's values are considered. This disparity was traced to the fact that on the one voyage, the full cargo capacity of the vessel was not utilized with the vessel only delivering 140,683m^3 of LNG compared to the 161,999m^3 and 161,947m^3 delivered on the other two voyages respectively.

The results from the trials in Case Study B are summarized in the table below:

Table 22: Case study B results summary

Engine Load	Speed (knots)	Shaft Power (kW)	SFC (g/kWh)
30%	11.75	7660	204
50%	15.05	12466	197
75%	17.79	15589	189
90%	19.56	22010	189
100%	20.69	24605	189

It is important to note the differences between the figures obtained from the sea trials and the actual operating conditions obtained from the case study vessel described in Table 5 in terms of fuel utilisation (In Chapter 4.3). From the data obtained from the case study and industry it can also be seen that the vessels in service spend less than 5% of their operational time using HFO. The only time during the 12 months of the case study that the vessel used HFO were periods when the vessel was in port or undergoing maintenance. The normal operating condition of the vessel is primarily utilising the BOG as the main fuel with the HFO or MGO as back up. Bearing in mind that the sea trial results become the benchmark from which the performance of the vessel would be evaluated during its lifetime and since data from the case study vessel and other DFDE vessels show that the vessels utilise NG as the primary fuel over 90% of the time it therefore follows that the results from sea trials when the fuel being used is HFO are not sufficient in providing an accurate enough benchmark needed for evaluating future vessel performance.

As a further point when calculating the Energy Efficiency Design Index (EEDI), which has been mandatory for LNGCs as of September 2015, that EEDI measure should be calculated from the sea trials using figures obtained while using BOG as fuel as opposed to the current practice of using HFO as fuel [50]. Research has shown that it is usual practice to use HFO during sea trials when the operating parameters are being evaluated and gas burning is not used.

It is also worth noting that since load conditions are not constant over the given period of sea trials, the measurements can be unreliable when considering other sea conditions.

Shipbuilders therefore guarantee fuel consumption for the engines on the basis of the measurements taken at shop trials with the data obtained from sea trials only being used for verification of the shop trials results. The focus of shop trials, like sea trails, is also based on the use of HFO/MGO and again is not representative to current commercial operational practice.

5.4. Improving Energy Efficiency in Design

5.4.1 Introduction

The development of competing LNGC technologies as well as tighter EEDI regulations has led to the need for improvement in DFDE technology if DFDE propulsion is to maintain its competitiveness and compliance to regulations. A range of possibilities exists with improvements in electrical machine technology, more efficient power electronics, use of energy storage to optimise diesel engine loading, etc. A large body of work in these areas has been published. However, this section focuses on the development of an exhaust gas waste heat recovery system (EGWHR) as one of the ways to improve the efficiency of LNGCs using DFDE. Three major aspects are covered:

- The EGWHRS design
- Trial Run of the EGWHRS in sea-going operations
- A discussion of results together with a discussion on the implications for future designs.

The study is carried out from both an academic and practical view point and contains observations from on-board a modified seagoing DFDE LNGC.

5.4.2 Design Concept

It has been estimated that between 48 to 51% of the total heat energy of ICEs is lost as waste heat [52], therefore the EGWHRS is considered an effective means to capture and exploit this heat energy for useful work and increase the overall efficiency of the plant. Figure 41 highlights the losses from the DFDE as well as other potential waste energy recovery options.

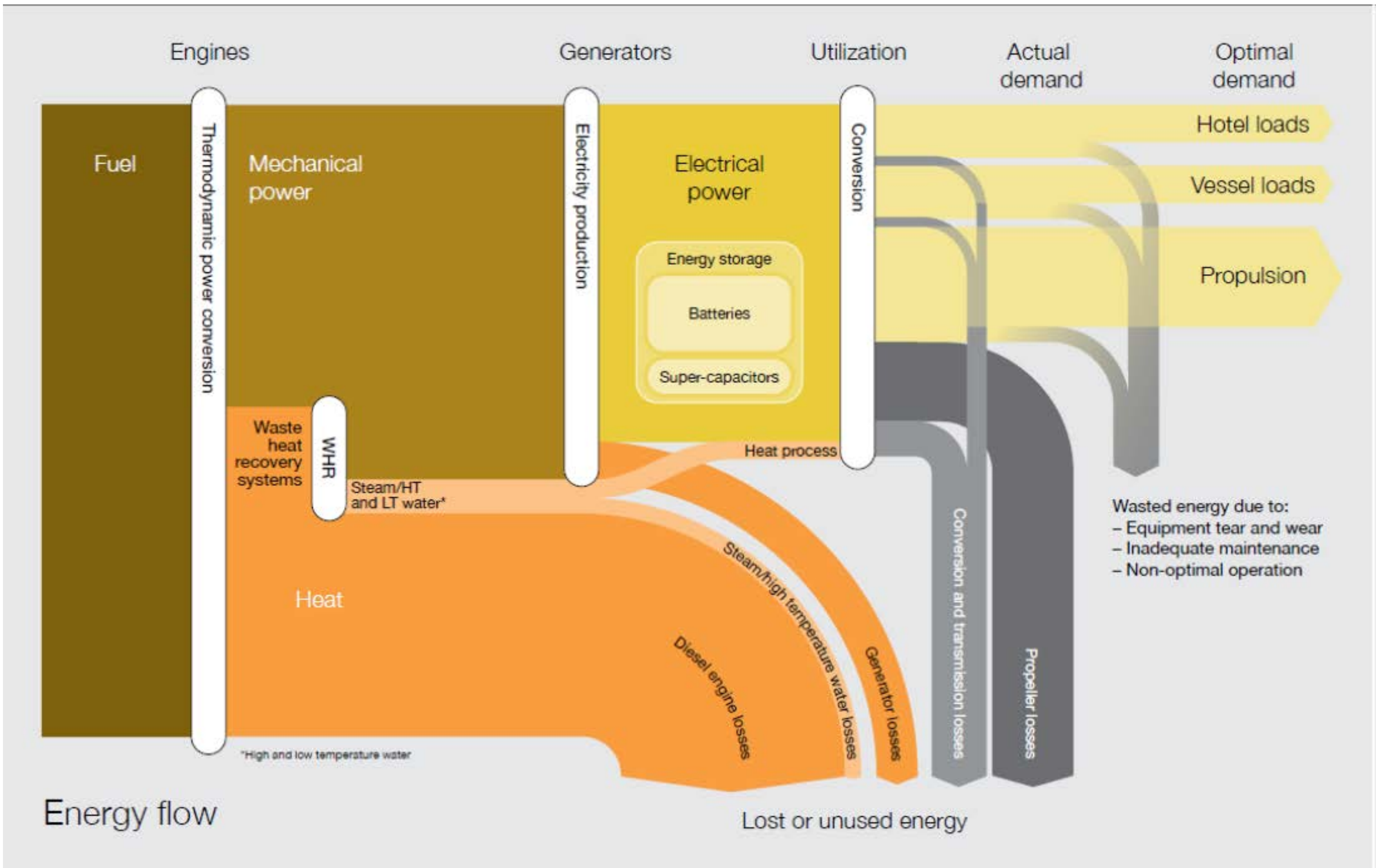


Figure 41: Sankey Diagram for DFDE Vessels. Source: [52]

Four-Stroke diesel engines tend to run at higher exhaust temperatures than 2-stroke diesel engines [51], hence the DFDE has a higher potential for exhaust gas waste heat recovery than the DDD propulsion equivalent that is based on 2-stroke technology. An EGWHRS can be used to generate steam which can be used for various applications, including electricity generation, contributing to increased efficiency. One study estimated the overall service load i.e. generated power and energy used for auxiliary systems, could be up to 3MW [51]. Figure 42 shows a simple design configuration of the EGWHRS.

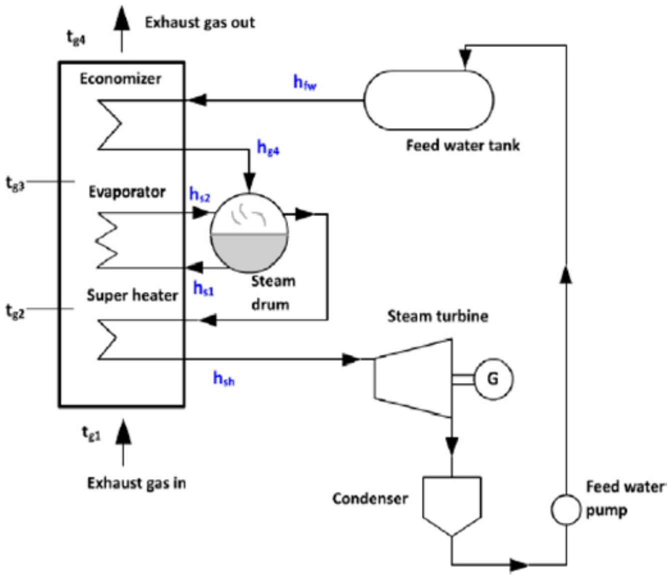


Figure 42: Simple configuration of a WHRS driving a Turbine Generator. Source: [53]

This case study EGWHRS design requires five exhaust gas economizers to be installed in the exhaust gas path where the waste heat of the DFDE is used for generating steam to drive a turbo generator. Steam is also available for other steam consumers on board the ship. The economizer comprises a forced evaporator and a superheater, both connected to a common steam drum and the output is fed to the steam turbine. The steam turbine is brought online when all the diesels units are running on at least 80% load such that there is sufficient steam available for the turbine to function reliably. Figure 43 shows the full schematic of EGWHRS installed on trial vessel.

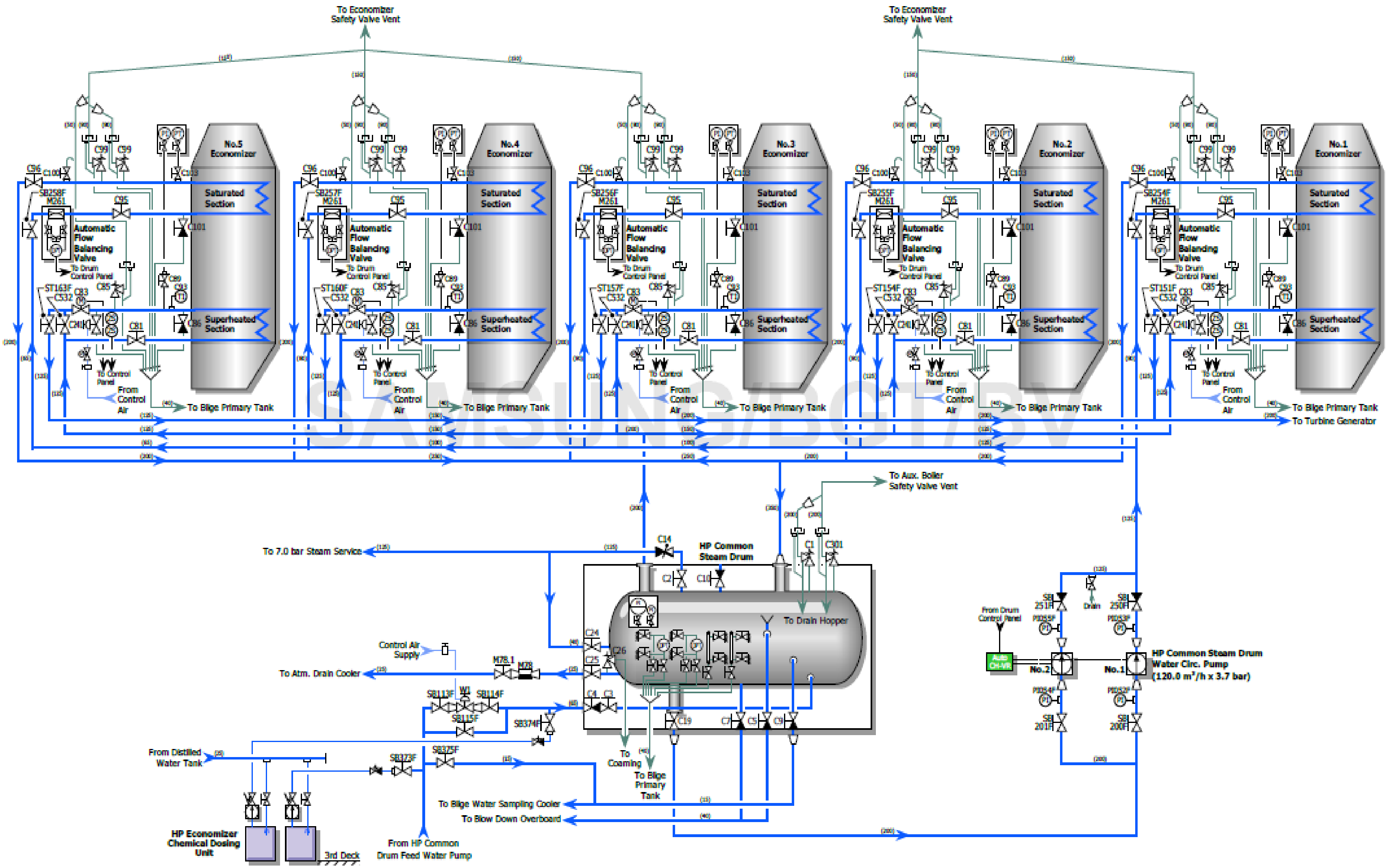


Figure 43: Full Schematic of DFDE WHRS System installed on Trial Vessel. Source: [54]

5.4.3 EGWHRS Trial

The details of the ship and relevant equipment with which the trial run was carried out are shown in Table 23 below [54]:

Table 23: Trial Vessel Particulars. Source [54]

Principal Ship Particulars		Exhaust Gas Economiser	
Shipbuilder	Samsung Heavy Ind.	Maker	Alfa Laval
Type of Ship & Cargo	DF-Electric LNG Carrier	Type	Aalborg XW-TG/Q5
Cargo Tanks	4GTT Mark III	No. of Sets	5
Cargo Capacity	$174904.2m^3$	Capacity	400 kg/h each
Length Overall	293.193m	Design Engine Load	80% MCR
LBP	280.0m	Ex. Gas Mass Flow	34560 kg/h (Gas)
Design Draft	11.65m	Ex. Gas inlet Temp	$404^{O}C$ (Gas)
Deadweight		Ex. Gas outlet Temp.	$187^{O}C$ (Gas)
Main Generator Engine		Diesel Engine Generators	
Maker	Wartsila	Maker	GE Energy
Type	8L50DF	Number of Sets	5
Number of Sets	5	Output	8367KVA (7530KW)
Output	7800KW	Voltage	AC 6600V/732A
Speed	514rpm	Frequency/Speed	60 HZ/514rpm

The test involved running the above vessel in two modes in order to ascertain the effectiveness of the EGWHRS and determine the reductions in fuel consumption and emissions when the EGWHRS equipment is in use:

- Mode 1: Vessel is fully laden and en-route at service speed. The test conditions are maintained for two hours between 09:00 hours and 11:00 Hours with four of the DFDE engines online at or above 80% load. The Turbo Generator is not in use and the parameters are monitored and recorded.
- Mode 2: Upon completion of Mode 1 the EGWHRS is brought online. The test conditions are maintained for two hours between the hours of 12:00Hrs and 14:00Hrs with the DFDE

engines under the same load conditions as in Mode 1. The Turbo Generator is in service and the electricity generated is fed to the main switchboard.

The next stage involves estimating the running hours of the TG during actual operations to ascertain the effectiveness of the EGWHRS during the actual voyage operations of the vessel. This trial was conducted on the four vessels where the EGWHRS was installed for a month of operation and included laden and ballast passages.

5.4.4 Trial Run Results

The results from Mode 1 and Mode 2 are represented in Table 24 and Table 25 respectively. The items recorded included test duration, ship condition, sea state, engine fuel consumption, and auxiliary load data.

Table 24: Mode 1 Results

	MODE 1	4Engines Running		
1	SHIP'S NAME:	XXXXXXX		
2	**DATE**	**11-Feb-17**		
4	TEST START	hrs	9:00	
5	TEST FINISH	hrs	11:00	
6	TEST DURATION	hours	2	
7	DISPLACEMENT	tonnes	118504	
8	DRAFT FORWARD	metres	11.26	
9	DRAFT AFT	metres	11.26	
10	SHIP'S HEADING	degrees	270	
11	WIND -	force & direction	3 x SW	
	SEA STATE		3, SLIGHT	
12	SWELL	metres & direction	0.5 x SW	
13	CURRENT	Spd x Dirn	0.6 x N	
14	OUTSIDE ATMOSPHERIC PRESSURE	mbar	1022	
15	OUTSIDE AMBIENT TEMPERATURE	°C	28	
16	S.W.TEMP	°C	29	
17	E.R. TEMP	°C	36	
18	OBSERVED DISTANCE	nautical miles	36.1	
19	SPEED BY OBSERVATION	knots	18.05	
20	SPEED BY LOG (GPS Log)	knots	17.75	
			PORT	STBD

21	REVOLUTION COUNTER AT START		9048359	9024012
22	REVOLUTION COUNTER AT FINISH		9055535	9031189
23	RPM	rpm	72.60	
24	ENGINE DISTANCE	nautical miles	38.40	
25	ENGINE SPEED	knots	19.20	
26	APPARENT SLIP	%	5.99	
			Start	End
27	PORT Shaft Total Power (From Shaft Torque Meter)	kWh	44446.88	44475.06
28	STBD Shaft Total Power (From Shaft Torque Meter)	kWh	41418.75	41446.94
29	No.1 GENERATOR LOAD	kW	6171	
30	No.2 GENERATOR LOAD	kW	6324	
31	No.3 GENERATOR LOAD	kW	6172	
32	No.4 GENERATOR LOAD	kW		
33	No 5 GENERATOR LOAD	kW	6472	
34	T/A LOAD	kW		
35	PORT PROPULSION MOTOR LOAD	kW	11064	
36	STBD PROPULSION MOTOR LOAD	kW	10881	
37	PORT SHAFT POWER	kW	10784	
38	STBD SHAFT POWER	kW	10360	
39	HOTEL LOAD	kW	3194	
40	No.1 MGE GAS METER AT START	Kg	4130437.90	
41	No.1 MGE GAS METER AT FINISH	Kg	4132588.70	
42	No.2 MGE GAS METER AT START	Kg	3625455.90	
43	No.2 MGE GAS METER AT FINISH	Kg	3627631.70	
44	No.3MGE GAS METER AT START	Kg	3429356.90	
45	No.3 MGE GAS METER AT FINISH	Kg	3431492.90	
46	No.4 MGE GAS METER AT START	Kg	1958211.20	
47	No.4 MGE GAS METER AT FINISH	Kg	1958211.20	
48	No.5 MGE GAS METER AT START	Kg	3718990.90	
49	No.5 MGE GAS METER AT FINISH	Kg	3721173.90	

In Mode 2, shown in Table 25, the same data (test duration, ship condition, sea state, engine consumption, and auxiliary load) as recorded in Mode 1 was also recorded and monitored for conformity to ensure accuracy of the analysis being carried out.

Table 25: Mode 2 Results

	MODE 2	4Engines + T/A Running		
1	SHIP'S NAME:	XXXXXX		
2	**DATE**	**11-Feb-17**		
4	TEST START	hrs	12:00	
5	TEST FINISH	hrs	14:00	
6	TEST DURATION	hours	2	
7	DISPLACEMENT	tonnes	118504	
8	DRAFT FORWARD	metres	11.26	
9	DRAFT AFT	metres	11.27	
10	SHIP'S HEADING	degrees	270	
11	WIND -	force & direction	3 X SW	
12	SEA STATE		3, SLIGHT	
13	SWELL	metres & direction	0.5 X SW	
14	CURRENT	Spd x Dirn	0.6 X N	
15	OUTSIDE ATMOSPHERIC PRESSURE	mbar	1020	
16	OUTSIDE AMBIENT TEMPERATURE	°C	29	
17	S.W.TEMP	°C	30	
18	E.R. TEMP	°C	36	
19	OBSERVED DISTANCE	nautical miles	36	
20	SPEED BY OBSERVATION	knots	18	
21	SPEED BY LOG (GPS Log)	knots	17.65	
			PORT	STBD
22	REVOLUTION COUNTER AT START		9034804	9059153
23	REVOLUTION COUNTER AT FINISH		9066366	9044019
24	RPM	rpm	72.40	
25	ENGINE DISTANCE	nautical miles	38.30	
26	ENGINE SPEED	knots	19.15	
27	APPARENT SLIP	%	6.01	
			Start	End
28	PORT Shaft Total Power (From Shaft Torque Meter)	kWh	44489.02	44517.34
29	STBD Shaft Total Power (From Shaft Torque Meter)	kWh	41460.89	41489.22
30	No.1 GENERATOR LOAD	kW	5879	
31	No.2 GENERATOR LOAD	kW	6119	
32	No.3 GENERATOR LOAD	kW	5758	
33	No.4 GENERATOR LOAD	kW		
34	No 5 GENERATOR LOAD	kW	5897	

35	T/A LOAD	kW	1520
36	PORT PROPULSION MOTOR LOAD	kW	11066
37	STBD PROPULSION MOTOR LOAD	kW	10881
38	PORT SHAFT POWER	kW	10786
39	STBD SHAFT POWER	kW	10361
40	HOTEL LOAD	kW	3226
41	No.1 MGE GAS METER AT START	Kg	4133604.90
42	No.1 MGE GAS METER AT FINISH	Kg	4135608.10
43	No.2 MGE GAS METER AT START	Kg	3628644.00
44	No.2 MGE GAS METER AT FINISH	Kg	3630668.90
45	No.3MGE GAS METER AT START	Kg	3432522.20
46	No.3 MGE GAS METER AT FINISH	Kg	3434528.50
47	No.4 MGE GAS METER AT START	Kg	1958211.20
48	No.4 MGE GAS METER AT FINISH	Kg	1958211.20
49	No.5 MGE GAS METER AT START	Kg	3722217.70
50	No.5 MGE GAS METER AT FINISH	Kg	3724255.50

The second case study involves the monitoring of the Turbo Generator's use across the other four vessels fitted with the EGWHRS over a one month period and recording the data to be used in the analysis. The data recorded includes date, average TG power, running hours, and average speed. The full results are summarized in Table 26.

Table 26: Vessels EGWHRS-TG Readings

VESSEL 1				
DATE	**TG POWER (KW)**	**RUNNING HOURS**	**DAY'S AVERAGE SPEED**	**COMMENTS**
01/05/2017	1630	24	17.92	Laden
02/05/2017	1554	24	17.75	Laden
03/05/2017	1460	24	17.5	Laden
04/05/2017	1428	23	17.65	Laden
05/05/2017	1521	24	17.63	Laden
06/05/2017	1062	24	16.92	Laden
07/05/2017	0	0	0	Transit Suez
08/05/2017	0	0	0	Transit Suez
09/05/2017	0	0	7.72	Slow steaming

10/05/2017	0	0	0	Slow steaming
11/05/2017	0	0	0	Slow steaming
12/05/2017	0	0	0	Slow steaming
13/05/2017	0	0	0	Slow steaming
14/05/2017	0	0	0	Slow steaming
15/05/2017	0	0	0	Discharging
16/05/2017	0	0	0	Discharging
17/05/2017	1565	0.1	16.33	Ballast
18/05/2017	1497	24	20	Ballast
19/05/2017	1632	24	19.79	Ballast
20/05/2017	1610	24	19.75	Ballast
21/05/2017	1596	24	20.46	Ballast
22/05/2017	1589	24	17.46	Ballast
23/05/2017	1450	24	17.5	Ballast
24/05/2017	1635	24	19.42	Ballast
25/05/2017	1636	24	20.04	Ballast
26/05/2017	1636	24	20.21	Ballast
27/05/2017	1607	24	19.29	Ballast
28/05/2017	1557	24	17.75	Ballast
29/05/2017	1620	25	18.08	Ballast
30/05/2017	1567	24	19.54	Ballast
31/05/2017	1518	24	19.8	Ballast

VESSEL 2

DATE	TG POWER (KW)	RUNNING HOURS	DAY'S AVERAGE SPEED	COMMENTS
01/05/2017	0	0	11.6	Ballast
02/05/2017	0	0	11.8	Ballast
03/05/2017	0	0	10	Ballast
04/05/2017	0	0	9.8	Ballast
05/05/2017	0	0	10.1	Ballast
06/05/2017	1593	16	17	Ballast
07/05/2017	1472	24	15.4	Ballast
08/05/2017	1537	14	16.6	Ballast
09/05/2017	1499	24	17.6	Ballast
10/05/2017	1409	25	19	Ballast
11/05/2017	1461	24	18.9	Ballast
12/05/2017	1502	24	18.5	Ballast
13/05/2017	0	0	0	Vessel in port

14/05/2017	0	0	0	Vessel in port
15/05/2017	0	0	16.7	Laden
16/05/2017	0	0	14.46	Laden
17/05/2017	0	0	14.38	Laden
18/05/2017	0	0	12.04	Laden
19/05/2017	0	0	12.08	Laden
20/05/2017	0	0	14.54	Laden
21/05/2017	0	0	12.13	Laden
22/05/2017	0	0	11.5	Laden
23/05/2017	0	0	12.46	Laden
24/05/2017	0	0	12.13	Laden
25/05/2017	0	0	12.91	Laden
26/05/2017	0	0	11.71	Laden
27/05/2017	0	0	12.08	GCU is on
28/05/2017	0	0	13	GCU is on
29/05/2017	0	0	12.5	GCU is on
30/05/2017	0	0	12.88	GCU is on
31/05/2017	0	0	12	GCU is on

VESSEL 3				
DATE	TG POWER (KW)	RUNNING HOURS	DAY'S AVERAGE SPEED	COMMENTS
01/05/2017	1147	23	15.875	Ballast
02/05/2017	1499	25	17.92	Ballast
03/05/2017	1477	24	17.5	Ballast
04/05/2017	1491	25	17.36	Ballast
05/05/2017	1072	24	17.04	Ballast
06/05/2017	931	25	15.48	Ballast
07/05/2017	948	24	15.42	Ballast
08/05/2017	897	25	15.64	Ballast
09/05/2017	1287	24	15.88	Ballast
10/05/2017	1492	24	17.96	Ballast
11/05/2017	1388	25	17.32	Ballast
12/05/2017	1493	24	16.96	Ballast
13/05/2017	1102	24	17.6	Ballast
14/05/2017	1116	24	17.83	Ballast
15/05/2017	969	24	16.16	Ballast
16/05/2017	981	24	16.32	Ballast
17/05/2017	936	24	16.16	Ballast
18/05/2017	0	0	15	Load port
19/05/2017	0	0	0	Load port
20/05/2017	0	0	15.83	Slow steaming
21/05/2017	997	2	10.6	Slow steaming
22/05/2017	0	0	9.42	Slow steaming
23/05/2017	0	0	9.5	Slow steaming
24/05/2017	0	0	9.2	Slow steaming
25/05/2017	0	0	12.5	Slow steaming
26/05/2017	0	0	9.03	Nil
27/05/2017	0	0	8.6	Slow steaming
28/05/2017	0	0	8.5	GCU is on
29/05/2017	0	0	8	Slow steaming
30/05/2017	0	0	8.17	Slow steaming
31/05/2017	0	0	10.17	Slow steaming

VESSEL 4				
DATE	**TG POWER (KW)**	**RUNNING HOURS**	**DAY'S AVERAGE SPEED**	**COMMENTS**
01/05/2017	1373	24	17.46	Laden
02/05/2017	1328	24	17.17	Laden
03/05/2017	1261	24	17.25	Laden
04/05/2017	1205	24	16.5	Laden
05/05/2017	1238	24	16.37	Laden
06/05/2017	1229	24	15.67	Laden
07/05/2017	1148	24	14.71	Laden
08/05/2017	1138	24	14.48	Laden
09/05/2017	0	0	0	Discharging
10/05/2017	1306	6	17.78	Ballast
11/05/2017	1320	24	17.28	Ballast
12/05/2017	1380	24	18.3	Ballast
13/05/2017	1380	24	17.37	Ballast
14/05/2017	0	0	13.87	Slow steaming
15/05/2017	0	0	9.17	Slow steaming
16/05/2017	0	0	8.62	Slow steaming
17/05/2017	0	0	8.87	Slow steaming
18/05/2017	0	0	8.62	TG is off
19/05/2017	0	0	7.08	TG is off
20/05/2017	0	0	6.54	NIL
21/05/2017	0	0	6.87	TG is off
22/05/2017	0	0	7.21	NIL
23/05/2017	0	0	7.75	TG is off
24/05/2017	0	0	7.67	NIL
25/05/2017	0	0	7.25	TG is off
26/05/2017	0	0	12.67	NIL
27/05/2017	0	0	0	Loading
28/05/2017	1280	14	18.64	Laden
29/05/2017	1330	24	18.5	Laden
30/05/2017	1344	24	18.21	Laden
31/05/2017	1318	24	18.08	Laden

5.4.5 Analysis of Results

From the results the following overall calculations were made in order to compare the fuel savings for the different modes of operation:

Table 27: Test 1 Results Summary

Mode 1 (Without Turbo Generator)		Mode 2 (With Turbo Generator)	
Total Gas consumption during test(T)	8.65	Total Gas consumption during test(T)	8.07
Total Gas consumption during test(m^3)	19.28	Total Gas consumption during test(m^3)	18.00
Equivalent Gas combustion 24Hrs(m^3)	231.27	Equivalent Gas combustion 24Hrs(m^3)	215.94
Gas Density: 0.448588 tons/m^3 GCV (Mass) : 54.8472 MJ/Kg			

In Mode 1, the following calculations have been applied to determine the gas consumption in 24 hours using steady state conditions:

$$Gas\ Consumption\ During\ Test = 8.645 Tonnes$$

$$Gas\ Consumption\ during\ Test = 8.65\ \div 0.45 = 19.27 m^3\ \ (Gas\ Density\ 0.45 tons/m^3)$$

$$Equivalent\ Gas\ Consumption\ in\ 24\ Hours = 19.27 m^3\ \times 12 = 231.75 m^3$$

In Mode 2, the following calculations have been applied to determine the gas consumption over 24 hours under steady state conditions

$$Gas\ Consumption\ During\ Test = 8.07 Tonnes$$

$$Gas\ Consumption\ during\ Test = 8.07\ \div 0.45 = 18.00 m^3\ \ (Gas\ Density\ 0.45 tons/m^3)$$

$$Equivalent\ Gas\ Consumption\ in\ 24\ Hours = 17.995 m^3\ \times 12 = 215.94 m^3$$

From the above the following can be ascertained:

$$Gas\ consumed\ in\ 24\ Hours\ without\ WHRS = 231.275 m^3$$

$$Gas\ consumed\ in\ 24\ Hours\ with\ WHRS = 215.94m^3$$

$$Fuel\ Saved\ in\ 24\ Hours = 15.34m^3$$

$$Percentage\ system\ improvement\ in\ Fuel\ Consumption\ with\ respect\ to\ WHRS$$
$$= {}^{15.3388}/_{231.275} = 6.6\%$$

5.4.6 EEDI Implication of Results

As explained in Chapter 5.2 it was seen that the current EEDI baseline, introduced in 2015, is easier to satisfy for DFDE vessels when compared to the less efficient steam LNGCs, since the same baseline equation is applied to both designs. As seen in the EEDI analysis for the DFDE propulsion option, an overwhelming majority (97%) of current DFDE designs will be compliant with the 2020 requirement without recourse to any efficiency improvement technologies, while 56% of current DFDE designs will still be compliant with the 2025 requirement. These results are summarized in Table 28 and Figure 44.

Table 28: EEDI Analysis of the Current DFDE Fleet

Propulsion Type (Nos)	Phase 0 Compliant	Phase 1 Compliant Sept 2015 – Dec 2019	Phase 2 Compliant 2 1 Jan 2020 – 31 Dec 2024	Phase 3 Compliant 1 Jan 2025 – Onwards
Diesel Electric (32)	32- (100%)	32- (100%)	31- (97%)	18- (56%)

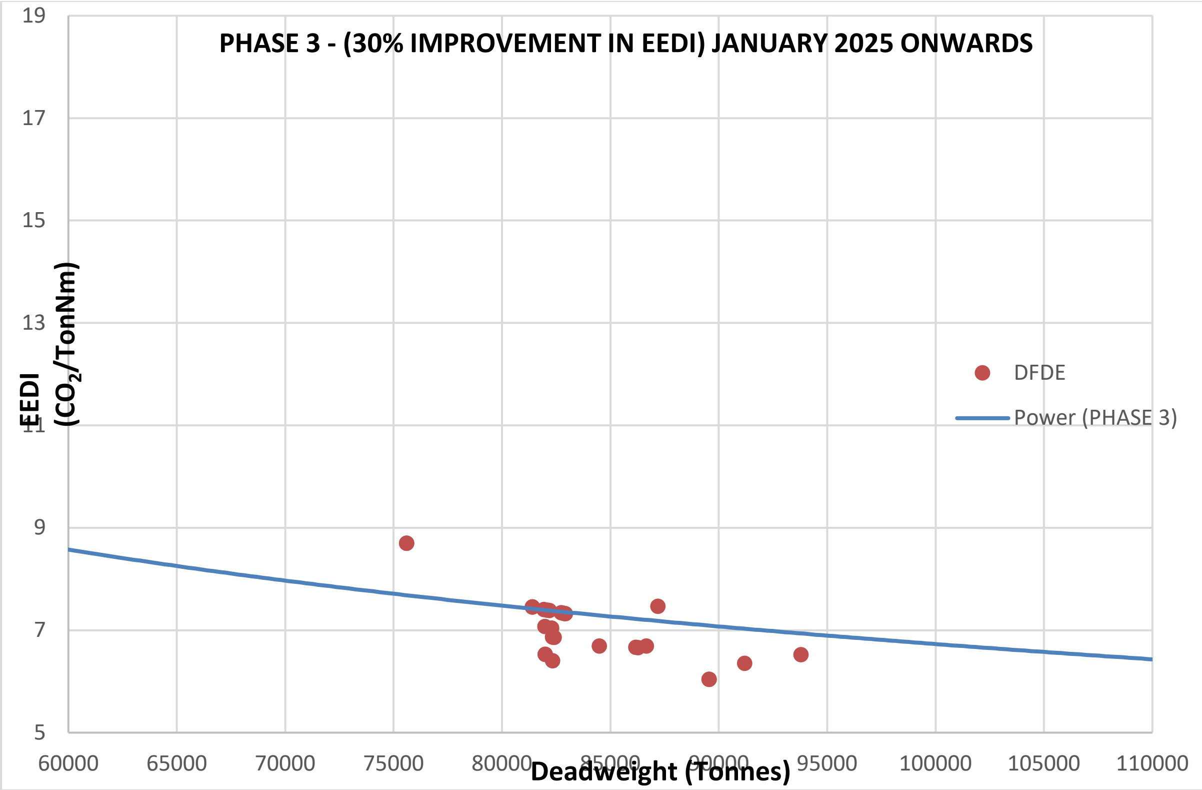


Figure 44- EEDI Analysis of the current DFDE LNGC Fleet. Source: [55]

However, the use of the EGWHRS system further improves the efficiency of the DFDE, by reducing the SFOC component. When the results of this study were applied to the EEDI analysis carried out in the EEDI study it is seen that this efficiency improvement would further increase the number of DFDE vessels that satisfy the compliance requirement. With such modification 91% of DFDE designs will satisfy the compliance requirement for 2025 onwards as detailed in Table 29 and Figure 45.

Table 29: EEDI Analysis of the Current LNGC Fleet with Upgraded DFDE Systems.

Propulsion Type (Nos)	Phase 0 Compliant	Phase 1 Compliant Sept 2015 – Dec 2019	Phase 2 Compliant 2 1 Jan 2020 – 31 Dec 2024	Phase 3 Compliant 1 Jan 2025 – Onwards
Diesel Electric (32)	32- (100%)	32- (100%)	31- (97%)	29- (91%)

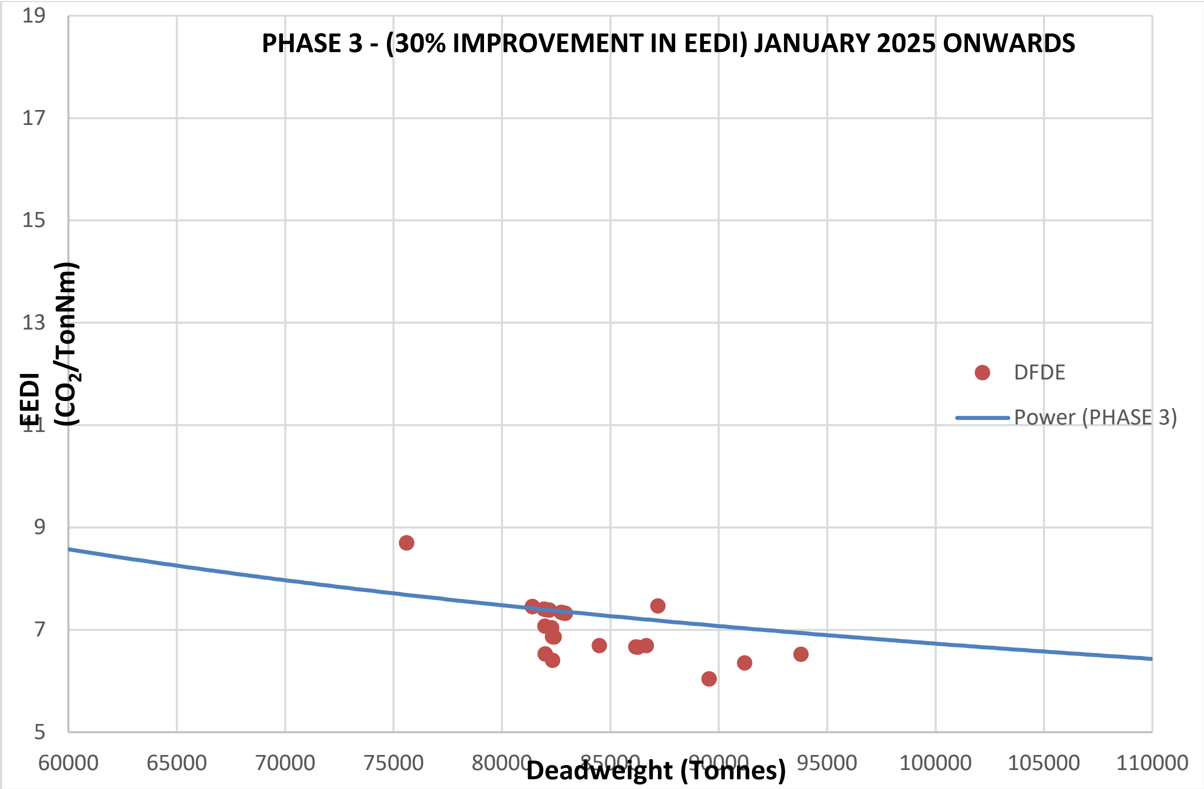


Figure 45- EEDI Analysis of the current DFDE LNGC Fleet if Upgraded WHRS systems.

This is particularly noteworthy. Through exploitation of WHRS no additional improvements in technology will be required from phase two as the adoption of the EGWHRS will meet the IMO mandated EEDI requirement for new LNGC designs.

5.4.7 Cost Implication of Results

The second part of the study also captured the use of the EGWHRS over a month of operation and compared the savings. From Table 30 it is seen that for Vessel 1, the operational profile was such that the TG was in use for 21 out of the 31 days, which equates to 67% of the time. On Vessel 2, it was used for 7 days (22%), while for Vessels 3 and 4 the usage was 18 days (58%) and 16 days (52%) respectively.

In order to extrapolate the results from the EGWHRS trials to reflect the usage on all four vessels, a factor was developed to estimate the gas savings per kW of Turbo Generator generated electrical Power.

$$Gas\ savings\ per\ kW\ TG\ Power = {}^{15.34}/_{1520} = 0.01009\,{}^{m^3}/_{kW}$$

This factor was then applied to the four ships to estimate the fuel savings, over the one month trial period by multiplying the factor obtained in the equation above to the TG readings recorded over the trial period, according to the equations below.

$$0.01009\, {}^{m^3}/_{kW} \times TGPower \times Monthly\ Running\ Hours = Total\ Gas\ Saving \tag{3}$$

Total gas saving was then multiplied by a fuel oil equivalent factor of 0.484 to obtain the equivalent HFO fuel saving to estimate the cost savings based on the cost of Bunkered HFO.

$$Total\ Gas\ Saving \times 0.484 = Total\ HFO\ Equivalent\ Saving (Tonnes) \tag{4}$$

Therefore, based on an average HFO bunker price of $305/Ton (as at February 2017) [56], the total HFO equivalent saving can be estimated according to the formula below

$$Total\ HFO\ Equivalent\ Saving\ \times 305 = Estimated\ Cost\ Saving\ per\ vessel \tag{5}$$

The full estimated monthly cost summary is represented in Table 30.

Table 30: Estimated monthly cost summary

Vessel 1	
Total Gas Saving in Month	313.01m^3
Fuel Oil Equivalent of Gas	151.0tonnes
Estimated Fuel Cost Savings	**$49,833**
Vessel 2	
Total Gas Saving in Month	94.8m^3
Fuel Oil Equivalent of Gas	45.8tonnes
Estimated Fuel Cost Savings	**$15,135**
Vessel 3	
Total Gas Saving in Month	207.7m^3
Fuel Oil Equivalent of Gas	100.6tonnes
Estimated Fuel Cost Savings	**$33,180**
Vessel 4	
Total Gas Saving in Month	193.0m^3
Fuel Oil Equivalent of Gas	93.4tonnes
Estimated Fuel Cost Savings	**$30,828**

From the above table it can be seen that the use of EGWHRS could realise average savings of circa $30,000.00 per month per vessel, with an annual yearly saving of approximately $360,000.00 per vessel. Such an annual saving, when compared to the installation costs of $1.2 million per vessel based on the construction prices in 2015, is expected to recover the equipment costs in 3.5 years. This cost recovery duration is expected to be shorter with higher fuel prices, or if the vessels spend more time at high transit speeds.

5.5 Dual Fuel Diesel Electric Propulsion System Summary

This chapter covered a comprehensive analysis the Diesel Electric Propulsion System as a propulsion option for LNGCs. The first section covered an analytical study of the propulsion system using the EEDI design analysis tool. Here it was shown that the current designs easily meet the current IMO mandated EEDI benchmark, while meeting more stringent EEDI requirements in the future can be achieved without recourse to significant technological improvement to the current designs.

The second section covered case studies of DFDE LNGCs in actual operation. Two case studies were presented and analysed. The first case study examined the operating efficiency of the DFDE and the second case study examined the sea trials of an actual DFDE vessel that had just been constructed. In the first case study, it was seen that the DFDEs exhibited good transport efficiencies when compared to the STPS. It was also observed that the transport efficiencies deteriorate rapidly when discharging to FSRUs or when the cargo carrying capacity is not optimally exploited. In the second case study it was seen that while sea trials are carried out using HFO as the fuel, during actual operation the vessels primarily use natural gas as fuel, with the vessels spending less than 5% of the time using HFO. Bearing in mind that EEDI regulations are calculated/computed using NG as fuel, it therefore follows that the current practice of utilising HFO for sea trials is not representative of actual operational practice, therefore the benchmark against which new DFDE designs are assessed is not truly realistic.

The final section covered the use of a design improvement technology. The assessment centred on a WHRS to improve the efficiency of the DFDE and the impact it has on the EEDI and associated system efficiency. Here it was seen that during actual operations, the WHRS brought about an increase in system fuel efficiency of about 6.6% bringing the total efficiency of the DFDE to 48%. In terms of EEDI, it meant that this new improvement technology could ensure an overwhelming majority of current DFDE designs would meet the 2025 IMO compliance requirement if fitted with this feature to recoup the cost of installation if fitted with EGWHRS through average fuel savings resulting from improved efficiency would require a three-and-a-half-year payback period.

6.

DIRECT DRIVE DIESEL PROPULSION SYSTEM

6.1 Introduction

Further to the analyses carried out on the Steam Turbine Propulsion System and the Dual Fuel Diesel Electric System in Chapters Four and Five respectively, this chapter presents an analysis of the direct drive diesel (DDD) propulsion option for LNG carriers. It is however important to note, that this analysis will not be in the same detail as the STPS or DFDE propulsion options as there are limited numbers of these vessels in actual operation and moreover steam turbine propulsion and DFDE propulsion collectively make up 90% of the current fleet and order book. To achieve the aforementioned research aim of characterising the different LNGC propulsion options in terms of efficiency and emissions, this chapter is subdivided into two parts. Firstly, an analytical study of the DDD option using the EEDI and secondly, an analytical analysis of future direct drive options that could be used for LNG Carriers.

6.2 An Analysis of Direct Drive Diesel (DDD) LNG carriers using the EEDI.

Using the same methodology utilized for calculating the EEDI in Chapter 4 and using the equations for the baseline and index values listed in Table 3 and Table 4, the EEDI analysis was carried out for this mode of propulsion option [37, 38].

For the direct drive diesel (DDD), the following assertions were made for this analysis:

- The boil off rate (BOR) is taken as 0.15% per day [38].
- The COP_{reliq} is a coefficient of design power performance, used in re-liquefying boil of gas per unit volume. It is given by the formula [38]: -

$$COP_{reliquefy} = \frac{425\ (\frac{kg}{m^3}) \times 511(\frac{kJ}{kg})}{24(h) \times 3600\ (\text{Sec}) \times COP_{cooling}} \quad (6)$$

- The $COP_{cooling}$ is a coefficient of design cooling performance and it is taken as 0.166

- R_{reliq} is the ratio of volume boil off gas (BOG) to be re-liquiefied to the entire volume of BOG. It is calculated according to the formula:

$$R_{reliq} = \frac{BOG_{reliq}}{BOG_{total}} \quad (7)$$

For the purpose of this analysis the R_{reliq} is taken as 1.

The baseline equation was applied and combined with the equation in Table 4, while taking into account the percentage tightening up of a compliance requirement due to the implementation of the EEDI phases to 2025 upwards.

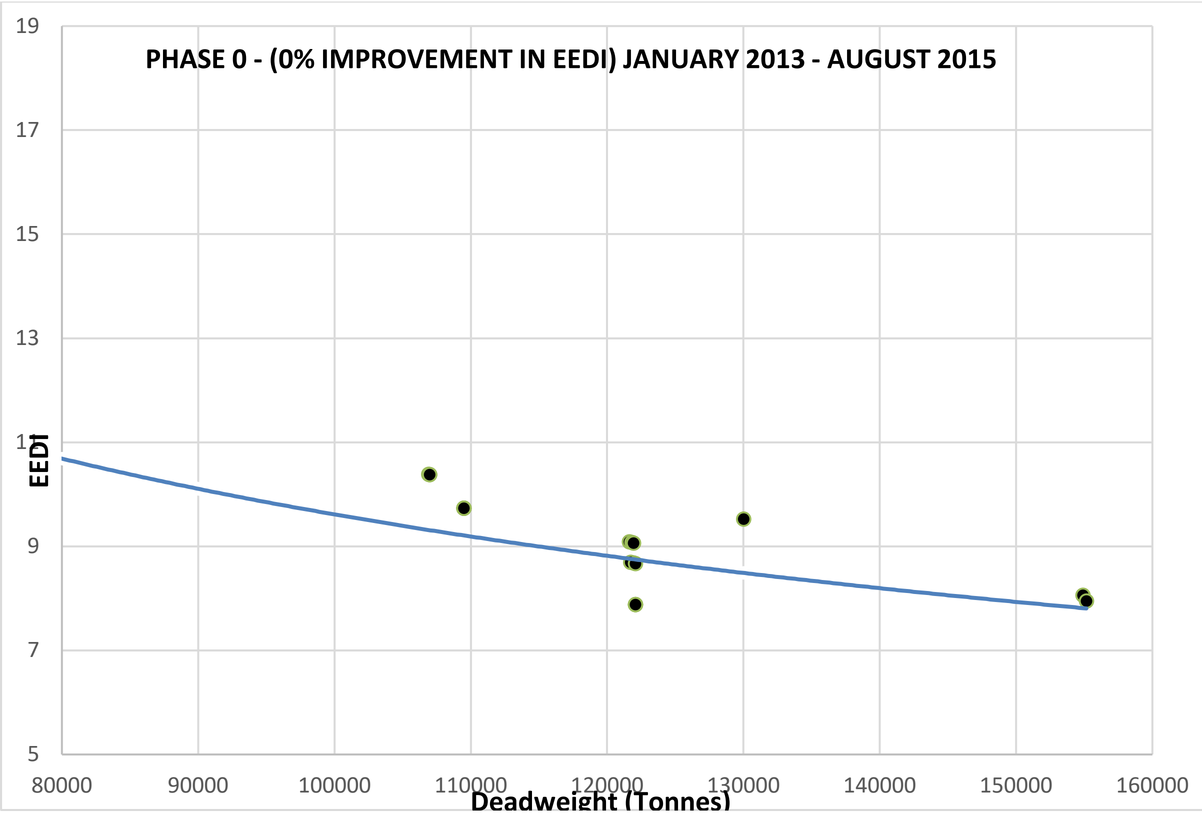


Figure 46- Phase 0 EEDI (0% Improvement in EEDI) January 2013 – August 2015

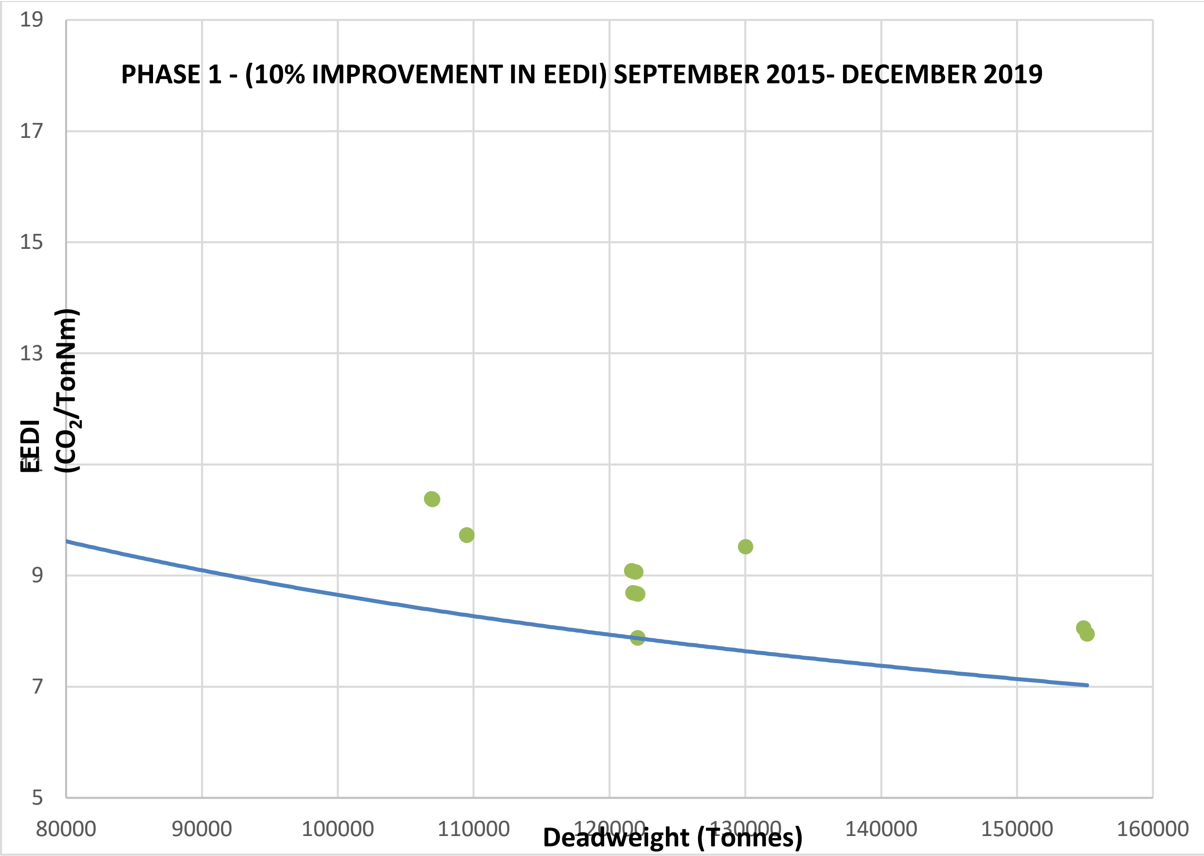


Figure 47- Phase 1 EEDI (10% Improvement in EEDI) September 2015 – December 2019

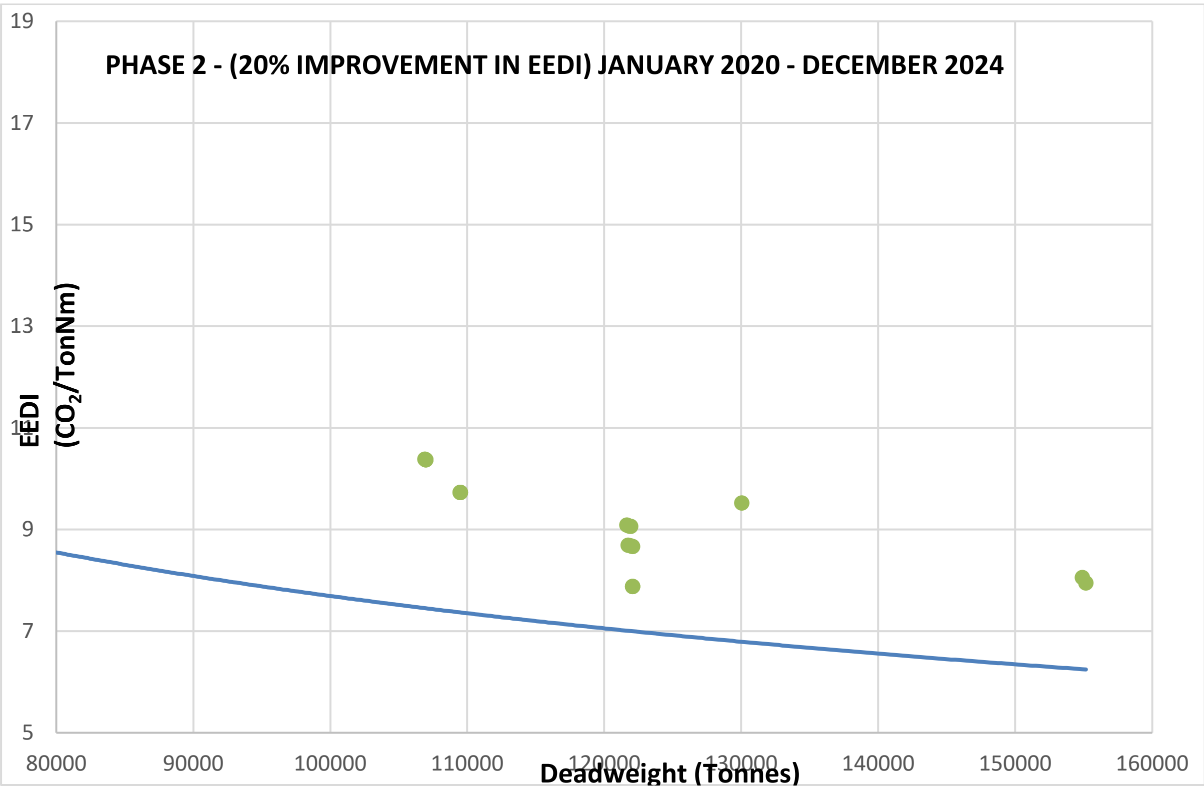


Figure 48- Phase 2 EEDI (20% Improvement in EEDI) January 2020 – December 2024

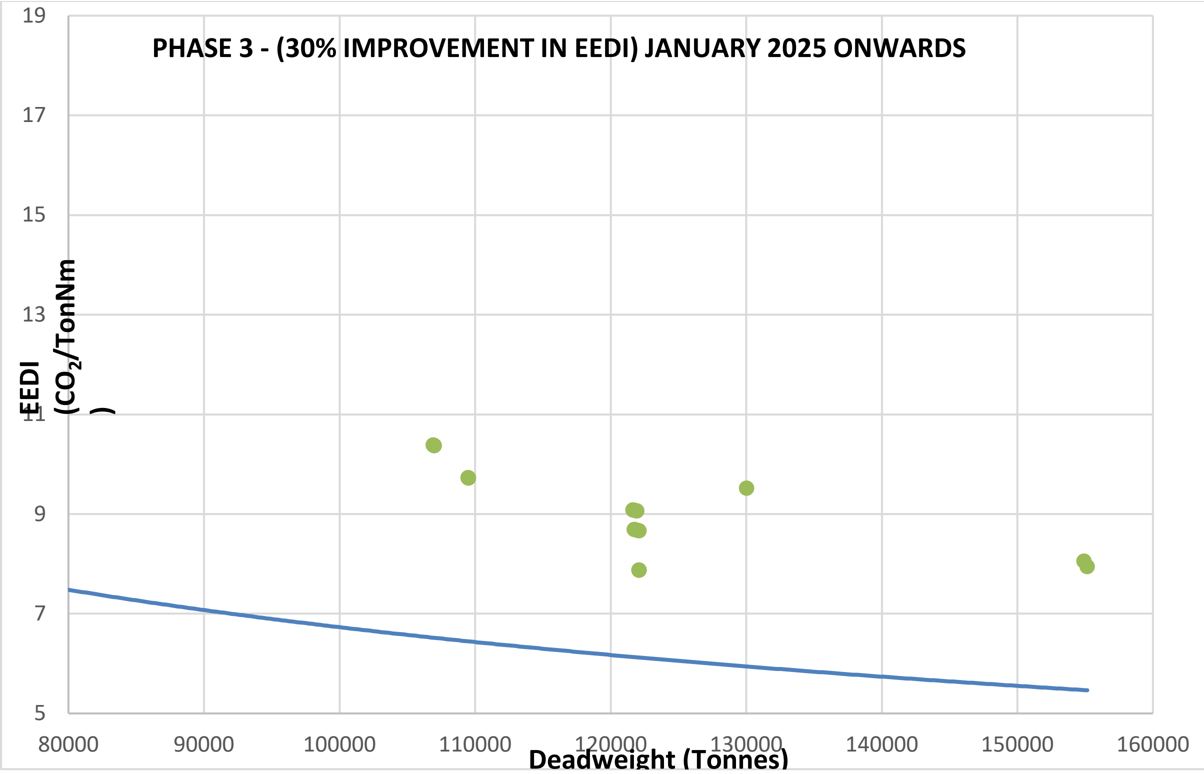


Figure 49- Phase 3 EEDI (30% Improvement) January 2025 onwards

The full dataset with associated calculations and results are presented in Appendix 1

From the results the following can be ascertained:

- The current baseline equation seems a fair representation for the Direct Drive Vessels as approximately 40% of these vessels currently being compliant, as the baseline value adopted by the MEPC is usually an average of the EEDI of current designs [37] [38].
- Phase 1 implementation sees this percentage dropping to 28% as more of the current vessels would no longer be compliant.
- Phase 2 implementation would result in all the current DDD Designs being non-compliant, as no ship with this propulsion design will meet the regulations from January 2020.
- The same occurs for Phase 3 as EEDI compliance moves further away from current DDD Designs.

Table 31 highlights the summary of the EEDI analysis of the DDD designs

Table 31: EEDI Analysis of DDD fleet

Propulsion Type (Nos)	Phase 0 Compliant	Phase 1 Compliant Sept 2015 – Dec 2019	Phase 2 Compliant 2 1 Jan 2020 – 31 Dec 2024	Phase 3 Compliant 1 Jan 2025 – Onwards
Direct Drive Diesel (21)	8- (38%)	5- (24%)	0- (0%)	0- (0%)

6.3 An Analysis of the EEDI of Future Direct Drive Designs

Despite having the highest thermal efficiency of all three propulsion types, the DDD is less dominant in the LNG shipping industry due to its limited capability in handling BOG. Although all the LNGCs that are of the slow speed diesel engine plant variant employ re-liquefaction plants to handle the boil off, reliability issues, new emission requirements, and the economics of re-liquefaction would suggest that such a solution is decidedly complex since utilising the cleaner boil of gas as fuel is should be a technically simpler solution.

A new gas injection propulsion system, based around a two-stroke engine that is capable of burning gas introduced by MAN B&W as well as Wartsila has been proffered as a solution to improve the overall energy balance by utilising BOG as a fuel instead of having to expend energy to re-liquefy said BOG. The concept of the ME-GI system is based on a high pressure gas injection principle with pilot fuel ignition, ensuring the same high thermal efficiency of the diesel combustion process as for heavy fuel oil burning can be achieved. It is claimed that this would have an advantage over the carburetted premixed Otto cycle gas process currently being used by the DFDEs as the gas is not yet charged to the cylinder during the compression stroke. This would help eliminate the risk of knocking, thus high compression/expansion ratios can be utilised offering higher energy efficiency and low gas emissions [30] as show in the schematic in Figure 16.

The gas injection principle implemented as described would have the following benefits over the current SSDR configuration when considering the reduction of EEDI values:

- The higher calorific value of the gas fuel would reduce the specific fuel consumption of the engine SFC_{ME}, thereby reducing the final index value,
- The carbon factor of natural gas fuel is lower than that of HFO,
- The reduction of the auxiliary power required to run the re-liquefaction plant.

Currently there is a limited number of GI engines in operation in LNGCs, but for 60% of the LNGCs in the order book proposing to have direct drive configurations, have gas injection as part of the design intent. An analysis was therefore carried out by proposing the replacement of that part of the existing fleet operating DDD configurations with the GI configurations and analysing the effect such a modification would have on the EEDI calculation for these vessels as the GI configuration is expected to be the new standard of DDD to be built in future. In making this analysis, the following assumptions and assertions were made [37, 57]:

- P_{ME} is taken as $P_{ME} = 0.75 \times MCR$.
- The SFC_{ME} is taken as 160 g/KWh.
- The pilot fuel amount at 75% MCR is taken as 3.75% or 6g/KWh.
- The P_{AE} is ascertained by the formula:

$$P_{AE} = (0.025 \times MCR) + 250 + (COP_{comp} \times SFC_{ME} \times \frac{P_{ME}}{1000}). \tag{7}$$

The additional power consumption in Equation 7 is that of the compressor that is used to raise the pressure of the BOG that is fed to the main engines. The COP_{comp} is the design power of the compressor and taken to be 0.33KWh/kg.

- Auxiliary power is supplied by HFO burning traditional diesel engines.
- The EEDI formula is thus:

$$EEDI = \frac{P_{ME} \times \left(C_{f(pilot)} \times SFC_{ME(pilot)} + C_{f(gas)} \times SFC_{ME(gas)}\right) + \left(P_{AE} \times C_{f(AE)} \times SFC_{AE}\right)}{Capacity \times V_{ref}} \quad (8)$$

$$EEDI = \frac{P_{ME} \times (3.114 \cdot 6 + 2.75 \cdot 160) + (P_{AE} \cdot 3.114 \cdot 215)}{Capacity \times V_{ref}} \quad (9)$$

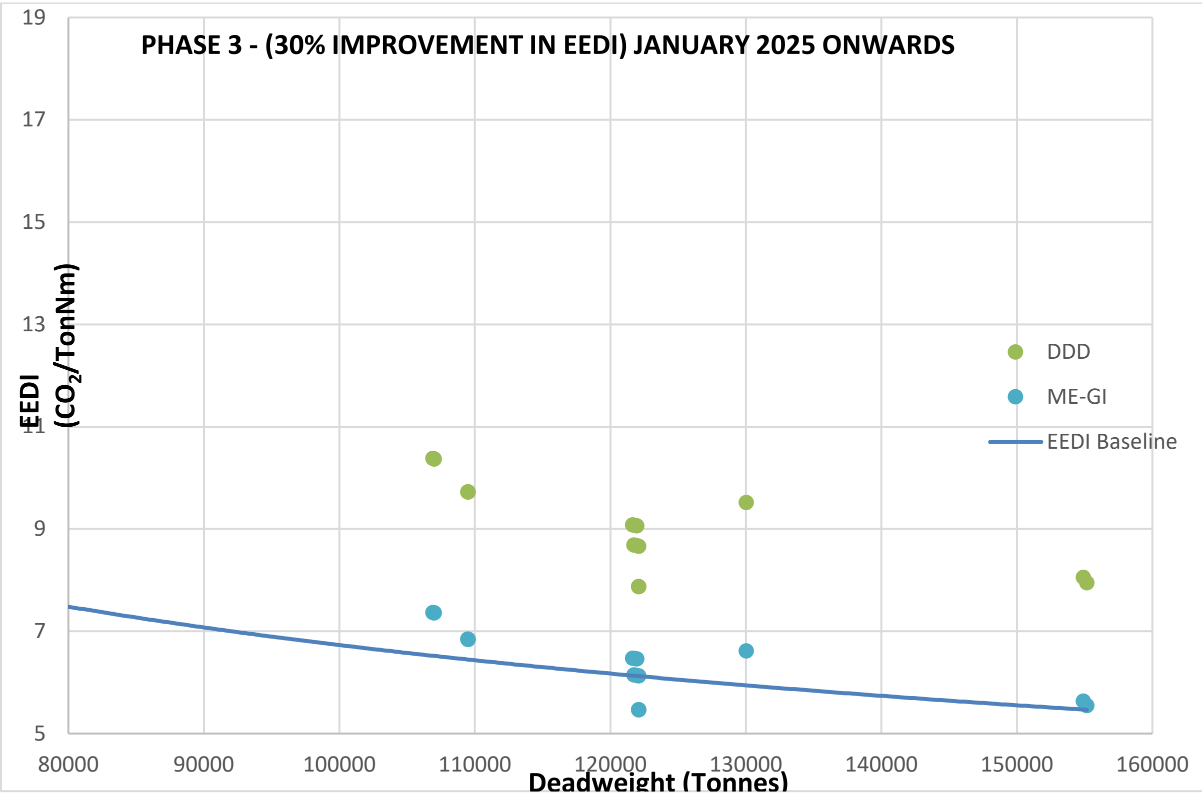


Figure 50- Phase 3 EEDI (30% Improvement in EEDI) with Gas-Injection Diesel Engines.

As seen in the graph displayed in Figure 50 the EEDI of the gas injection engines fall within limits of the Phase 3 baseline limits unlike the fuel powered DDD alternative. This is largely due to two factors; firstly the use of the cleaner BOG with a higher calorific value as well as lower carbon content; secondly, the elimination of the requirement of a re-liquefaction plant essentially eliminates the substantial power required to run this re-liquefaction plant. These improvements are further highlighted in improved performance against the EEDI baseline would indicate suitability for the upcoming legislation before taking into account any improvements in technology that might come to fruition before 2025.

6.4 Direct Drive Propulsion Summary

Having completed a comprehensive analysis of the other two propulsion options: DFDE and STPS, this chapter presented an analysis of the DDD propulsion system as an option for LNGCs. The first section covered an analytical study of the SSDR design using the EEDI measure. Here it was seen that the EEDI benchmark index seemed to be a good average of the current DDD as at Phase 0 implementation, 40% of current designs fall below the benchmark. The current designs will however become non-compliant by the time the 2020 restrictions are put in place.

The second section presented a similar analysis for gas injection engines. The Gas-Injection design shows a marked improvement upon the SSDR option of approximately 30% improvement in efficiency, due to the removal of the power requirement for the Re-liquefaction plant as well as the utilisation for the BOG for fuel in place of HFO. This marked improvement in EEDI values indicates the gas injection designs can satisfy the benchmark index values up to 2025. Unlike the previous two chapters the analysis was limited due to the obsolesce of the old designs- Slow Speed Diesel with Re-liquefaction plants, and the lack of operational data of the new gas injection designs. As explained in chapter 3, these new designs are yet to be adequately defined as different configurations currently exist and more are still under development. Furthermore, due to the limited number of DDD in operation, it was not feasible to carry out case studies of actual vessel operational conditions. This was considered critical for the development of conclusions from the research process as seen in the cases of the DFDE and the STPS. Nevertheless, steam and DFDE make up 90% of the current fleet therefore the impact of not having a similar robust study as was carried out on the DFDE and STPS is deemed not to be of a magnitude that would overly affect the overall results of the complete LNGC study.

7.

COMPARATIVE ANALYSIS OF THE DIFFERENT LNGC PROPULSION OPTIONS

7.1 Introduction

In Chapters 4, 5 and 6, different LNGC propulsion technologies were examined in terms of each design's suitability in terms of EEDI compliance, using case studies of actual vessels in operation and subsequent application of modelling techniques or practical demonstrations to improve the current designs to make them better suited for upcoming amendments in legislation. This chapter presents a comparative study of the different designs in order to identify optimised propulsion options as well as indicate opportunities for improvement. This chapter is sub-divided into three parts- 1) Comparative Analysis of the EEDI of the different propulsion plant design options. 2) Comparative Analysis of the Case Studies of the different propulsion plant design options. 3) A comparative analysis of the technological improvements proposed for the different propulsion plant design options.

7.2 EEDI Comparative Analysis

The equations used in the EEDI analysis are shown in Table 4 reproduced on the next page [37, 38]:

Table 4- EEDI Formulas for LNGCs. Source: [37, 38]

	Direct Drive Diesel	**Dual Fuel Diesel Electric**	**Steam Turbine**
Margin	Engine: 10% Sea: 20%	Engine: - Sea: 20%	Engine: - Sea: 20%
Design Margin	$M\arg in = \frac{0.9}{1.2}$ $M\arg in = 75\%$	$M\arg in = \frac{1}{1.2}$ $M\arg in = 83\%$	$M\arg in = \frac{1}{1.2}$ $M\arg in = 83\%$
P_{ME}	$P_{ME} = 0.75 \times MCR_{ME}$	$P_{ME} = 0.83 \times \frac{MPP}{\eta_{Electrical}}$	$P_{ME} = 0.83 \times MCR_{ME}$
SFC_{ME} (g/kWh)	190 (HFO)	175 (FBO)	285 (FBO)
P_{AE}	$P_{AE} = (0.025 \times MCR_{ME}) + 250 + (Capacity \times BOR \times COP_{reliq} \times R_{reliq})$	$P_{AE} = (0.025 + 0.02) \times P_{ME} + 250$	$P_{AE} = 0$
EEDI	$3.1144(gCO2/gHFO) \times \frac{(190 \times P_{ME}) + 215 \times P_{AE}}{Capacity \times V_{ref}}$	$2.75(gCO2/gBOG) \times \frac{(175 \times P_{ME}) + 175 \times P_{AE}}{Capacity \times V_{ref}}$	$2.75(gCO2/gBOG) \times \frac{285 \times P_{ME}}{Capacity \times V_{ref}}$

The full dataset for the different propulsion systems is summarized below:

For the DDD, the following assertions and assumptions were made for this analysis:

- The boil off rate (BOR) is taken as 0.15% per day [38].
- The COP_{reliq} is a coefficient of design power performance, used in re-liquefying boil of gas per unit volume. It is given by the formula shown here

$$COP_{reliquefy} = \frac{425\,(\frac{kg}{m^3}) \times 511(\frac{kJ}{kg})}{24(h) \times 3600\text{ (Sec)} \times COP_{cooling}} \tag{10}$$

- The $COP_{cooling}$ is the coefficient of design performance and is given as 0.166

- R_{reliq} is the ratio of boil off gas (BOG) to be re-liquefied to the entire BOG. It is calculated according to the formula:

$$R_{reliq} = \frac{BOG_{reliq}}{BOG_{total}} \quad (11)$$

For the purpose of this analysis the R_{reliq} is 1 as gas losses are negligible.

For the DFDE, the following assertions and assumptions were made for this analysis [37, 38]:

- The $\eta_{electrical}$ is given as 91.3% with generator, transmission, transformer and converter losses all considered.

- It is assumed that the additional energy required to compress the BOG to supply the DFDE engine is approximately an addition of `2% of P_{ME} compared to the energy required to compress BOG to supply the boilers in the steam turbine system. Hence the addition of a factor of 0.02 in the equation in Table 4.

- The pilot fuel requirement is less than 1% of the energy requirement, thus not considered as part of this equation as the effect is negligible.

For the STPS, the following assertions and assumptions were made [37] [38];

- The SFC_{ME} takes into account the total energy input into the boilers for supply to the steam turbines, and as the electrical power is primarily supplied by the turbine generator which is integrated to these boiler supply systems, the P_{AE} is taken to be zero.

For the Gas Injection diesel engines, the following assumptions and assertions were made [37, 57]:

- P_{ME} is taken as $P_{ME} = 0.75 \times MCR$.

- The SFC_{ME} is taken as 160 g/KWh.

- The pilot fuel supply at 75% MCR is taken as 3.75% or 6g/KWh.

- The P_{AE} is ascertained by the formula:

$$P_{AE} = (0.025 \times MCR) + 250 + (COP_{comp} \times SFC_{ME} \times \frac{P_{ME}}{1000}) \tag{12}$$

With the extra power consumed being due to the compressor which is being used to supply high pressure gas derived from the boil off gas to the main engines. The COP_{comp} is the design power of the compressor and given to be 0.33KWh/kg.

- Auxiliary power is supplied by HFO fuelled, diesel generators.
- The EEDI formula is thus:

$$EEDI = \frac{P_{ME} \times \left(C_{f(pilot)} \times SFC_{ME(pilot)} + C_{f(gas)} \times SFC_{ME(gas)}\right) + \left(P_{AE} \times C_{f(AE)} \times SFC_{AE}\right)}{Capacity \ \times V_{ref}} \tag{13}$$

$$EEDI = \frac{P_{ME} \times (3.114 \cdot 6 + 2.75 \cdot 160) + (P_{AE} \cdot 3.114 \cdot 215)}{Capacity \times V_{ref}} \tag{14}$$

7.2.1 Including the Effect of Methane Slip

The DFDE, despite having good EEDI performance when compared to the other propulsion types, has a major disadvantage in its technology and that is methane slip. This term refers to unburned methane exhausted to atmosphere via a methane burning engine's exhaust along with the combustion products. As methane is a highly potent greenhouse gas, methane slip could in effect offset some or all of gains obtained from reducing the CO_2 emissions [58]. The impact of methane slip is of concern because methane has a global warming potential that is 20 to 25 times that of CO_2 over a 100 year period, while over a 20 year period the effect is 72 times greater [59], and as a consequence release of even very small volumes of NG would more than negate the entire reduction in greenhouse gas emissions gained from increased engine efficiency. Therefore, when calculating the effect of CO_2 emissions within indexes such as the EEDI, any methane emissions in addition to those of CO_2 need to be accounted for and quantified. This concern was highlighted by the delegation of Vanuatu at the MEPC 66/4/7 while proposing draft amendments to the *2012 Guidelines of the method of calculation of the attained EEDI for new ships*, to include LNGCs [37].

The methane slip issue is specific to four-stroke DFDEs i.e. not the two-stroke gas injection diesel engines, primarily because in the four-stroke DFDEs, unburned methane is trapped in clearances found in the combustion chamber, such as piston rings, anti-polishing ring, valve seats etc. within which the air/fuel ratio mixture is such that the gas would not completely combust during the firing (power) stroke but is then released with the exhaust gases during the exhaust stroke. On the other hand, the two-stroke gas injection engines operate with direct gas (fuel) injection as with conventional diesel engines, therefore no gas is present during the compression stroke or scavenging period, thereby reducing methane emissions to levels comparable with conventional liquid fuel such as HFO and MGO.

Some research has gone into reducing methane emissions with the research focusing on the following:

- use of pre-chamber technology;
- improving the combustion chamber technology (optimising injection timing, boosting pressure, increasing charge air temperature) [60];
- optimising the combustion space such that the combustion duration is extended to help achieve more complete combustion; and
- oxidising any unburnt methane using a catalyst.

Following these technological interventions, for most state of the art DFDE technologies, the methane emissions have been reduced to between 3 and 4 g/kWh compared to the between 8 to 15 g/kWh recorded for the DFDEs in the existing LNG fleet [30, 31].

The methane slip measured for the Wartsila 50DF engine which is fitted on majority of the DFDE engines is given as 8 g/kWh [31]. Given that the average SFC_{ME} of these engines is given as 175 g/kWh, the following calculations are used to determine the CO_2 equivalent emissions of the methane slip;

$$Methane\ Slip = 8\ g/kWh \tag{15}$$

$$SFC_{\boldsymbol{ME}} = 175\ g/kWh \tag{16}$$

$$Methane\ equivalent\ of\ SFC_{ME} = \frac{8}{175} = 4.57\% \tag{17}$$

If 1 Tonne of methane gas is burnt in the DFDE engines;

$$\begin{gathered} 1\ Tonne\ of\ CH_{4\ gas}\ fuel\ burnt\ in\ DFDE\ Engines \\ = 2.75\ Tonnes\ of\ CO_2\ emitted \end{gathered} \tag{18}$$

Using a 4.57% methane slip;

$$1\ Tonne\ of\ CH_4\ gas\ fuel = 2.624tCO_2 + 0.0457tCH_4 \tag{19}$$

Based on the 100 year life cycle of methane, the GWP is 21 times that of CO_2, then;

$$Total\ CO_{2equiv} = 2.624 + (0.0457 \times 21) = 3.5837tCO_{2equiv} \tag{20}$$

Based on the 20 year life cycle of methane, the GWP is 72 times that of CO_2, then;

$$Total\ CO_{2equiv} = 2.624 + (0.0457 \times 72) = 5.9144tCO_{2equiv} \tag{21}$$

Therefore, the carbon equivalent factor of one tonne of methane fuel is 3.5837t @ 100 year life cycle and 5.9144t @ 20 year life cycle

7.2.1.1 Methane Slip Calculation Method

The full summary of the method used for this research is given below:

1. Gather ship particulars for relevant dataset for STPS, DFDE and SSDR for ships delivered into service from 2000.
2. Calculate the EEDI baseline for the LNGCs listed in 1 above.
3. Estimate the EEDI values of the LNGCs in the dataset using equations in Table 3.
4. Calculate the approximated EEDI values of Gas-Injection Engines using current SSDR parameters.
5. Include the carbon equivalent factor that would result from methane emissions in the subsequent EEDI calculations.

6. Compare the EEDI values of the different technologies, against the baseline and each other.

7.2.2 Analysis Precision Comparison

The method chosen involves data inputs for 212 vessels, obtained from a variety of sources, with each source having various degrees of accuracy, therefore any errors in the data input source or in the method itself would be carried on to the results and reduce its overall veracity. To improve the confidence of the results obtained, as well as ensure that not only can the results be extrapolated, but also that its extrapolation/predictability limits be extendable; an experimental precision method using uncertainty and sensitivity analyses is carried out. Uncertainty analysis employs varied probabilistic descriptions of data inputs so as to derive probabilistic distribution of results while sensitivity analysis explores and quantifies the impact of errors from the input data on the results obtained [61]. Simply put, the uncertainty analyses quantify the uncertainty as well as the propagation of uncertainty, while the sensitivity analyses identify how these uncertainties or propagation of uncertainty affects both the input data and results obtained.

The first part of the uncertainty analysis would involve a comprehensive identification of all the sources of uncertainty that could contribute to the joint probability distribution of the input variable. In the case of this research, five main sources are identified;

1. Deadweight: - Different for each individual component. Source based on data from the Clarkson's World Fleet Register.

2. Specific Fuel Consumption: - Different for each specific propulsion system obtained from MEPC 65

3. Carbon Factor: - Based on the type of fuel used [1].

4. Propulsion Power: Different for each individual component. Source based on data from the Clarkson's World Fleet Register.

5. Speed: - Different for each individual component. Source based on data from the Clarkson's World Fleet Register.

Two secondary data inputs are identified:

1. P_{ME}: - Obtained by multiplying the propulsion power by a margin factor based on the propulsion class.

2. P_{AE}: - Obtained by multiplying the P_{ME} or the propulsion power by varied factors, based on propulsion class.

Table 32 shows the data inputs, sources of uncertainty and the uncertainty distribution factors associated with each individual parameter.

Table 32 – Uncertainty Sources and Uncertainty Distribution Factors

Data Input	Uncertainty Source	Uncertainty Distribution Factors
Deadweight	Database Errors	±5% [Database used compared against real values of vessels]
Specific Fuel Consumption	SFC quoted by the IMO is not an ideal value as vessels have individual SFCs	Steam: ±9% [SFC varies from IMO value of 285g/kWh to as low as 250g/kWh for newer steam designs] DFDE: ±6% [Varies from 165g/kWh to the IMO value of 175g/kwh] SSDR: ±9% [Range from 170g/kWh to 190g/kWh]
Carbon Factor	C_f are constant values although propulsion types	0%
Propulsion Power	Database Errors	±1%
Reference Speed	Database source error, calculation method error.	±8% [Error level of speed at PME compared to database speed]
PME	Calculation method error	STPS and SSDR: 0% DFDE: ±2% [Due to variation in maximum propulsion power]
PAE	BOR accuracy; R_{reliq} accuracy	BOR ranges from 0.1% to 0.15% for laden and 0.06% to 0.10% for ballast. R_{reliq} is always <1.

The uncertainty distribution factors were obtained by comparing the data sources- Clarksons [2], IMO MEPC [37] [38] with actual data sources from a sample group of actual vessel particulars data. The factors were based on the deviation between the actual vessel data as obtained from the vessel specific particulars [41] [42] [50], and the data obtained from the group database.

The different sources of uncertainty and associated distribution factors have been added to the analysis in order to identify and quantify any errors in the analytical method. The major error margin was seen in the specific fuel consumption figures of the steam propulsion plant, where the reheat plants had specific fuel consumptions lower than the average values of 285g/kWh but these units represented less than 3% of the group analysed and the impact on the final results was insignificant. Deadweight figures obtained from the database were consistent with individual cases investigated. The reference speed was compared against individual cases of individual service speeds and errors of up to 8% were seen in isolated cases but this was considered acceptable for this analysis as since these errors were for isolated instances they were deemed not to be of a magnitude that would overly affect the overall results within the data set. For the P_{ME}, the magnitude of the errors was negligible as the calculation methods used were consistent with IMO/MEPC mandated calculations process. For the P_{AE}, the boil off rate (BOR) ranged from 0.1% to 0.15% for laden transits and 0.06% - 0.1% for ballast transits. Under some loaded conditions the BOR peaked at 0.2%, but for the purposes of this calculation a BOR of 0.15% was used for all calculations as this was deemed a realistically representative average and is consistent with the IMO/MEPC mandated calculations system.

7.2.3 Results Discussion

7.2.3.1 EEDI Analysis Results

Table 33 summarizes the results from the EEDI analysis.

Table 33: LNGCs EEDI Compliance

Propulsion Type (Number)	Phase 0 Compliant	Phase 1 Compliant Sept 2015 – Dec 2019	Phase 2 Compliant 2 1 Jan 2020 – 31 Dec 2024	Phase 3 Compliant 1 Jan 2025 – Onwards
Diesel Electric (32)	32- (100%)	32- (100%)	31- (97%)	18- (56%)
Direct Drive Diesel (21)	8- (38%)	5- (24%)	0- (0%)	0- (0%)
Steam Turbine(159)	7- (6%)	1- (0.6%)	0- (0%)	0- (0%)
Total (212)	47 (23%)	38 (18%)	31 (15%)	18 (8%)

The current baseline equation seems a reasonable average of the current fleet with approximately 23% of the fleet within compliance of the baseline value during the phase 0 period as shown in Figure 51. However majority of the STPS vessels fail to achieve the baseline value.

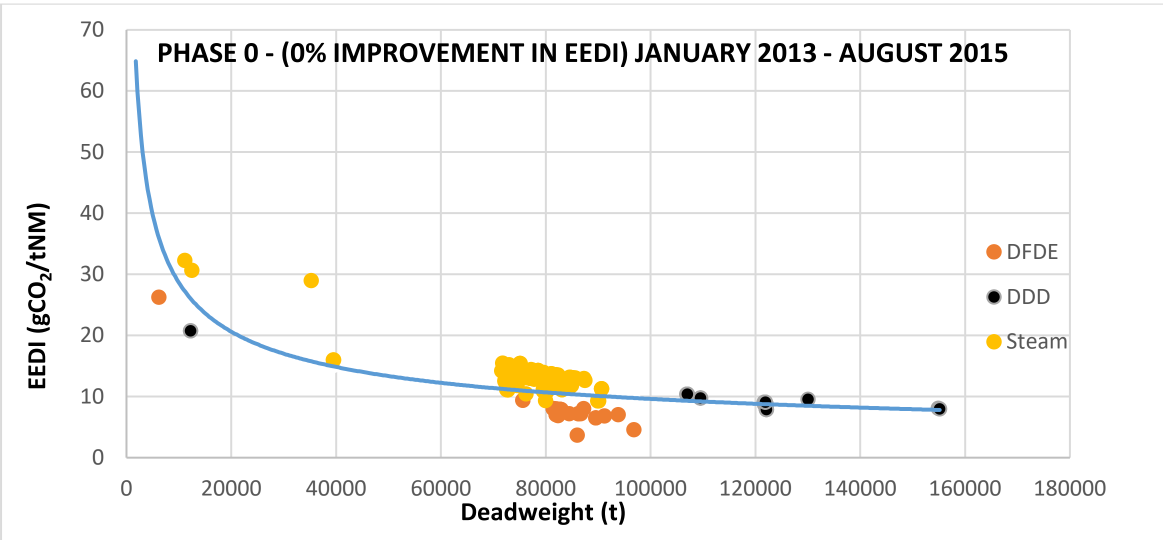


Figure 51- Phase 0 (0% Improvement in EED) January 2013 – August 2015

Phase 1 implementation sees almost all vessels employing steam power failing to achieve compliance against the requirement. 76% of the direct drive diesel systems are not within compliance of the baseline value. The LNGCs employing the DFDE systems are all in compliance of the baseline.

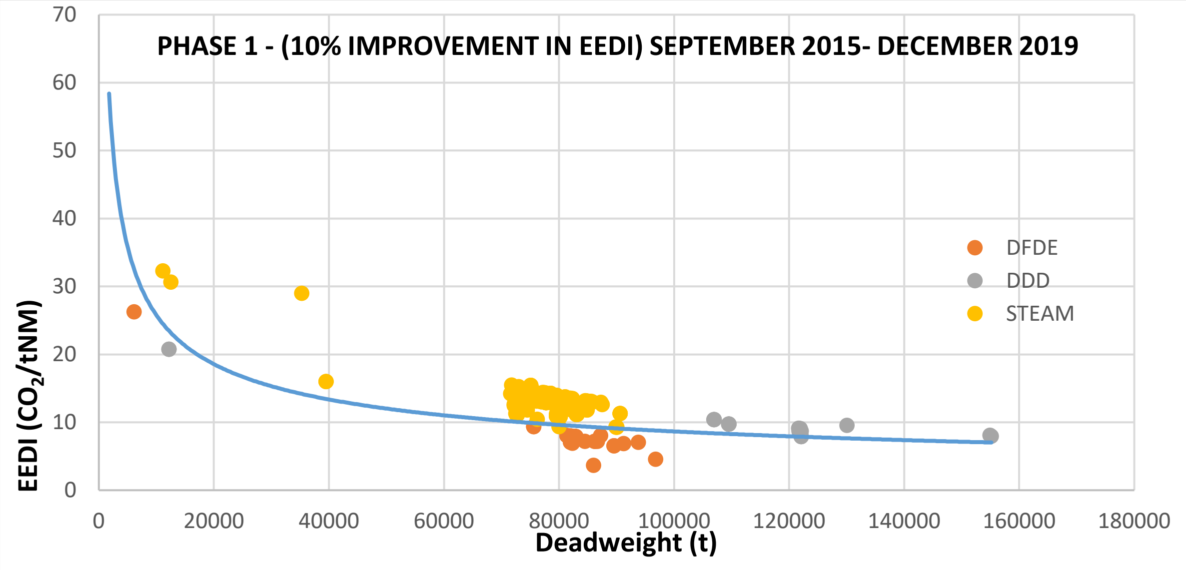


Figure 52- Phase 1 (10% Improvement in EEDI) September 2015 – December 2019

Phase 2 implementation sees all steam and direct drive propulsion systems not compliant baseline with 97% of DFDEs within compliance of the baseline.

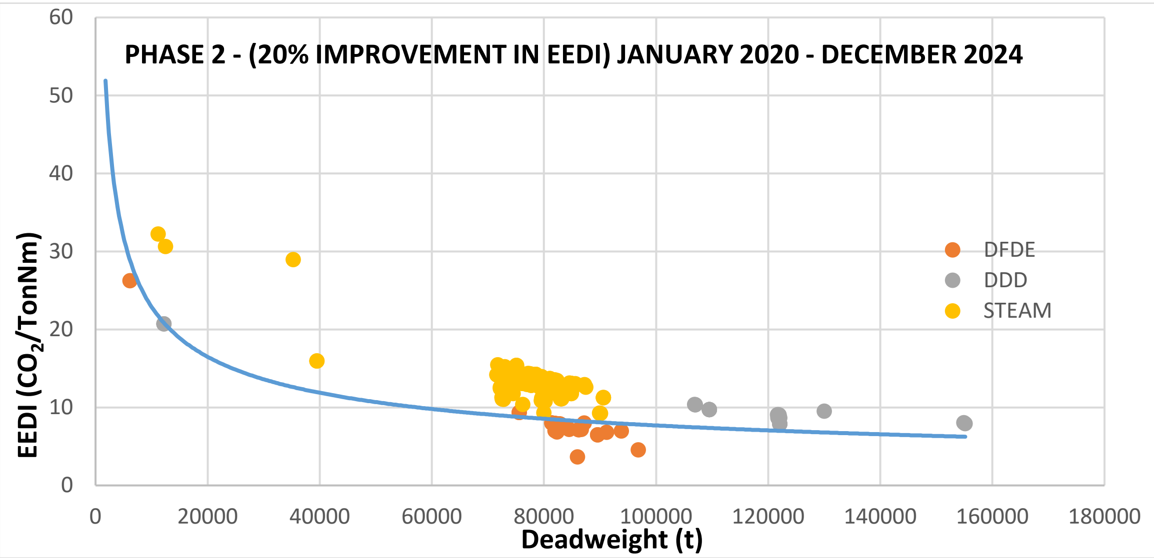


Figure 53- Phase 2 (20% Improvement in EEDI) January 2020 – December 2024

Phase 3 implementation shows 56% of current DFDEs still compliant and within the baseline requirement. With only 8% of all the total number vessels compliant within the baseline requirement

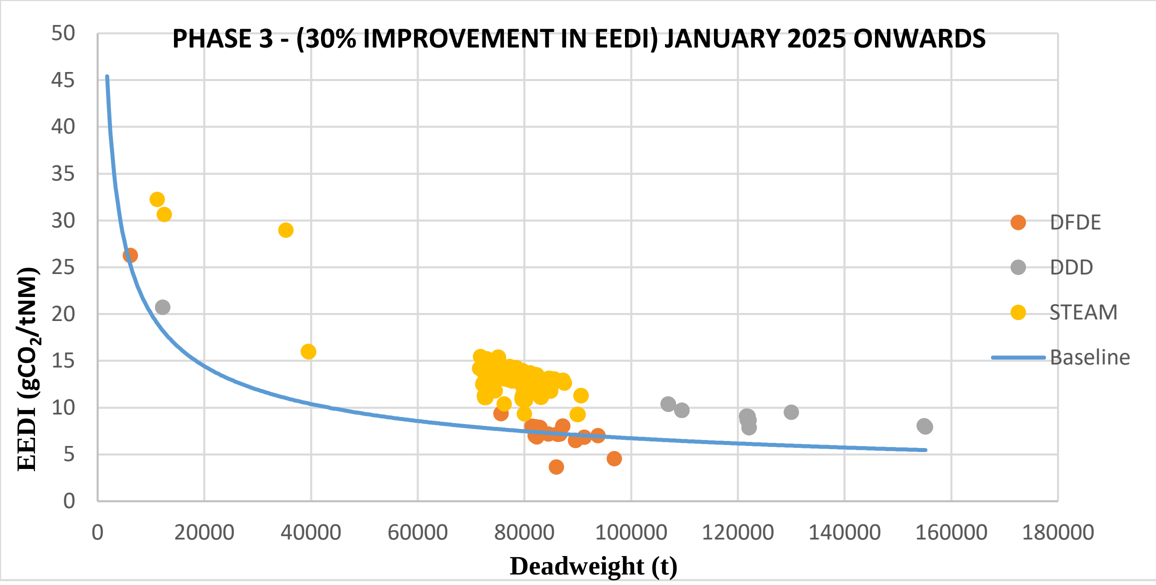


Figure 54- Phase 3 (30% Improvement) January 2025 onwards

Two major points are ascertained from this EEDI analysis of the current fleet:

1. In terms of energy efficiency in gCO_2/tNM, of the current fleet, with regards to the current baseline, the DFDE propulsion system offers the most efficient option with the steam propulsion offering the least. The direct drive diesel lies between.

2. The current baseline mandated by the IMO is aligned to the current fleet with about 23% of the current fleet group analysed being at or below the baseline value and so may be deemed compliant. However, this figure is collective of the different propulsion systems being used by LNGCs, and the more efficient DFDEs fall way below the baseline value. Considering that 72% of the future order book for LNGCs is diesel electric, the 30% improvement mandated by the IMO from 2025 onwards would have no effect on the DFDEs as current designs would meet this baseline. However, the current baseline may not incentivise improvements in DFDE technology for future designs of LNGCs.

7.2.3.2 Gas Injection Engines EEDI Results

Figure 55 is a repeat of Figure 54 but now includes the results of the ME-GI EEDI analysis.

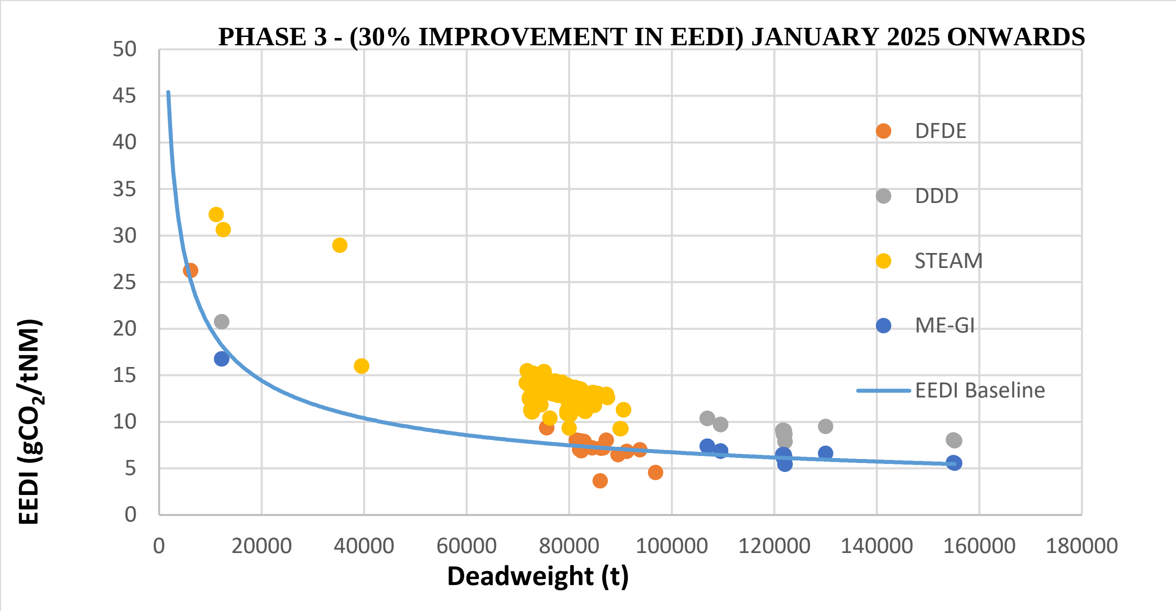


Figure 55- Phase 3 (30% Improvement) with Gas-Injection Diesel Engines.

The gas injection engines currently on order in 60% of future direct drive diesels LNGCs [4] offer up to 30% improvement in EEDI performance compared to the current (DDD) due to a reduction in SFC_{ME}, a reduction in the carbon factor, and the elimination of the power consumption by a re-liquefaction plant. These improvements in technology place DDDs on a par with current DFDEs to meet the EEDI regulation even beyond 2025.

7.2.3.3 Including the Effect of Methane Slip

When methane slip is considered and analysed as part of the EEDI analysis the superior efficiency of the DFDEs is compromised. When Considering a time horizon of 100 years, the carbon factor increases by 30% with the corresponding index value getting to around or just below the baseline value. When considering a 20 year time horizon, the carbon factor increases by 115% with the corresponding EEDI (modified) index value far above the baseline, even greater than the most inefficient steam propulsion systems.

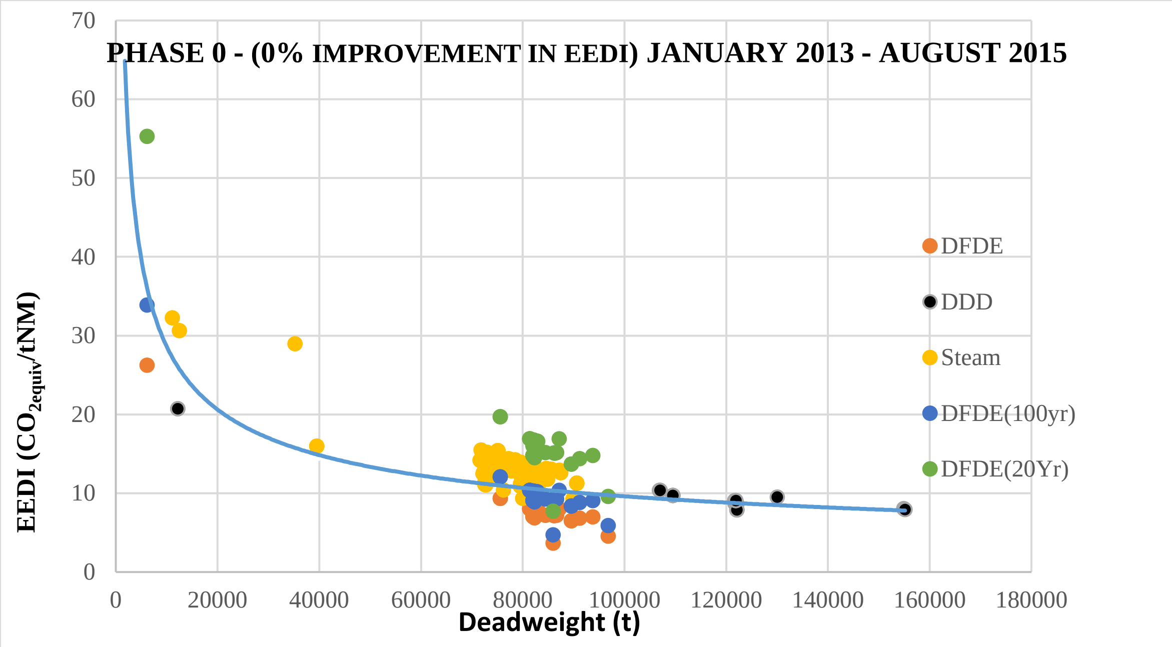


Figure 56- Phase 0 (0% Improvement) with CO_2 equivalent index value showing the 20Yr and 100Yr increase.

7.2.3.4 Impact of Methane Emissions

The impact of methane emissions on the global environment needs to be looked at in greater detail, especially in light of the significance of methane emissions from LNGCs with DFDE systems. Some [60][62] have attempted to downplay the impact of methane emissions from the DFDE by stating that the combination of methane slip emissions and CO_2 emissions are actually lower in terms of total CO_2 equivalents than HFO burning powering options. The EEDI analysis results presented here clearly contradicts this assertion, as the analysis has shown that the carbon factor effect of methane slip emission is potentially far worse than the carbon other LNG propulsion powering options when considering a 20 year plant in service life impact. The life time of methane is also shorter than that 20 year life cycle thus how its impact compares with that of CO_2, which remains in the atmosphere for a far longer time, is also worth considering. This section examines such points by considering the climate science of methane.

Methane emissions are released to the atmosphere through a number of sources, classed as natural and anthropogenic human activity related sources. The natural sources of methane include wetlands, termites and oceans accounting for 29% of emissions while anthropogenic sources which include fossil fuels, agriculture, landfill and the burning of biomass make up the other 71% of methane emissions. Figure 57 provides a breakdown.

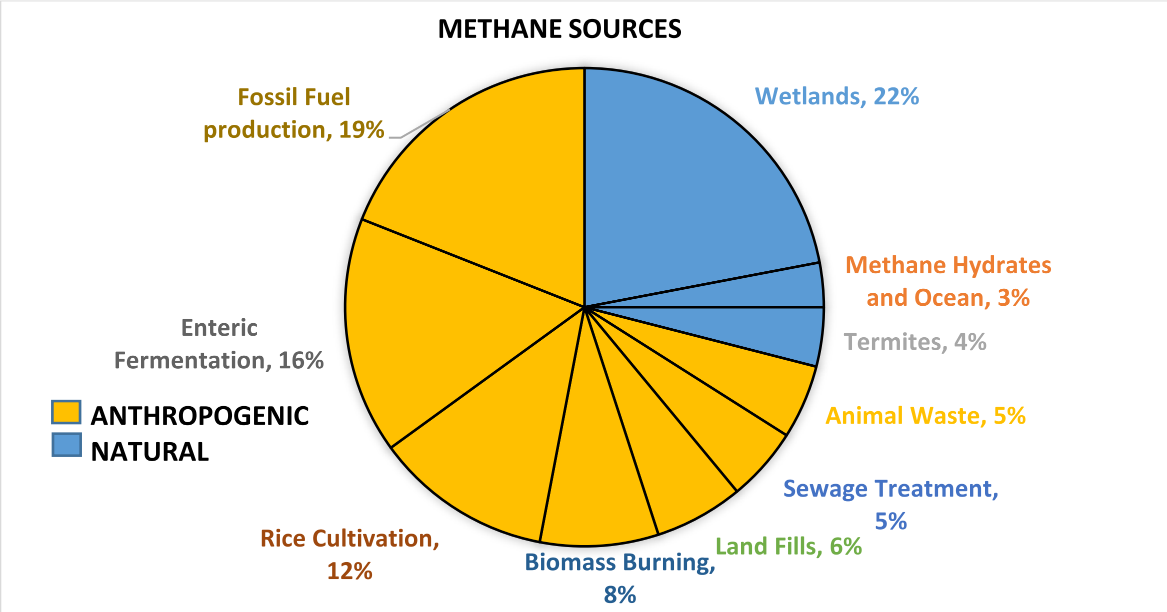


Figure 57: Methane Sources. Source: NASA

Methane is removed from the atmosphere by a range of chemical and biological processes which include tropospheric oxidation, stratospheric oxidation and uptake by soils with these processes converting the methane into less harmful products. The majority of methane is contained in the troposphere where tropospheric oxidation removes 87% of the total quantity of methane absorbed by the atmosphere. Above the troposphere is the stratosphere where 7% of the methane absorption takes place through stratospheric oxidation while the remaining 6% occurs due to soil uptake at the ground-atmosphere interphase, as bacteria present in the soil oxidizes methane thereby removing it from the atmosphere [63].

Because the methane removal processes is fixed, increases in methane emissions subsequently increase the atmospheric burden of methane, and it is estimated that the atmospheric concentration of methane has increased by a factor of 2.6 since pre-industrial times [64]. This is considerably higher than CO_2 emissions which are estimated to have increased by only 40% as seen in Table 34a. These increases in GHG concentrations increase the amount of energy being trapped within the atmosphere, and this extra energy termed "Radiative Forcing" is estimated to be 2.9 W/m^3 [64]. Of this 1.88 W/m3 is attributed to CO_2

making it the most significant greenhouse gas while 0.49 W/m^3 is attributed to methane. As can be seen, methane contributes 17% of the total radiative forcing, which far outweighs its proportion within the atmospheric concentration, as just 1,190 ppb contributes to the 17% of total radiative forcing compared to 115,400 ppb of CO_2 which contributes 64% of the total radiative forcing thus highlighting the potency of methane emissions.

Table 34a: Radiative Forcing of Selected Greenhouse Gases. Source: [63]

	CO_2	**CH_4**	**N_20**
Pre-Industrial Concentration (ca. 1750) ppb	280,000	700	270
Concentration in 2013 (ppb)	395,400	1,890	326
Relative Concentration 2013/1750	1.4	2.6	1.21
Radiative Forcing (W/m^2)	1.88	0.49	0.17
Atmospheric lifetime (years)	5-200	12	114

Radiative forcing of emitted gas decays exponentially as the gas is removed from the atmosphere over time. Because this rate of removal is dependent on the atmospheric lifetime of the emissions, it is therefore complex to ascertain the absolute measurable effect of one tonne of gas because the quantity varies with time. It is also impossible to combine the two variables of potency and lifetime into a single decisive figure that reflects both properties of the GHG. However, it is quite useful to represent the climatic influence of the different gases using one single parameter. It is for this reason, that the GWP was adopted. The GWP is the cumulative radiative forcing from the release of 1kg of a trace substance relative to that of 1kg of CO_2. The GWP is relative to the radiative forcing up to a certain time limit. Therefore, short-lived gases such as methane have higher GWP under short time horizons. Table 34 shows the GWP of a group of six greenhouse gases over three different timeframes [65] [66].

Table 34b: Global Warming Potential for the greenhouse gas basket. Source: [65] [66]

Gas	Lifetime (years)	GWP 20 Years	GWP 100 Years	GWP 500 Years
CO_2	5-200	1	1	1
CH_4	12	72	25	7.6
N_2O	114	289	298	153
HFCs	0.3-260	40-12000	12-14800	4-12200
PFCs	2600-50000	3900-8000	5700-11900	8900-18000
SF_6	3200	16300	22800	32600

The concept of different timeframes has led to debate with regards to applicability, as to which GWP should be used to compare the relative importance of methane emissions against those from CO_2 as was the case with the EEDI calculation. The Kyoto protocol uses the 100 year time horizon, while the Intergovernmental Panel on Climate Change (IPCC) frequently utilises the 100 year GWP figure, although it has made no policy recommendations on which GWP timescale to use [63]. Therefore, when attempting to measure the potency of greenhouse gas emissions in one set of units, the tonnes CO_2 equivalent (tCO_2e), the mass emitted is then multiplied by the 100 year GWP. One literature source [67] however highlights that the 20 year GWP is a more relevant figure, owing to the large effect that methane reductions can have over the next 20 years and the serious climate disruption expected within the next 20 years if no significant reduction of GHG is achieved. This is because gases with a short life span would be less likely to reach high atmospheric concentrations if their emission rates are constant since they are being removed from the atmosphere at a relatively high rate. If the emissions are reduced significantly, then the atmospheric concentration of these gases will reduce more rapidly than for a gas with a longer lifespan.

7.3 Case Studies Comparative Analysis

7.3.1 EEOI Results Analysis

The Energy Efficiency Operational Indicator (EEOI) is used in this paper to analyse vessel efficiency. The EEOI provides a representative value of the ship's efficiency over a given period or voyage and can be used to investigate trading patterns of the vessel. The EEOI describes transport efficiency expressed in the mass of CO_2 emitted per unit mass of cargo and nautical mile for a specified voyage. The formula is expressed below [48]:

$$EEOI = \frac{Fuel\ Consumption\ \times Carbon\ Factor}{Mass\ of\ Cargo\ \times Distance\ Covered} \tag{22}$$

The trading period of the DFDE LNG carrier investigated in this section is between 16 May 2012 and 26 May 2013 during which time the vessel delivered ten cargoes, all originating from Nigeria. Three of these cargoes were delivered to France, two cargoes were delivered to Brazil, Korea and Portugal and one cargo was delivered to Japan. The calculated EEOI for these voyages are shown in Table 21. All input values for the calculation were obtained from on-board vessel's records. These routes are typical trading routes for vessels loading LNG from Nigeria with the vessels operating at service speed for the majority of the time.

Table 21: Calculated EEOI for case DFDE Vessel

Voyage	**Distance (nm)**	**LNG Delivered(m^3)**	**LSDO Consumed(t)**	**LNG Consumed(t)**	**HFO Consumed(t)**	**EEOI (CO_2/t.nm)**
1- NG-FRA	7,960	140,683	18	2,666	44	29.7
2- NG-SKR	19,050	146,480	33.7	5314	103.3	23.9
3- NG-SKR	19,050	145,579	49.8	5100	61.2	23.0
4- NG-PGL	7,306	163,959	18.3	1635	21.1	17.0
5- NG-FRA	7,960	161,999	32.3	2173	30.7	21.2
6- NG-FRA	7,960	161,947	29.7	2233	22.7	21.6
7- NG-JPN	25,260	153,939	64	6425	50.8	20.5
8- NG-PGL	7,306	162,612	24	1833	20.8	19.3
9- NG-BRA	6,784	160,734	32.7	2992	16.6	34.0
10- NG-BRA	6,784	159,323	34.3	3408	40.7	39.3

The figures obtained for the DFDE LNG carrier can be compared against a steam LNG carrier which also traded over this period (the trading period actually covered is between 19 June 2012 and 26 May 2013). These vessels delivered six cargoes again all originating from Nigeria. Two cargoes each were delivered to Japan and Korea and one each to Spain and

India. The results of the EEOI for these voyages are shown in the Table 9. Again all data was obtained from on-board vessel's records [68].

Table 9: Calculated EEOI for comparative steam vessel. Source: [68]

Voyage	Distance (nm)	LNG Delivered(t)	LSDO Consumed(t)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/t.nm)
1- NG-JPN	22,559.3	129,683	12	4,694	2,676	32.37
2- NG-IND	16,242.8	128,887	33	4,649	637	31.74
3- NG-SPA	7,179.5	134,445	39.2	2,039	247	29.65
4- NG-JPN	22,406.1	128,848	4	4,861	2,505	32.65
5- NG-SKR	22,289.7	128,596	14	5,261	2,438	34.35
6- NG-SKR	22,249.6	128,480	7	5,304	2,568	35.26

As highlighted in page 119, it is important to note that whilst the voyages to Brazil are the shortest in terms of distance travelled, they return figures that indicate that they were the most inefficient voyages. However, on closer analysis, it was determined that the source of these inefficiencies was due to the relatively high amount of LNG utilized during operations that were linked to, but were not directly attributable to the voyage itself. These high values are due to the peculiarities of the discharge operations that were undertaken in Brazil as the discharge terminal is a Floating Storage and re-gasification unit (FSRU), and quite large amounts of natural gas are consumed during discharge operations for tank stabilisation purposes. Another issue of note is the disparity amongst the voyages to France, with one of the voyages returning an EEOI figure that is considerably higher (40%) than those for the other two voyages. This disparity was traced to the fact that on that particular voyage, the full cargo carrying capacity of the vessel was not utilized with the vessel only delivering 140,683m^3 of LNG compared to 161,999m^3 and 161,947m^3 delivered on the other two voyages.

In Table 9, when the values obtained are compared with values obtained by a steam LNG carrier operating similar routes, it is seen that the figures for the DFDE vessel are generally better. When the voyages to Japan are analysed, the EEOI of the steam vessel is 32.5 gCO_2/ton.NM which is 61% higher than the EEOI for the DFDE vessel. For the voyages to

Korea the EEOI of the steam vessel is 31.9 gCO_2/ton.NM which is 36% higher than a similar voyage to Korea by the DFDE LNG carrier. The voyages to Europe also have a similar trend with the average EEOI of the steam vessel being 29.65gCO_2/ton.NM which is still 64% higher the similar voyage to Europe by the DFDE vessels. The EEOI's values for voyages to Brazil are comparatively high for the DFDE vessels and comparable to steam vessels but as mentioned earlier this is due to the fact that they discharge to FSRUs. Overall, when comparing the EEOI values of the DFDE vessels to those of the steam vessels, the DFDE returns on average a 45% improvement in efficiency.

7.3.1.1 Including the impact of Methane Slip

The DFDE vessels, despite delivering better overall EEOI performance than vessels with steam plant propulsion systems, the engine technology itself allows methane slip, as detailed earlier. This term refers to unburned methane emitted into the exhaust ports of the diesel engine and hence into the atmosphere. A full description of methane slip as well as the estimation method has been detailed in Chapter 5. This calculation method highlighted that when accounting for CO_2 and Methane Slip; one tonne of NG is equivalent to 3.58t CO_2 using the 100-year NG life cycle and 5.91t CO_2 using the 20-year life cycle. Using these figures, it is possible to recalculate the EEOI values for the DFDE vessels in Table 19 to include the impact of methane slip as summarised in Table 35 reproduced below.

Table 35: Recalculated EEOI for case DFDE Vessel considering methane slip

Voyage	Distance (nm)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/t.nm)	EEOI- 100Yr (CO_{2eq}/t.nm)	EEOI- 25Yr (CO_{2eq}/t.nm)
1- NG-FRA	7,960	2,666	44	29.7	38.5	63.0
2- NG-SKR	19,050	5314	103.3	23.9	31.0	50.7
3- NG-SKR	19,050	5100	61.2	23.0	29.8	48.9
4- NG-PGL	7,306	1635	21.1	17.0	22.1	36.1
5- NG-FRA	7,960	2173	30.7	21.2	27.4	44.7
6- NG-FRA	7,960	2233	22.7	21.6	28.0	45.9
7- NG-JPN	25,260	6425	50.8	20.5	26.6	43.6
8- NG-PGL	7,306	1833	20.8	19.3	24.9	40.9
9- NG-BRA	6,784	2992	16.6	34.0	44.1	72.4
10- NG-BRA	6,784	3408	40.7	39.3	50.9	83.4

When methane slip is taken into account, it is seen that the performance of the DFDE vessel is not as less polluting as previously indicated: Comparing the EEOI results for the DFDE and STPS vessels' voyages to France, the EEOI calculated for the DFDE vessel is 38.5 gCO_2/ton.NM when considering a 100 year life cycle of methane. This value is 9.2% higher than the EEOI value of the steam vessel on a similar voyage distance to Spain. If the 25 year lifecycle of methane considered then the EEOI for the DFDE LNG carrier is doubled over that of the steam LNG carrier. For the voyages to Korea, when the 100 year methane cycle is considered the index values for the DFDE is 15% lower than the steam LNG carriers but when the 25 year life cycle is considered then the EEOI value for the DFDE is 58% greater.

It is clear by these comparisons that when methane slip is considered as part of the EEOI calculations, which are designed to measure the relative effectiveness of a ships performance efficiency with respect to the generation of atmospheric gases that contribute to global warming then the performance of the DFDE is generally worse than that of the STPS equivalent as shown in Tables 9 and Table 35. However general opinion is counter to this argument since methane slip is not accounted for within EEOI analysis. This clearly highlights the need for methane slip to be regulated if the overall goal of the IMO is to reduce the impact of anthropogenic shipping emissions on global warming.

7.3.2 Energy Use- Design vs Actual Comparative Analysis

Another analysis method looks at the actual efficiencies of the different technologies compared to the design efficiencies of the technologies themselves. In the case studies observed, the actual efficiencies of the vessel in real operations were observed and compared with the design efficiencies. The results are summarized below:

For Steam:

$$Efficiency = \frac{Useful\ Work}{Fuel\ in} \tag{23}$$

For The Design Values, The useful work is a sum of the Turbo Generator (TG) work and the Main Turbine (ME) work

$$Efficiency = \frac{TG\ Work + ME\ Work}{Fuel\ In} \tag{24}$$

$$Efficiency = \frac{6.1794 + 84.6}{302.72} \tag{25}$$

$$Effciency = 30\% \tag{26}$$

For the actual operating condition values, an average was taken across the values obtained during the case study duration. The Maximum efficiency obtained during the period being analysed is shown below:

$$Efficiency = \frac{5.67 + 77.05}{334.71} \tag{27}$$

$$Efficiency = 24.7\% \tag{28}$$

However the average efficiencies based on 90% MCR (the speed at which the vessel would normally be transiting) is shown below:

$$Efficiency = \frac{5.72 + 76.37}{341.15} \quad (29)$$

$$Efficiency = 24.06\% \quad (29)$$

For the DFDE Design Values, the useful work is defined as the sum of the propulsion shaft work (Shaft Work) and the Hotel load (Auxiliary Work) Work.

$$Efficiency = \frac{Shaft\ Work + Auxiliary\ Work}{Fuel\ In} \quad (30)$$

$$Efficiency = \frac{24000 + 3000}{62502} \quad (31)$$

$$Efficiency = 43.19\% \quad (32)$$

For the actual operating conditions values from the case study results, the figures were substituted in the equation below:

$$Efficiency = \frac{21144 + 3194}{65859} \quad (33)$$

$$Efficiency = 37\% \quad (34)$$

For the Direct Drive diesel, no field study had been conducted hence there was an inability to compare design values with actual figures.

The summary of the energy use design vs comparative analysis is shown in Table 36:

Table 36: Different Propulsion Technologies Design vs Actual Efficiencies

Propulsion Technology	**Design Efficiency**	**Actual Efficiency**
Steam Turbine Propulsion	30%	24%
Dual Fuel Diesel Electric	43%	37%

7.4 Comparative Analysis of Design Improvement Technologies

The original efficiencies of each of the propulsion options that were presented in Table 1 in the literature review are shown below.

Table 1: Comparing the Original Efficiencies of the different Propulsion Systems

Prime Mover	**STPS**		**DFDE**		**SSDR**	
Plant Efficiencies;	Fuel/BOG	100%	Fuel/BOG	100%	Fuel	100%
	Boilers	89%	DF Engines	48%	Engines	49%
	St'm Cycle	35%	Conversion	98%	Shafting	98%
	Shafting	99%	Motors	98%		
			Gearbox	98%		
			Shafting	99%		
	Propulsion Eff'cy: 30%		Propulsion Eff'cy: 43%		Propulsion Eff'cy: 48%	
	Fuel BOG	100%	Fuel/BOG	100%	Fuel	100%
	Boilers	89%	DF Engines	48%	Aux Engines	45%
	St'm Cycle	30%	Alternators	97%	Conversion	96%
	Conversion	96%				
	Electric Pwr Eff'y: 26%		Electric Pwr Eff'y: 47%		Electric Pwr Eff'y: 43%	

As intended, the different design improvement technologies will lead to increases in the overall efficiencies of the different plant technologies indicated in the Table 37:

Table 37: Recalculated Efficiency increases due to design Improvement Technologies

Propulsion Type	Design Improvement Technology	Efficiency Improvement	New Efficiency
Steam	Based on the design configurations in Trial 1: Condenser Pressure, Uptake Temperature increase and Air heater Optimisation	2.2%	**33.25%**
	Based on the design configurations in Trial 2: Condenser Pressure, Uptake Temperature increase and Air heater Optimisation	5.36%	**36.43%**
DFDE	Use of a Waste Heat Recovery System on the Dual Fuel Diesel Engine	3.4%	**48%**
Direct Drive Diesel	Design improvements effectively do not increase the thermal efficiency of the system, but improves the energy use of the technology.	0%	**48%**

The improvements in efficiency are then reflected Table 37 above. The updated efficiencies are shown in Table 38:

Table 38: Comparing the Updated Efficiencies of the different propulsion systems

Prime Mover	**STPS**		**DFDE**		**SSDR/DDD**	
Plant Efficiencies;	Fuel/BOG	100%	Fuel/BOG	100%	Fuel	100%
	Boilers	92%	DF Engines	51.4%	Engines	49%
	St'm Cycle	40%	Conversion	99%	Shafting	98%
	Shafting	99%	Motors	99%		
			Gearbox	98%		
			Shafting	99%		
	Propulsion Eff'cy: 36%		Propulsion Eff'cy: 49%		Propulsion Eff'cy: 48%	
	Fuel BOG	100%	Fuel/BOG	100%	Fuel	100%
	Boilers	92%	DF Engines	51.4%	Aux Engines	45%
	St'm Cycle	30%	Alternators	97%	Conversion	96%
	Conversion	96%				
	Electric Pwr Eff'y: 27%		Electric Pwr Eff'y: 49%		Electric Pwr Eff'y: 43%	

As seen from the comparative analysis in Table 38 the DFDE technology offers the highest design energy efficiency at 49% propulsion efficiency with the DDD only 1% lower than the DFDE. Considering the acceptable errors and margins, the DDD can be considered identical to the DFDE in propulsion efficiency. The modern STPS vessels are a distant third.

7.5 Comparative Analysis Summary

The previous three chapters looked at the different propulsion technologies of LNGCs in terms of EEDI, Operational Characteristics involving case studies and design improvement technologies applied to such carriers. This chapter however carried out a comparative analysis of the different propulsion technologies with regards to the aforementioned factors and areas of consideration.

The comparative analysis of the EEDI revealed four key points:

- As far as current designs go, the DFDE offers the lowest emission factor of the three propulsion systems in terms of gCO_2/tNM, with the steam propulsion system having the highest emission factor.
- As far as upcoming designs go, the new gas injection diesel engines offer a 30% improvement in EEDI values when compared to previous DDDs due to reduction in SFC_{ME}, reduction in the carbon factor, and the elimination of the power requirements of a re-liquefaction plant. Such improvements in technology places DDD on a par with current DFDEs to satisfy the EEDI regulation from 2025 onwards.
- When methane slip is considered and analysed the efficiency gains of the DFDEs are greatly reduced. When using a time horizon of 100 years, the carbon factor increases by 30% with the corresponding index value falling around or just below the baseline value, while with a 25 year time horizon the carbon factor increases by up to 115% with the corresponding index value being higher than the baseline and even higher than the most inefficient steam propulsion systems.
- The current baseline mandated by the IMO is a fair representation of the current fleet with about 23% of the current fleet group analysed satisfying or even exceeding the baseline for IMO compliance. However, this However, this figure is collective of the different propulsion systems being used by LNGCs, and the more efficient DFDEs fall way below the baseline value. Taking into consideration 95% of the future order

book for LNGCs are either diesel electric or the upgraded DDDs, the 30% improvement mandated by the IMO from 2025 onwards would have no effect on the LNG Fleet as current designs would meet this baseline. Therefore, the current baseline in itself may not instigate improvements in technology for future designs of LNGCs

A comparative analysis of the case studies on the Steam vessel and the DFDE vessel was carried out. Both case studies covered a 12 month duration including voyages from Africa to Europe; Asia; and South America. The results indicated, that in terms of EEOI, the DFDE vessel performed on average 45% better than the steam vessel for the voyages analysed over the periods. However, when methane slip was factored in because of its detrimental impact as a greenhouse gas, the results were significantly different. Based the 100 Year life cycle of methane, the DFDE vessel performed an average of 9% less emission efficiently than the case study steam vessel, while based on the 25 Year life cycle of methane; the DFDE vessel performed 40% less emission efficiently than the steam vessel. The results show the impact of methane emissions on the performance in terms of CO_2 equivalents and the significant impact this can have on the emissions performance of the vessel.

Also seen during the analysis of the case studies, was an obvious disparity between the design efficiency quoted by the manufacturers and the actual sea going efficiency. For DFDE technology, the Design Efficiency calculated based on data from sea trials and vessel builders is 43%. However, during the 12 month period being analysed the efficiency based on actual operating conditions is about 37% percent. These efficiencies were measured throughout the study period in the case study. It was a similar situation for the steam propulsion system, where design efficiencies obtained from the vessel designers showed an efficiency of 30%. In this case during the actual operation of the vessel, the maximum efficiency recorded was within the 24% range.

The final part of the comparative analysis compared the efficiency increases through technological improvement applied to the different LNGC propulsion designs. The results were as follows:

- For the steam design, the original efficiency from the designer is 30%. However, with the use of validated models used for design improvements combined with newer reheat designs, efficiency was improved to about 37%.
- For the DFDE design the original efficiency from the designer is 43%. However, the use of the WHRS model, combined with improvement designs to the converters/electric motors improved the efficiency to 49%.

For the direct drive designs, no study was carried out on it due to the unavailability of relevant and applicable data as the design is novel.

8.

CONTRIBUTION TO KNOWLEDGE AND IMPLICATIONS FOR THE FUTURE

8.1 Introduction

The objective of this research is to make a contribution to knowledge with regards to improving the efficiency of LNG Carriers with the benefit of reducing anthropogenic emissions as well as operating costs. The research covered three key areas:

1) Analytical studies utilising the EEDI,
2) Case studies based on actual vessel operations
3) Design improvements to available technology.

The combination of the three above approaches is expected to achieve the afore mentioned objective, as the EEDI Analytical Study not only compares the different designs based on Design Efficiency, it also mathematically predicts the impact new regulation will have on the design of future carriers. The second approach involving case studies examined the operational efficiency of LNGCs identifying specific peculiarities specific to the different LNGC technologies. The final approach proposed technological improvements required to reduce fuel consumption, emissions and costs. In each of these approaches, contributions to the knowledge are identifiable and they are summarized below;

From the overall research study, one noticeable finding is highlighted below:

- LNGC design technology is in constant flux

For the Analytical Study using the EEDI two contributions have been identified:

- EEDI is not a suitable benchmark to stimulate improvements of LNGCs
- Methane slip is a real issue

For the Case studies four key contributions were identified:

- Operational profiles differ markedly from design profiles

- Sea trials for LNG Carriers are outdated
- Discharging to FSRUs contribute to considerable increases in the emission profile
- Inefficient operations are at times necessary for safe operation

From the Design improvements approach, two key contributions:

- Steam Turbine Propulsion will not be able to attain the efficiency levels achieved with the diesel/diesel-electric technology
- DFDE propulsion is the propulsion of choice with regards to cost savings

Each contribution is highlighted in the subsequent sub-chapters below.

8.2 Background: LNG Maritime Transportation is a volatile constantly changing matrix

Over the course of this research, analysis has shown the changing face of technology within the LNGC industry. In 2014, analysis of the Fleet and Order book showed that in the current fleet at the time 70% of the vessels had STPS, while both the DFDE and DDD designs each composed 13% of the then current fleet. The 2014 Orderbook had DFDE as the Majority of future orders (80%) with STPS and DDD at 11% and 9% respectively. In 2014 the DDD designs utilized a slow speed diesel engine utilizing liquid fuel with a re-liquefaction plant installed to handle BOG. By 2017, the outlook had completely changed, with DDDs no longer requiring a re-liquefaction plant with the introduction of high pressure gas injection designs. Even the high pressure gas designs are already being replaced by Low pressure designs [14]. The higher thermal efficiency of the DDD designs meant they became an attractive choice going forward and this is evidenced by the orderbook in 2017, as the direct drive diesels now dominate the orderbook [6] with 56% of orders of LNGCs having this design. DFDE future orders have dropped to 39%.

An analysis of the future orderbook also highlights the emerging propulsion technologies. One of which is the combined system or Steam Turbine and Gas Engines (STaGE), a hybrid propulsion system combining a high efficiency steam turbine, a dual-fuel diesel engine and electric motor being developed by MHI. If the results from this study on DFDES are also considered the expectation is that future designs will also be altered towards the DFDE due the flexibility offered by multiple prime movers. Nevertheless, if historical precedents are considered, it will be prudent to suggest that the direction of future travel is uncertain due to rapid developments in propulsion technologies.

During the Five years that have elapsed while this research was carried out, we have seen a total of eight different designs and design variants currently in service or on the orderbook. The conventional steam turbine design (STPS) (1) was modified and gave rise to the reheat turbine system (2). The more recent STaGE propulsion system (3) has now begun to gain interest and may come to prominence For the Direct Drive Systems it started with the (4) Slow Speed Diesel with reliquefaction Plant, which then evolved to the (5) ME-GI engines, with future orders utilising the (6) low pressure designs. The DFDE systems have had the (7) conventional DFDE, as well as the (8) waste heat recovery optimised design. As seen above, not only do three different technologies exist, these systems are also further divided into smaller sub-systems. The different technologies are summarized in Table [39] below:

Table 39: Overview of the different Subgroups of LNGC Propulsion Technologies

Steam Propulsion	**Direct Drive Propulsion**	**DFDE**
Conventional Steam Turbine (1) Reheat Steam Turbine (2) Combined (STaGE) (3)	SSDR (4) ME-GI (5) Low Pressure Gas Designs (6)	Conventional DFDE (7) DFDE with Optimised WHRS (8)

This research not only highlighted the different designs, but it also carried out analytical studies, case studies as well as modelling simulation and experimental analysis in order to compare and select the ideal propulsion of choice.

8.3 Contribution 1: EEDI Not Suitable to Stimulate Design Improvements:

8.3.1 Background

The essence of the IMO EEDI regulation is to stimulate more energy efficient and less polluting equipment and engines for ship propulsion systems. It achieves this by specifying minimum energy level efficiency per capacity mile, and then this level is tightened incrementally every five years. This will then ensure that the EEDI regulation will stimulate continued innovation and technical developments of the different components influencing the vessel efficiency from its design phase. This was implemented for LNGCs in 2015, and the EEDI was utilised for an analytical study of the different propulsion systems.

8.3.2 Study Findings

The study found that the EEDI Baseline adopted for LNG carriers was largely inadequate in stimulating more efficient designs essentially not achieving any of its stated objectives. This was because the EEDI is applicable to the different designs, and although current EEDI benchmark is a mean value of current fleet however, due to the large scatter, the more efficient designs (DFDE and Gas Injections DDDs) fall way below the base line while the less efficient steam designs are way above the baseline value. This essentially means that even the 30% improvement in efficiency in designs required by the IMO will not be achieved, especially as new designs are of either the DFDE or Gas Injection DDDs.

8.3.3 Significance of Findings

The finding indicating the objective of the EEDI not achieving the reduction of anthropogenic CO_2 emissions is significant in its own right. As the EEDI is a regulation, and compliance is mandatory, having an inadequate benchmark is an opportunity missed for the 30% improvement in energy efficiency as existing and future designs will be compliant with the upcoming incremental changes in EEDI regulations. However, no innovations or technical improvements influencing vessel efficiency will be carried out as it is not required. A singularity of approach is required where the baseline is dependent on technology and not on the current fleet.

8.3.4. Impact

If a singular approach is adopted, i.e. where each of the different technologies has baselines specified for each of them, then each technology will be mandated to create better systems as time progresses, essentially achieving the objectives mandated for the EEDI. This is particularly critical as it has been seen in the previous sub-chapter, there are currently different technologies in the LNGC industry so a "one size fits" all benchmark approach is inadequate. Commercial pressures often ensure ship owners will migrate towards more efficient technologies in any case, therefore if a singular approach is adopted, it will ensure that these efficient technologies are progressively improved thereby achieving the desired effect of reducing anthropogenic CO_2 emissions.

8.4 Contribution 2: Methane Slip is a Problem

8.4.1 Background

A peculiar problem with regards to gas burning engines is the tendency to emit unburnt methane through its exhaust ports to the atmosphere. This is particularly noteworthy as methane is a potent greenhouse gas, having 20 to 25 times the global warming potential of CO_2 over a 100 year interval, while over a 20 year interval the effect is 72 times. This is peculiar to the DFDE due to its particular engine operational technology. The methane issue is noteworthy as release of even very small volumes of methane will offset the entire added benefit derived from the increased engine efficiency. This analytical study quantified the impact of this methane slip on EEDI.

8.4.2 Study Findings

The study found that when methane slip was considered as part of the calculations in EEDI in terms of gCO_2/tNM, the efficiency gains of the DFDE are completely eroded, because when using a time horizon of 100 years, the carbon factor increases by 30% with the EEDI figure increasing in a corresponding manner. When a 20 year time horizon was considered the carbon factor increases by 115% with the EEDI measure much worse than the less fuel efficient steam turbine propulsion systems. Even the case study on DFDE vessels showed that EEOI was 58% worse than a corresponding steam vessel on similar routes when methane slip is considered. This methane slip effectively made the DFDE the most polluting of the propulsion options.

8.4.3 Significance of Findings

The EEDI and EEOI are effectively the efficiency benchmarks of the entire shipping industry with the EEDI specifying design efficiency and the EEOI specifying operational efficiency. Without considering methane slip, the research has shown the DFDE being the most efficient in terms of the EEDI and EEOI, in terms of reduced CO_2 emissions, when in fact there are the worst in terms of greenhouse gas effect in CO_2 equivalents. This is particularly noteworthy, as both the EEDI and EEOI are now regulations and if the methane slip issue is inadequately captured, it might actually be making the overall pollution situation worse while giving a positive outlook.

8.4.4. Impact

This research introduced a formula for calculating CO_2 equivalents for both EEOI and EEDI, to ensure the true picture for LNG carriers is adequately captured so that things are not inadvertently made worse. The impact of this stretches beyond LNGCs, as the global sulphur cap by 2020 introduced by the IMO, has driven a rapid rise in LNG Propelled vessels, most of which are adopting the DFDE technology. Therefore, there exists the potential to increase pollution if the effect of methane slip is not adequately captured.

8.5 Contribution 3: Operational Profile of vessels differ widely from Design Profile

8.5.1 Background

One key objective of this research was to carry out a comparative analysis of the design characteristics of the vessels, as provided by the vessel manufacturers and the actual operating data of the respective vessels. This is because design data is usually the benchmark which a vessel will continually be referred. The design data is also used by regulators when creating a benchmark for new and upcoming regulations relating to emissions and efficiency. This research carried out field studies over a range of conditions including periods on-board as well as in vessel construction shipyards gathering data and carried out a comparative analysis with manufacturer’s data and operational information.

8.5.2 Study Findings

The study showed considerable differences between the design and operational data. For the STPS the design efficiency was 30%, whereas in actual operation, of steam vessels, the efficiency never exceeded 24% at service speed conditions, a net 6% reduction and a comparative reduction in efficiency of 20% against the design measure. This value was consistent among the different voyages for the STPS vessel analysed. For the DFDE, the design efficiency is 43%, while in actual operation the efficiency never exceeded 37% at service speed conditions, a net 6% reduction and a comparative reduction in efficiency of 14% against the design measure. This magnitude in reduction was consistent across the four vessels analysed during the case studies.

8.5.3 Significance of Findings

This research highlighted a factor to which operational conditions can be estimated from design data, as it shows an average of operational efficiencies for STPS and DFDE vessels, figures that had never been previously found in any published literature. This research was the first in quantifying the differences that exist within design and operating efficiencies as it relates to LNG Carriers, the significance of which is particularly noteworthy when estimating the efficiency and emissions of DFDE and STPS vessels while in service.

8.5.4 Impact

The impact gained through having the ability to estimate the actual operating efficiency of LNGCs is considerable, as previous studies have largely relied on data supplied by manufacturers. The results from this study can be used by future researchers as well as regulatory bodies, such as the IMO and ECA, in formulating legislation, especially as results from the case studies have indicated that performance that replicates manufacturers' data is difficult to achieve in the real world. This will help in ensuring that new regulation is kept within proper context, and therefore relevant in achieving its required objectives.

8.6 Contribution 4: Sea Trials of LNGCs are outdated

8.6.1 Background

This research necessitated the requirement to carry out field study in shipyards during construction of LNGCs and associated sea trials and link with actual vessel operations. This was done so as to identify gaps between the design parameters and conditions when compared to actual vessel operating parameters and conditions which were being covered under another case study. The field research was carried out on a DFDE vessel being constructed at the sea trial stage with comparison made with a DFDE vessel during actual trade. The sea trial would establish the standards that will be used as the benchmark from which the vessel would be measured in terms of efficiency and emissions through its operating lifetime.

8.6.2 Study Findings

The study showed that the sea trial conditions bore little comparison with and were unrelated to the actual operating conditions. While the sea trials were conducted using HFO, throughout the operating lifetime of the vessel it uses BOG fuel 90% of the time it is in operation, reverting to HFO when in port or while undergoing maintenance. Furthermore, the EEDI calculation for LNGCs is based on BOG as fuel, whereas the sea trials for the vessels where this verification is to be carried out is based on HFO as the fuel. The study also recommended that future sea trials for all DFDE vessels be carried out using BOG as fuel to accurately capture the vessel characteristics.

8.6.3 Significance of Findings

First, in order to effectively benchmark the operation of an LNGC vessel over its lifetime, the conditions under which the sea trials are carried out should be quite similar to the normal operating conditions it will experience during its lifetime. The notion that HFO is the primary fuel for these vessels is inaccurate based on three key factors: 1) The industry practice is to utilize BOG due to the associated risks associated with bunkering HFO 2) The move towards cleaner fuels, means that there is a general trend towards natural gas as it is the cleanest fossil fuel. 3) The EEDI benchmark for LNGCs is calculated using natural gas as a fuel. The three points above highlight the criticality of having sea trials conducted using BOG and not

HFO as the results would be more relevant to the low carbon based emissions economy being adopted.

8.6.4 Impact

The impact of using BOG for sea trials moves beyond just LNGCs. The global sulphur cap as well as tightening emission regulations have meant there is a move towards gas burning propulsion technologies in the non-LNGC sectors of the shipping industry. Recent studies [70] [71] have shown that the use of LNG as a marine fuel is likely to rise by as much as 2000% in the period from 2020 to 2030 with the upcoming IMO sulphur cap coming into force in 2020. Recent developments in the shipyards are showing that this is very likely as orders are increasing for LNG propelled vessels. Therefore these recommendations for these sea trials will move beyond just the LNGCs industry.

8.7 Contribution 5: Discharging to FSRUs is very inefficient compared to Terminals

8.7.1 Background

Field studies were carried out on the two dominant LNGC propulsion Technologies: Steam and DFDE to examine particular peculiarities of these technologies in their normal operational setting. One such finding relates to when these vessels discharge to mobile terminals commonly termed Floating Gasification and Storage Units (FSRU). FSRUs have become increasingly popular due to the rising demand for LNG, insufficient LNG terminal Capacities, lower cost and commercial flexibility.

8.7.2 Study Findings

The study covered discharge operations to FSRUs on both DFDE and Steam vessels as part of its analysis on operational efficiency of LNGCs. The findings indicated that discharge to FSRUs showed a drop in operational efficiency of between 60% and 90% due to insufficient gas handling capacities at the FSRUs, which then resulted in the vessels consuming significant amounts of BOG to maintain the gas pressure within acceptable/safe limits. The results were consistent across both the DFDE and the Steam Propulsion systems,

8.7.3 Significance of Findings

The significance of this finding is best highlighted by the incredible growth rate of the FSRU market. A recent report by the International Group of Liquefied Natural Gas Importers [72] estimated that close to 50 FSRUs could be in operation by 2025, with the capacity to import close to 200 million metric tonnes per annum (mtpa)- which is essentially 60% of the worlds LNG production in 2016. To put this in context, 60% of the current world LNG transportation will be between 60% and 90% less efficient by 2025 due to the increasing use of FSRUs to meet energy demands. This directly translates to between 60% and 90% increase in CO_2 emissions in 2025.

8.7.4 Impact

The increase in CO_2 emissions during a period where regulatory bodies such as the IMO are providing legislation to reduce emissions will have a significant impact on emission reduction targets. The IMO has specified a reduction target of between 10% and 50% to reduce CO_2 emissions from vessels in operation [73], however with the current FSRU growth rate the consequent increase in CO_2 emissions would render the reduction targets unachievable, and even result in increasing the CO_2 emissions from LNGCs in operation.

8.8 Contribution 6: Inefficient Operation is necessary at times for safe operations

8.8.1 Background

A component of this research study was to identify areas where efficiency can be improved, both in the design and operations of LNGCs. In the operations of LNGCs, key areas of inefficiencies have been identified following the case studies carried out, and solutions proposed in order to close these gaps identified. However, some particular cases of inefficient operations have been deemed necessary to ensure the safety of the vessels. These areas were identified in both the case study of the steam and DFDE vessels.

8.8.2 Study Findings

When the case study for the steam vessel was carried out, it was observed that the vessel was utilising significantly more energy when the main turbine was shut down than was required. It was seen that for the loading, discharging, and OPL operations, the steam vessel used 100%, 38%, and 260% extra energy respectively. The extra energy is usually in the form of dump steam. In the case of the DFDE vessel, the use of the WHRS TG was shut down in non-full load conditions due to the fact that the power capacity of the TG was lower at reduced vessel load and hence considered unstable or unsuitable to be synchronised with the much larger loads of the Dual Fuel Diesel generators. This essentially meant that these vessels were utilising 6% more fuel on these conditions.

8.8.3 Significance of Findings

This finding tends to highlight the disparity that exists between the "design operations", and the "actual operation" of LNGC vessels. It is necessary to integrate these specific operational requirements into the design of the vessels so as to mitigate energy wastage and optimise the energy efficiencies of these vessels. This research highlighted the operational steps required to achieve the design operation, while also highlighting areas where these steps have been taken, for example, shutting down one boiler during loading, discharging and OPL operations on steam vessels, and utilising the TG on lower speeds on the DFDE. However, while these steps are effective in achieving the "design operation", they are not sufficient from a safety standpoint.

8.8.4 Impact

As far as the operations of LNGCs go, safety remains a priority of ship operators. Therefore the "design operations" of these vessels has been seen to be secondary when operational safety has been prioritized. This highlights the requirements to design a more robust system which minimizes the risks associated with design operation of these vessels to enable the vessel to achieve the energy efficiency required.

8.9 Contribution 7: Steam Turbine Propulsion will not be able to Catch Up

8.9.1 Background

A key objective of this research was to design improvements on the propulsion technologies available to LNGCs so as to improve the energy efficiency and reduce emissions. Steam Propulsion, being the dominant propulsion of choice was selected, and comprehensive models were created and validated so as to simulate the actual operation of these vessels.

These validated models were then used to design improvements on the actual configuration of the vessel so as to achieve increased energy efficiency. This was then compared with the best case scenarios from the other propulsion options.

8.9.2 Study Findings

During the trial run of the scenarios for the STPS; improvements in efficiency of between 7% and 17% were recorded, resulting in an improved steam cycle efficiency of 33.5% - 36.4%. When these results are added to other technological improvements developed by the propulsion manufacturers: Kawasaki and Mitsubishi, the maximum efficiency obtainable rarely exceeds 39%. This figure when compared with the updated efficiencies of the DFDE at 48% and that of the ME-GI direct drive designs at 48%, shows quite a large gap and radical improvements in technology will be required to bridge this gap.

8.9.3 Significance of Findings

This finding scientifically agrees with the commercial presumption that steam turbine propulsion is incapable of meeting modern standards on efficiency and emissions. The two other options DFDE and ME-GI are considerably ahead in terms of energy efficiency. A similar set of results was obtained from the EEDI analysis which showed the gap between the different designs with steam propulsion some way behind the other two options. Even the EEOI analysis of actual voyages displayed a similar set of results.

8.9.4 Impact

The impact is less drastic as commercial pressures have ensured ship owners have moved away from the steam turbine propulsion as evidenced by the order-book. The financial benefits the other two options present are considerable when the OPEX is considered over the operating lifetime of the vessel. However, as indicated in the research, if methane slip is considered, the steam system actually presents a less polluting option in terms of CO_2 equivalents. Nevertheless, it is highly unlikely this will trigger a propulsion shift in the industry as methane emissions are not currently being regulated.

8.10 Contribution 8: DFDE Propulsions appears the Optimised Propulsion of Choice for future designs.

8.10.1 Background

This study carried out different facets of research in attempting to ascertain the ideal propulsion of choice for LNGCs. A literature review was carried out, followed by an analytical study using the EEDI, then case studies of actual operations, followed by modelling and simulation of new design technologies. A comparative analysis of the results from the different facets of research carried out was undertaken so as to identify the ideal propulsion of choice.

8.10.2 Study Findings

The study found that, in terms of current designs, the steam propulsion system returned the least efficient performance from an operational and design perspective in terms of energy efficiency, while the DFDE designs returned the best performance in both design and in operation. Current Direct Drive Designs fall somewhere in-between. For Future designs, when possible design improvements have been taken into account, the steam propulsion system is still the worst performing while the upgraded Gas Injection Direct Drive Designs are on a par with upgraded DFDE designs in terms of energy efficiency in design and operation. However, the flexibility offered by the number of prime movers of the DFDE increases the reliability and gives it the edge over the direct drive designs.

8.10.3 Significance of Findings

This finding is a peculiar one as the direct drive designs are theoretically more thermally efficient than their DFDE counterparts. However, the higher exhaust temperatures of the DFDE offer an opportunity to improve the efficiency further through Waste Heat Recovery. This research has shown that operationally a 6.6% reduction in fuel consumption is possible and this has been demonstrated. This efficiency improvement matched the DFDE to the Direct Drive Designs in terms of efficiency. There were however operational issues regarding the use of the EGWHR at lower operational speeds.

8.10.4 Impact

The impact of this finding on the LNGC industry is quite significant. This is primarily because an analysis of the LNGC orderbook has shown that most future LNGC orders are of the gas-injection Direct Drive Designs, as this is on the premise of the higher thermal efficiency of the Direct Drive Designs. However, as shown in the research the DFDE designs provide the same efficiency and a higher reliability that is particularly required in new designs. The direction of future LNGC orders should return to the upgraded DFDE designs to provide maximum benefit to LNGC owners.

8.11 Contribution Summary

The key essence of original research at doctorate level is to add significantly to the existing body of knowledge. The body of knowledge in this case refers to the design and operation of LNG carriers with regards to efficiency. The methods chosen to achieve the original contribution requirement were threefold: Analytical study of the current and future fleet using the EEDI, Case studies of LNGCs in actual sea going operations, and design improvements of LNGCs to achieve improvements in efficiency.

The first noticeable finding was the dynamic nature of the LNG propulsion technology, where it was seen that over the course of this research, a total of eight different configurations existed when a historical perspective was adopted. When the EEDI analytical study was carried out, it was seen that the EEDI was not sufficient to stimulate design improvements as required, as having a number of propulsion types but one baseline offers quite a selective and ineffective outcome. Methane slip was also highlighted, its impact on efficiency as well as the shortcoming of not including it in EEDI calculations. A factor for including methane emissions into EEDI calculations was proposed as part of this research.

During the case studies it was seen that operational characteristics and design characteristics differ widely, as real world conditions are usually considerably less ideal. A review of the design sea trials of these vessels highlighted that these vessels underwent trials with a set of conditions such as fuel, weather, and loaded conditions that were markedly different when compared to actual operational conditions. This in turn resulted having a set of design characteristics that were basically of limited relevance when compared to realistic sea going conditions. A similar observation was highlighted with a disparity between design and operational conditions as it was seen ship operators operate inefficiently so as to guarantee safety in critical conditions. The increasing popularity of mobile terminals, FSRU, was highlighted, with the associated increase in maritime emissions specific to FSRU operations.

From the design improvement section, two noticeable points were ascertained. First modelling and simulation carried out as part of this research was combined with practical case studies on actual vessel operations. However, the efficiency gains of the steam turbine system were not sufficient to favourably compare with other modern LNGC propulsion systems. Further investigation highlighted that upgraded DFDE vessels showed the highest potential in terms of efficiency and operational flexibility of the various options. Although the DFDE was matched with the direct drive systems in terms of efficiency, the use of multiple prime movers increases the reliability of the DFDE design when compared to the direct drive designs.

9.

CONCLUSIONS AND IMPLICATIONS FOR THE FUTURE

9.1 Introduction

The overarching aim of this research thesis is to analyse and characterise LNG carriers in terms of efficiency and emissions so that optimal choices for LNGC propulsion are identified. The individual objectives that needed to be satisfied in order to achieve this aim were to Carry out a comprehensive review of LNGC propulsion systems; Analyse the current and future propulsion technologies from both a qualitative and quantitative viewpoint; and conduct comparative analysis of the different options. The expectation was that the results from this research will not only provide a valuable insight to LNG efficiency and emission performance but also provide a pathway for informing future designs of LNGC propulsion systems.

9.2 Conclusions

The literature review carried out highlighted the move from the traditional STPS propulsion plant towards more efficient LNGC propulsion technology such as the DFDE and Slow Speed Diesel options, purely due to associated commercial benefits. This was examined in detail. Also reviewed were the preferences for the newer LNGCs in terms of NG, HFO, and MDO price mix in relation to transport distances. The change in condition and quality of the emissions profile due to the propulsion changes was also reviewed. However, the literature review highlighted three key gaps in areas that are critical to achieving the objective of this research and they are: Lack of analytical study using the EEDI, mainly due to the EEDI not yet being applicable to LNGCs at the time; Lack of case study evidence of actual vessel operations, and the need for a theoretical and practical demonstration of design improvement technologies.

The research carried out an analytical study of the LNGCs using the EEDI to plug this identified gap. From the results obtained in this analytical study, it was determined that the legislated performance requirements of the current EEDI protocol were insufficient to stimulate design improvements, as the current baseline offers quite a selective and ineffective outcome. The research suggested that having multiple baselines for the different individual technologies might yield a more productive outcome. Also highlighted was the issue of methane slip, a characteristic peculiar to NG burning DFDE systems but largely ignored in emission estimation. This research highlighted its impact on efficiency and also proposed a method of calculating methane slip and including it in EEDI calculations. Research findings from this EEDI analytical study detailing the effect of methane slip have been published in one conference [75] and one journal [78].

Practical case studies were carried out on board sea going LNGCs to plug the second major gap identified in the literature review. By analysing the operational data it was determined that the operational profile differs markedly from the design profile that was presented in the literature review. Sea trials conditions were found to be non-representative of realistic operational conditions, and this research identified methods where this could be remedied. Also highlighted were the specific operational safety practices carried out by ship operators which reduce the efficiency of the vessel below the design point. The research identified and tested methods to reduce inefficiencies in these specific practices. Finally the case study highlighted the increasing popularity of the FSRUs and the associated increases in transport efficiencies and the need to reduce energy usage in these scenarios. Published works from the case studies include two conferences papers [74] and [76].

In the design improvement section, it was demonstrated through modelling and simulation carried out on the current STPS combination, and combined with work from the STPS manufacturers, that the efficiency gains for this upgraded STPS system were insufficient to compete favourably with the modern LNGC propulsion options. However, when a comparative analysis of the different modern designs and upgraded options were carried out, it was seen that modern DFDE designs showed the highest efficiency and operational flexibility of the various options, due to its flexibility in the use of multiple prime movers which increases the reliability of these engines. One conference paper [77] was published detailing these research findings.

The aim of this research was to effectively characterise LNG carriers in terms of efficiency and emissions. The first objective in achieving this aim was to carry out a comprehensive literature review. This was carried out and research gaps identified that needed to be plugged. The second objective that required to be achieved was the quantitative and qualitative analysis of current and future LNGCs. In terms of the quantitative analysis the EEDI was utilized and valuable insights and contributions were garnered. The qualitative analysis of the case studies highlighted particular aspects that plugged research gaps identified in the literature review. The comparative analysis of the different modern and upgraded technologies enabled the identification of optimal propulsion choices for the future. In achieving each objective, structured researched processes were adopted and research papers published to ensure quality of the research process and the novelty of research contributions.

The real challenge in carrying out a research of this sort is that each propulsion technology is large enough to warrant several research doctorate topics, therefore a comparative analysis might not provide the depth required at this level of research. However, as a holistic research perspective is required as it relates to improving efficiency and reducing anthropogenic emissions for LNGCs, a deepening of the research depth might not easily meet the aim of the research process. Therefore this research placed special emphasis on the practical-realistic conditions such that contributions are immediate and relevant to the operating environment and results are easily discernible.

Unfortunately, the lack of data on the newer two stroke gas burning designs meant this research was focused on the DFDE designs and STPS designs. Therefore, the lack of practical research does not allow conclusions to be drawn on the operational characteristics of these direct drive designs. However, since analytical and theoretical analyses on these designs have been carried out and the results compared with the other options there has been value gained in this approach. Moreover, the DFDE and Steam Designs make up over 90% of current designs [2] hence the relevance.

9.3 Implications of Findings

This study appears to support the argument for a change in policy on the implementation of the EEDI. As seen in EEDI analysis, there is suggestive evidence that the current EEDI policy is ineffective and might actually be making the situation worse. Therefore, the EEDI should be technology specific and not industry specific. Making the EEDI technology specific will in turn ensure that improvement technologies will be directed towards the more efficient technologies and there will be maximum benefit to the industry, primarily because, as it stands, the EEDI will not stimulate design improvements. However, a baseline based on the average of the DFDE or DDD technology, which is then tightened incrementally will provide a more effective outcome as design increments will be based on earlier versions of the specific DFDE and DDD technology and hence the EEDI increments will have a significant impact as future LNGC propulsion systems are based on the DFDE and DDD concepts.

A further policy change required is that methane slip calculations should be included in EEDI and EEOI calculations and presented in terms of CO_2 equivalents. This research showed the importance of including methane slip as it was seen that the emissions of even small amounts of methane can quickly eliminate the perceived benefits of reducing global warming/anthropogenic emissions as was seen in the case with the more efficient DFDE technology. This research presented a numerical method through which methane slip equivalents can be calculated and represented.

This study supports the argument for a stronger correlation between the design process and the operating condition of the LNGCs. The research showed operational data vary widely from design data and this has been traced to a number of factors. First the sea trials where the ship design baseline performance data is compiled are completely outdated due to the recognised practice of using HFO during the trials when these vessels spend over 90% of their operational lifetime being powered by gas fuel. This is unlikely to change due to upcoming regulations being stiffer and thus supporting the use of cleaner fuels. Second, standard operational practices for safety of the vessels are not prioritised in the design process from an EEOI/EEDI standpoint. These specific practices were not considered when the design process was reviewed. The EEDI regulations for LNGCs is calculated based on the BOG as fuel therefore the importance of the sea trials to follow suit cannot be over stated, as this will improve the accuracy and confidence in the design data as a measurement tool.

The rise of FSRUs demands an in-depth assessment of the impact on efficiency through operations of discharge to these units. On the face of this research there is a potential drop in operational efficiency of between 60% - 90% and as such there exists the certainty increase in emissions as the use of FSRUs continues to rise.

It is also important to note that the results from this research can be generalised beyond the current scope of LNGCs. The global sulphur cap has driven non-LNGC operators towards NG fuelled propulsion options as a means of meeting the new regulations. Therefore, the conclusions of this research have become more pertinent within the wider shipping industry. If the methane slip issue is not resolved, this will likely create an industry wide pollution problem if methane emitting propulsion options are adopted. Furthermore, WHRS can be added to DFDE options in power plants so as to optimise the power generation cycle, save costs and reduce emissions. The modelling and simulation can be adapted for steam power plants as a way of upgrading the efficiency of these systems, especially in steam power plants that are currently upgrading to utilisation of natural gas fuel systems. Finally the application of actual operating data against the design benchmark is one that is quite valuable particularly with the industry wide adoption of NG as a fuel.

9.4 Recommendations for Future Research

The peculiarity of having a PhD with such a wide scope presents several opportunities for future research. Such research will ensure that sufficient depth is obtained to support a bottom up analysis of the LNGC propulsion efficiency. One such opportunity is with regards to two stroke gas injection technologies. As seen from the analysis, this research did not cover the two stroke designs in as much detail as either the DFDE or the STPS systems, and there were not enough of these designs in operation during the course of this research. In future, the expectation is that more of these designs will become common as evidenced in the future orderbook [6] therefore there will be sufficient numbers of these designs in operation to carry out analytical study of these designs.

Another such opportunity earmarked during the course of this research is the quantifying, assessing and offering solutions to the problem of methane slip. It is expected that stiffer regulations on methane slip will become regulatory and as such the need to provide mitigation against this factor will become mandatory. This shall impact on the DFDE, which as this research has shown, is likely to be a popular choice moving forward. There will be therefore demand for research work in methane slip mitigating technologies as a means to reducing the anthropogenic emissions. Furthermore if methane slip is adopted into EEDI calculations, methane slip reduction technologies will become a requirement if the desired EEDI value is to be attained.

A key finding of this research was the disparity that presently exists between design conditions and actual operating conditions when assessing and measuring ship performance. However, no previous research paper has highlighted this disparity within the LNG propulsion sphere. As seen from this research, various differences occur between the design and operating conditions and this has an impact on the way efficiency analysis is carried out for the vessels. A key recommendation will be to carry out high level research where operating conditions of LNGCs become a benchmark for future designs, such that ship specific design conditions, such as slow steaming on one boiler, in the case of STPS, or the use WHRG-TG, in the case of the DFDE, are optimised for improved efficiency across the speed range.

On a final note, there seems to be a dearth of adequate numbers of high level research initiatives in the shipping industry. This is particularly pronounced in the LNG shipping industry and this was experienced throughout the course of this research. Information acquired with regards to LNG propulsion technology was only available through propulsion manufacturers, and access to information on actual sea going conditions was heavily restricted. This in turn limits the quality of research outcomes while reducing the impact of research analysis undertaken. The research opportunities listed in the previous paragraphs are mainly as a result of the restricted information available in the LNG shipping industry. In the course of this research, these research opportunities would not have been discovered without employee access to Industry which is not normally available to most researchers. As a final recommendation, there should be an open supply of information from LNG vessel operators, such that the entire research process can be iterative amongst researchers, regulators, ship operators and ship designers so as to improve the quality of the research outcomes.

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APPENDICES

Appendix 1- Full Dataset and EEDI calculations

Vessel Name	Type	GT	Dwt	Built	Speed (knots)	Power Type	Fuel Type	Capacity (cu m)	Total Generated Power KW	Propulsion Power KW	Prop PWR	PME	PAE	CF ME (LNG)	CF ME (HFO)	CFME (MDO)	SFC (DDD)	SFC (STEAM)	SFC (DFDE)	EEDI (A)	EEDI (B)	PHASE 1	PHASE 2	PHASE 3
Abdelkader	LNG Carrier	114277	87194	2010	19.5	Diesel Electric	LNG - MDO	155000	39507	38500	28450	25863.64	1413.864	2.75	3.114	3.206	190	285	175	8.029256	10.25901	9.233109	8.207208	7.181307
Amali	LNG Carrier	98490	82000	2011	19.5	Diesel Electric	LNG - MDO	148000	34900	34200	23340	21218.18	1204.818	2.75	3.114	3.206	190	285	175	7.018385	10.56205	9.505848	8.449642	7.393437
Arctic Aurora	LNG Carrier	100236	84604	2013	19.5	Diesel Electric	LNG - MDO	154899	33000	33000		0	250	2.75	3.114	3.206	190	285	175					
Arkat	LNG Carrier	98490	82000	2011	19.5	Diesel Electric	LNG - MDO	147228	34900	34200	23340	21218.18	1204.818	2.75	3.114	3.206	190	285	175	7.018385	10.56205	9.505848	8.449642	7.393437
Arwa Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	2.75	3.114	3.206	190	285	175	8.016668	10.59888	9.538996	8.479107	7.419219
Aseem	LNG Carrier	97874	86655	2009	19.5	Diesel Electric	LNG - MDO	155000	30000	30000	25300	23000	1285	2.75	3.114	3.206	190	285	175	7.192863	10.28921	9.260287	8.231366	7.202445
Asia Vision	LNG Carrier	101427	82487	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
British Diamond	LNG Carrier	102064	84553	2008	20	Diesel Electric	LNG - MDO	155046	39900	39900		0	250	2.75	3.114	3.206	190	285	175					
British Emerald	LNG Carrier	102064	84303	2007	20	Diesel Electric	LNG - MDO	154983	39900	39900		0	250	2.75	3.114	3.206	190	285	175					
British Ruby	LNG Carrier	102064	84491	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	2.75	3.114	3.206	190	285	175					
British Sapphire	LNG Carrier	102064	84455	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	2.75	3.114	3.206	190	285	175					
BW GDF Suez Brussels	LNG Carrier	103670	89556	2009	19.5	Diesel Electric	LNG - MDO	162400	33392	33000	23600	21454.55	1215.455	2.75	3.114	3.206	190	285	175	6.497019	10.12985	9.116869	8.103884	7.090898
BW GDF Suez Paris	LNG Carrier	103670	89556	2009	19.5	Diesel Electric	LNG - MDO	162400	33392	33000	23600	21454.55	1215.455	2.75	3.114	3.206	190	285	175	6.497019	10.12985	9.116869	8.103884	7.090898
Castillo de Santisteban	LNG Carrier	111665	93796	2010	19.7	Diesel Electric	LNG - MDO	173673	40116	40000	27000	24545.45	1354.545	2.75	3.114	3.206	190	285	175	7.015218	9.910162	8.919145	7.928129	6.937113
Cool Runner	LNG Carrier	102097	81891	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
Cool Voyager	LNG Carrier	102097	81890	2013	19.5	Diesel Electric	LNG - MDO	160372	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
Coral Methane	LNG/Ethylene/LPG	7833	6150	2009	15.5	Diesel Electric	LNG - IFO	7500	13100	12900	5000	4545.455	454.5455	2.75	3.114	3.206	190	285	175	26.25156	36.05532	32.44978	28.84425	25.23872
Cubal	LNG Carrier	100723	82857	2012	20	Diesel Electric	LNG - MDO	160534	39900	39900	27200	24727.27	1362.727	2.75	3.114	3.206	190	285	175	7.879648	10.51013	9.459116	8.408103	7.357091
Experience	LNG/Regasification	116486	95105	2014	18	Diesel Electric		173660	35750	35100		0	250	2.75	3.114	3.206	190	285	175					
Gaselys	LNG Carrier	97741	75600	2007	19	Diesel Electric	LNG - MDO	154472	39900	39900	28000	25454.55	1395.455	2.75	3.114	3.206	190	285	175	9.355367	10.97683	9.879143	8.781461	7.683778
GasLog Santiago	LNG Carrier	98075	82178	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					

GasLog Savannah	LNG Carrier	97818	82291	2010	19.5	Diesel Electric	LNG - MDO	155000	39900	39900	25300	23000	1285	2.75	3.114	3.206	190	285	175	7.57431	10.54433	9.489899	8.435466	7.381033
GasLog Seattle	LNG Carrier	98075	81982	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500	25300	23000	1285	2.75	3.114	3.206	190	285	175	7.602859	10.56315	9.506837	8.450522	7.394206
GasLog Shanghai	LNG Carrier	98075	82104	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
GasLog Singapore	LNG Carrier	97818	82339	2010	19.5	Diesel Electric	LNG - MDO	155000	39900	39900	23000	20909.09	1190.909	2.75	3.114	3.206	190	285	175	6.888807	10.54142	9.487277	8.433135	7.378993
GasLog Skagen	LNG Carrier	98075	81847	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
GasLog Sydney	LNG Carrier	98075	82010	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
GDF Suez Global Energy	LNG Carrier	49700	36145	2006	17.5	Diesel Electric	LNG - MDO	74130	22800	22800		0	250	2.75	3.114	3.206	190	285	175					
Golar Celsius	LNG Carrier	102100	82048	2013	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
Golar Crystal	LNG Carrier	102100	82058	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
Golar Seal	LNG Carrier	102100	82048	2013	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	2.75	3.114	3.206	190	285	175					
Independence	LNG/Regasification	110303	80305	2014	18	Diesel Electric	LNG - MDO	170000	29042	28650		0	250	2.75	3.114	3.206	190	285	175					
Lena River	LNG Carrier	100236	84565	2013	19.5	Diesel Electric	LNG - MDO	155165	33000	33000		0	250	2.75	3.114	3.206	190	285	175					
Lobito	LNG Carrier	100723	82929	2011	20	Diesel Electric	LNG - MDO	161337	39900	39900	27200	24727.27	1362.727	2.75	3.114	3.206	190	285	175	7.872807	10.5058	9.455223	8.404642	7.354062
Magellan Spirit	LNG Carrier	104169	82187	2009	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	2.75	3.114	3.206	190	285	175	7.939902	10.55065	9.495589	8.440524	7.385458
Malanje	LNG Carrier	100723	82728	2011	20	Diesel Electric	LNG - MDO	160400	39900	39900	27200	24727.27	1362.727	2.75	3.114	3.206	190	285	175	7.891935	10.51789	9.466105	8.414316	7.362526
Marib Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	2.75	3.114	3.206	190	285	175	8.016668	10.59888	9.538996	8.479107	7.419219
Meridian Spirit	LNG Carrier	104169	81929	2010	19.5	Diesel Electric	LNG - MDO	165772	38500	38500	26500	24090.91	1334.091	2.75	3.114	3.206	190	285	175	7.964906	10.56639	9.509751	8.453112	7.396473
Methane Becki Anne	LNG Carrier	109004	86269	2010	19.75	Diesel Electric	LNG - MDO	170678	39900	39900	25400	23090.91	1289.091	2.75	3.114	3.206	190	285	175	7.161496	10.311	9.279903	8.248803	7.217703
Methane Mickie Harper	LNG Carrier	109004	86170	2010	19.75	Diesel Electric	LNG - MDO	170000	39900	39900	25400	23090.91	1289.091	2.75	3.114	3.206	190	285	175	7.169724	10.31662	9.284955	8.253294	7.221632
Methane Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	2.75	3.114	3.206	190	285	175	8.016668	10.59888	9.538996	8.479107	7.419219
Provalys	LNG Carrier	97741	75600	2006	19	Diesel Electric	LNG - MDO	154472	38500	38500	28000	25454.55	1395.455	2.75	3.114	3.206	190	285	175	9.355367	10.97683	9.879143	8.781461	7.683778
Seri Balhaf	LNG Carrier	105000	85999	2008	19.5	Diesel Electric	LNG - MDO	152300	40206	39820	12650	11500	767.5	2.75	3.114	3.206	190	285	175	3.661171	10.32634	9.293702	8.261068	7.228435
Seri Balqis	LNG Carrier	107633	91198	2009	19.5	Diesel Electric	LNG - MDO	157611	40206	39820	25300	23000	1285	2.75	3.114	3.206	190	285	175	6.834553	10.04299	9.038692	8.034393	7.030094
Soyo	LNG Carrier	100723	82857	2011	20	Diesel Electric	LNG - MDO	161337	39900	39900	27200	24727.27	1362.727	2.75	3.114	3.206	190	285	175	7.879648	10.51013	9.459116	8.408103	7.357091
Stena Clear Sky	LNG Carrier	109949	96811	2011	20.4	Diesel Electric	LNG - MDO	173593	42100	41250	18667	16970	1013.65	2.75	3.114	3.206	190	285	175	4.557376	9.762652	8.786387	7.810121	6.833856
Stena Crystal Sky	LNG Carrier	109949	96889	2011	20.4	Diesel Electric	LNG - MDO	173611	42100	41250		0	250	2.75	3.114	3.206	190	285	175					
Tangguh Foja	LNG Carrier	97897	82338	2008	20	Diesel Electric	LNG - MDO	155641	39900	39900	25300	23000	1285	2.75	3.114	3.206	190	285	175	7.380737	10.54148	9.487331	8.433183	7.379035
Tangguh Hiri	LNG Carrier	101957	84467	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	2.75	3.114	3.206	190	285	175					

Tangguh Jaya	LNG Carrier	97897	82338	2008	20	Diesel Electric	LNG - MDO	155641	39900	39900	25300	23000	1285	2.75	3.114	3.206	190	285	175	7.380737	10.54148	9.487331	8.433183	7.379035
Tangguh Palung	LNG Carrier	97897	82407	2009	20	Diesel Electric	LNG - MDO	155642	39900	39900	25300	23000	1285	2.75	3.114	3.206	190	285	175	7.374557	10.53729	9.483565	8.429836	7.376106
Tangguh Sago	LNG Carrier	101957	84484	2009	20	Diesel Electric	LNG - MDO	154971	39900	39900	25300	23000	1285	2.75	3.114	3.206	190	285	175	7.193257	10.4137	9.372329	8.330959	7.289589
Velikiy Novgorod	LNG Carrier	113876	93486	2014	19.5	Diesel Electric	LNG - MDO	170567	34000	34000		0	250	2.75	3.114	3.206	190	285	175					
Woodside Donaldson	LNG Carrier	104169	82085	2009	19.5	Diesel Electric	LNG - MDO	165936	38500	38500	26500	24090.91	1334.091	2.75	3.114	3.206	190	285	175	7.949768	10.55687	9.501181	8.445494	7.389807
Woodside Rogers	LNG Carrier	103928	90327	2013	19.9	Diesel Electric	LNG - MDO - HFO	160668	35852	35460			250	2.75	3.114	3.206	190	285	175					
Yenisei River	LNG Carrier	100236	84604	2013	19.5	Diesel Electric	LNG - MDO	155000	33000	33000			250	2.75	3.114	3.206	190	285	175					
Bahrain Vision	LNG/Ethylene/LPG	11327	12210	2011	16.5	Motor Ship 2-Stroke	HFO	12022	11882	8280		6210	730.0196	2.75	3.114	3.206	190	285	175	20.73513	26.04911	23.4442	20.83929	18.23438
Norgas Unikum	LNG/Ethylene/LPG	11327	12210	2011	16.5	Motor Ship 2-Stroke	HFO	12000	11882	8280		6210	729.52	2.75	3.114	3.206	190	285	175	20.73342	26.04911	23.4442	20.83929	18.23438
Aamira	LNG Carrier	163922	130026	2010	19.5	Motor Ship 2-Stroke	HFO	267335	60109	42909		32181.75	7393.903	2.75	3.114	3.206	190	285	175	9.519673	8.48879	7.639911	6.791032	5.942153
Al Samriya	LNG Carrier	168189	154900	2009	19.5	Motor Ship 2-Stroke	HFO	261700	60740	43540		32655	7281.707	2.75	3.114	3.206	190	285	175	8.05809	7.81289	7.031601	6.250312	5.469023
Lijmiliya	LNG Carrier	168189	155159	2009	19.5	Motor Ship 2-Stroke	HFO	261700	60109	42909		32181.75	7265.932	2.75	3.114	3.206	190	285	175	7.948501	7.806706	7.026035	6.245365	5.464694
Al Aamriya	LNG Carrier	136685	121935	2008	19.5	Motor Ship 2-Stroke	HFO	210168	52686	37246		27934.5	5954.065	2.75	3.114	3.206	190	285	175	8.677092	8.751273	7.876146	7.001019	6.125891
Al Ghariya	LNG Carrier	137535	121730	2008	19.5	Motor Ship 2-Stroke	HFO	210100	54150	37250		27937.5	5952.621	2.75	3.114	3.206	190	285	175	8.692033	8.758256	7.88243	7.006605	6.130779
Al Hamla	LNG Carrier	136410	106983	2008	19.5	Motor Ship 2-Stroke	HFO	216000	56501	39240		29430	6136.36	2.75	3.114	3.206	190	285	175	10.37418	9.311098	8.379988	7.448878	6.517769
Al Huwaila	LNG Carrier	136410	109503	2008	19.5	Motor Ship 2-Stroke	HFO	217000	52520	37320		27990	6111.07	2.75	3.114	3.206	190	285	175	9.728272	9.208909	8.288018	7.367127	6.446236
Al Kharsaah	LNG Carrier	135848	109484	2008	19.5	Motor Ship 2-Stroke	HFO	217000	52520	37320		27990	6111.07	2.75	3.114	3.206	190	285	175	9.729961	9.209666	8.2887	7.367733	6.446766
Al Khuwair	LNG Carrier	136410	109503	2008	19.5	Motor Ship 2-Stroke	HFO	217000	52520	37320		27990	6111.07	2.75	3.114	3.206	190	285	175	9.728272	9.208909	8.288018	7.367127	6.446236
Al Oraiq	LNG Carrier	136685	122079	2008	19.5	Motor Ship 2-Stroke	HFO	210100	52686	37246		27934.5	5952.521	2.75	3.114	3.206	190	285	175	8.66641	8.746379	7.871741	6.997103	6.122465
Al Shamal	LNG Carrier	136410	109503	2008	19.5	Motor Ship 2-Stroke	HFO	217000	52520	37320		27990	6111.07	2.75	3.114	3.206	190	285	175	9.728272	9.208909	8.288018	7.367127	6.446236
Duhail	LNG Carrier	137535	121639	2008	19.5	Motor Ship 2-Stroke	HFO	210100	56440	39240		29430	6002.371	2.75	3.114	3.206	190	285	175	9.085281	8.761361	7.885225	7.009089	6.132953
Fraiha	LNG Carrier	135100	122079	2008	19.5	Motor Ship 2-	HFO	210100	48618	33178		24883.5	5850.821	2.75	3.114	3.206	190	285	175	7.878666	8.746379	7.871741	6.997103	6.122465

						Stroke																		
Murwab	LNG Carrier	135100	12207 9	2008	19.5	Motor Ship 2-Stroke	HFO	210100	48618	33178		24883 .5	5850. 821	2.7 5	3.1 14	3.20 6	190	285	175	7.878 666	8.746 379	7.871 741	6.997 103	6.122 465
Umm Al Amad	LNG Carrier	135100	12207 9	2008	19.5	Motor Ship 2-Stroke	HFO	210100	48618	33178		24883 .5	5850. 821	2.7 5	3.1 14	3.20 6	190	285	175	7.878 666	8.746 379	7.871 741	6.997 103	6.122 465
Al Gattara	LNG Carrier	136410	10689 8	2007	19.5	Motor Ship 2-Stroke	HFO	216224	56532	39240		29430	6141. 447	2.7 5	3.1 14	3.20 6	190	285	175	10.38 411	9.314 607	8.383 146	7.451 685	6.520 225
Al Ruwais	LNG Carrier	137535	12182 3	2007	19.5	Motor Ship 2-Stroke	HFO	210100	56440	39240		29430	6002. 371	2.7 5	3.1 14	3.20 6	190	285	175	9.071 559	8.755 086	7.879 577	7.004 069	6.128 56
Al Safliya	LNG Carrier	137535	12193 6	2007	19.5	Motor Ship 2-Stroke	HFO	210134	56440	39240		29430	6003. 143	2.7 5	3.1 14	3.20 6	190	285	175	9.063 376	8.751 239	7.876 115	7.000 991	6.125 868
Tembek	LNG Carrier	136410	10698 3	2007	19.5	Motor Ship 2-Stroke	HFO	216000	56499	39240		29430	6136. 36	2.7 5	3.1 14	3.20 6	190	285	175	10.37 418	9.311 098	8.379 988	7.448 878	6.517 769
Coral Anthelia	LNG/Ethylene/LPG	6441	6554	2013	15.5	Motor Ship 4-Stroke		6500	9162	6000				2.7 5	3.1 14	3.20 6	190	285	175		34.98 421	31.48 579	27.98 737	24.48 895
Coral Energy	LNG Carrier	13501	12200	2012	15.8	Motor Ship 4-Stroke	LNG - MDO	15600	9911	7800				2.7 5	3.1 14	3.20 6	190	285	175		26.05 923	23.45 331	20.84 738	18.24 146
Akebono Maru	LNG Carrier	4505	2400	2011	15.8	Motor Ship 4-Stroke	IFO	3556	2942	2942				2.7 5	3.1 14	3.20 6	190	285	175		56.32 173	50.68 956	45.05 738	39.42 521
Norgas Conception	LNG/Ethylene/LPG	10105	10441	2011	16	Motor Ship 4-Stroke	HFO	10030	10054	7000				2.7 5	3.1 14	3.20 6	190	285	175		28.05 513	25.24 962	22.44 411	19.63 859
Norgas Invention	LNG/Ethylene/LPG	10105	10441	2011	16	Motor Ship 4-Stroke	HFO	10030	10054	7000				2.7 5	3.1 14	3.20 6	190	285	175		28.05 513	25.24 962	22.44 411	19.63 859
Norgas Creation	LNG/Ethylene/LPG	10105	10441	2010	16	Motor Ship 4-Stroke	HFO	10030	10054	7000				2.7 5	3.1 14	3.20 6	190	285	175		28.05 513	25.24 962	22.44 411	19.63 859
Norgas Innovation	LNG/Ethylene/LPG	10105	10441	2010	16	Motor Ship 4-Stroke	HFO	10030	10054	7000				2.7 5	3.1 14	3.20 6	190	285	175		28.05 513	25.24 962	22.44 411	19.63 859
North Pioneer	LNG Carrier	3056	1938	2005	13.3	Motor Ship 4-Stroke	HFO	2512	2206	2206				2.7 5	3.1 14	3.20 6	190	285	175		62.32 904	56.09 613	49.86 323	43.63 033
Shinju Maru No. 1	LNG Carrier	2936	1781	2003	12.7	Motor Ship 4-Stroke	IFO	2513	1912	1912				2.7 5	3.1 14	3.20 6	190	285	175		64.87 56	58.38 804	51.90 048	45.41 292
Energy Horizon	LNG Carrier	141136	87257	2011	19.5	Steam Turbine		177441	29890	29890		24808 .7	0	2.7 5	3.1 14	3.20 6	190	285	175	12.93 995	10.25 55	9.229 949	8.204 399	7.178 849
Exemplar	LNG/Regasification	93179	83125	2010	19.2	Steam Turbine	LNG - MDO	151000	42152	26478		21976 .74	0	2.7 5	3.1 14	3.20 6	190	285	175	12.22 064	10.49 405	9.444 649	8.395 243	7.345 838
Expedient	LNG/Regasification	100361	83166	2010	19.2	Steam Turbine	MDO	151000	42152	26478		21976 .74	0	2.7 5	3.1 14	3.20 6	190	285	175	12.21 461	10.49 16	9.442 441	8.393 281	7.344 121
GDF Suez Point Fortin	LNG Carrier	101129	79592	2010	19.5	Steam Turbine		154914	29400	29400		24402	0	2.7 5	3.1 14	3.20 6	190	285	175	13.95 355	10.71 233	9.641 098	8.569 865	7.498 632
Taitar No. 3	LNG Carrier	118634	76899	2010	19.5	Steam Turbine		147366	26478	26478		21976 .74	0	2.7 5	3.1 14	3.20 6	190	285	175	13.00 683	10.88 854	9.799 687	8.710 833	7.621 979
Taitar No. 4	LNG Carrier	118634	72282	2010	19.5	Steam Turbine		147546	26478	26478		21976 .74	0	2.7 5	3.1 14	3.20 6	190	285	175	13.83 764	11.21 284	10.09 156	8.970 276	7.848 991

Cygnus Passage	LNG Carrier	122444	79555	2009	19	Steam Turbine		147200	22930	22930		19031.9	0	2.75	3.114	3.206	190	285	175	11.17441	10.71469	9.643223	8.571754	7.500285
Express	LNG/Regasification	93179	82500	2009	19.2	Steam Turbine	LNG - MDO	150900	42152	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.31322	10.53166	9.478496	8.42533	7.372164
Exquisite	LNG/Regasification	100325	82500	2009	19.2	Steam Turbine	LNG - MDO	151000	42152	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.31322	10.53166	9.478496	8.42533	7.372164
LNG Jupiter	LNG Carrier	121675	81950	2009	19.5	Steam Turbine		153659	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	13.55206	10.56511	9.508596	8.452086	7.395575
Min Rong	LNG Carrier	97871	72989	2009	19.5	Steam Turbine		147000	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	15.21587	11.16123	10.04511	8.928985	7.812862
Pacific Enlighten	LNG Carrier	122361	80023	2009	19.5	Steam Turbine		147200	22930	22930		19031.9	0	2.75	3.114	3.206	190	285	175	10.82421	10.68494	9.61645	8.547956	7.479461
Taitar No. 1	LNG Carrier	118634	76939	2009	19.5	Steam Turbine		147362	26478	26478		21976.74	0	2.75	3.114	3.206	190	285	175	13.00007	10.88586	9.797272	8.708686	7.6201
Taitar No. 2	LNG Carrier	118634	76971	2009	19.5	Steam Turbine		147500	26478	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.99466	10.88371	9.795341	8.70697	7.618598
Trinity Glory	LNG Carrier	101126	79605	2009	20.1	Steam Turbine		154999	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	13.53482	10.7115	9.640352	8.569202	7.498052
Alto Acrux	LNG Carrier	122361	80229	2008	19.5	Steam Turbine		147798	22930	22930		19031.9	0	2.75	3.114	3.206	190	285	175	10.79642	10.67193	9.604738	8.537545	7.470352
Cheikh Bouamama	LNG Carrier	52855	39483	2008	17.5	Steam Turbine		75558	24518	15000		12450	0	2.75	3.114	3.206	190	285	175	15.99133	14.93474	13.44127	11.94779	10.45432
Clean Force	LNG Carrier	100244	84598	2008	19.5	Steam Turbine		149743	28684	28684		23807.72	0	2.75	3.114	3.206	190	285	175	12.80815	10.40704	9.36634	8.325636	7.284931
Dapeng Moon	LNG Carrier	97871	73275	2008	19.5	Steam Turbine		147210	27300	27300		22659	0	2.75	3.114	3.206	190	285	175	14.07388	11.14056	10.0265	8.912448	7.798392
Dapeng Sun	LNG Carrier	97871	73275	2008	19.5	Steam Turbine		147236	27300	27300		22659	0	2.75	3.114	3.206	190	285	175	14.07388	11.14056	10.0265	8.912448	7.798392
Energy Navigator	LNG Carrier	118842	73640	2008	19	Steam Turbine		147558	26507	26507		22000.81	0	2.75	3.114	3.206	190	285	175	13.95516	11.11435	10.00292	8.891482	7.780047
Explorer	LNG/Regasification	100325	82500	2008	19.2	Steam Turbine		151008	26478	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.31322	10.53166	9.478496	8.42533	7.372164
Grace Cosmos	LNG Carrier	100481	85224	2008	19.5	Steam Turbine		149700	29420	29420		24418.6	0	2.75	3.114	3.206	190	285	175	13.0403	10.37074	9.333666	8.296592	7.259518
Grand Aniva	LNG Carrier	122239	74044	2008	19.5	Steam Turbine	HFO	147200	23600	23600		19588	0	2.75	3.114	3.206	190	285	175	12.04007	11.08557	9.97701	8.868453	7.759897
Grand Mereya	LNG Carrier	120525	74497	2008	19.5	Steam Turbine		145964	23259	23259		19304.97	0	2.75	3.114	3.206	190	285	175	11.79395	11.05356	9.948207	8.842851	7.737495
K. Jasmine	LNG Carrier	97529	84935	2008	20.3	Steam Turbine	HFO	145877	40007	28460		23621.8	0	2.75	3.114	3.206	190	285	175	12.15888	10.38745	9.348706	8.309961	7.271216
K. Mugungwha	LNG Carrier	99151	87488	2008	19	Steam Turbine		151812	40007	28460		23621.8	0	2.75	3.114	3.206	190	285	175	12.61172	10.24265	9.218389	8.194124	7.169858
LNG Barka	LNG Carrier	121514	82308	2008	19.5	Steam Turbine		155982	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	13.49312	10.5433	9.48897	8.43464	7.38031
LNG Ebisu	LNG Carrier	118910	81032	2008	19.5	Steam Turbine		147546	26918	26918		22341.94	0	2.75	3.114	3.206	190	285	175	12.54854	10.62167	9.559505	8.497338	7.435171
LNG Imo	LNG Carrier	98798	83684	2008	19.75	Steam Turbine		148300	37520	26728		22184.24	0	2.75	3.114	3.206	190	285	175	11.91238	10.46077	9.414692	8.368615	7.322538
Seri Bijaksana	LNG Carrier	104881	89953	2008	19.5	Steam Turbine	HFO	152888	22065	22065		18313.95	0	2.75	3.114	3.206	190	285	175	9.266063	10.10864	9.097775	8.086911	7.076047
Tangguh Towuti	LNG Carrier	97432	84992	2008	19.5	Steam Turbine		145700	40260	29400		24402	0	2.75	3.114	3.206	190	285	175	13.06701	10.38415	9.345734	8.307319	7.268904
Trinity Arrow	LNG Carrier	101080	79556	2008	20.1	Steam Turbine		154982	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	13.54316	10.71463	9.643166	8.571703	7.50024
Al Areesh	LNG Carrier	99106	90617	2007	19.5	Steam Turbine		148786	27057	27057		22457.31	0	2.75	3.114	3.206	190	285	175	11.27916	10.07346	9.066115	8.058769	7.051423

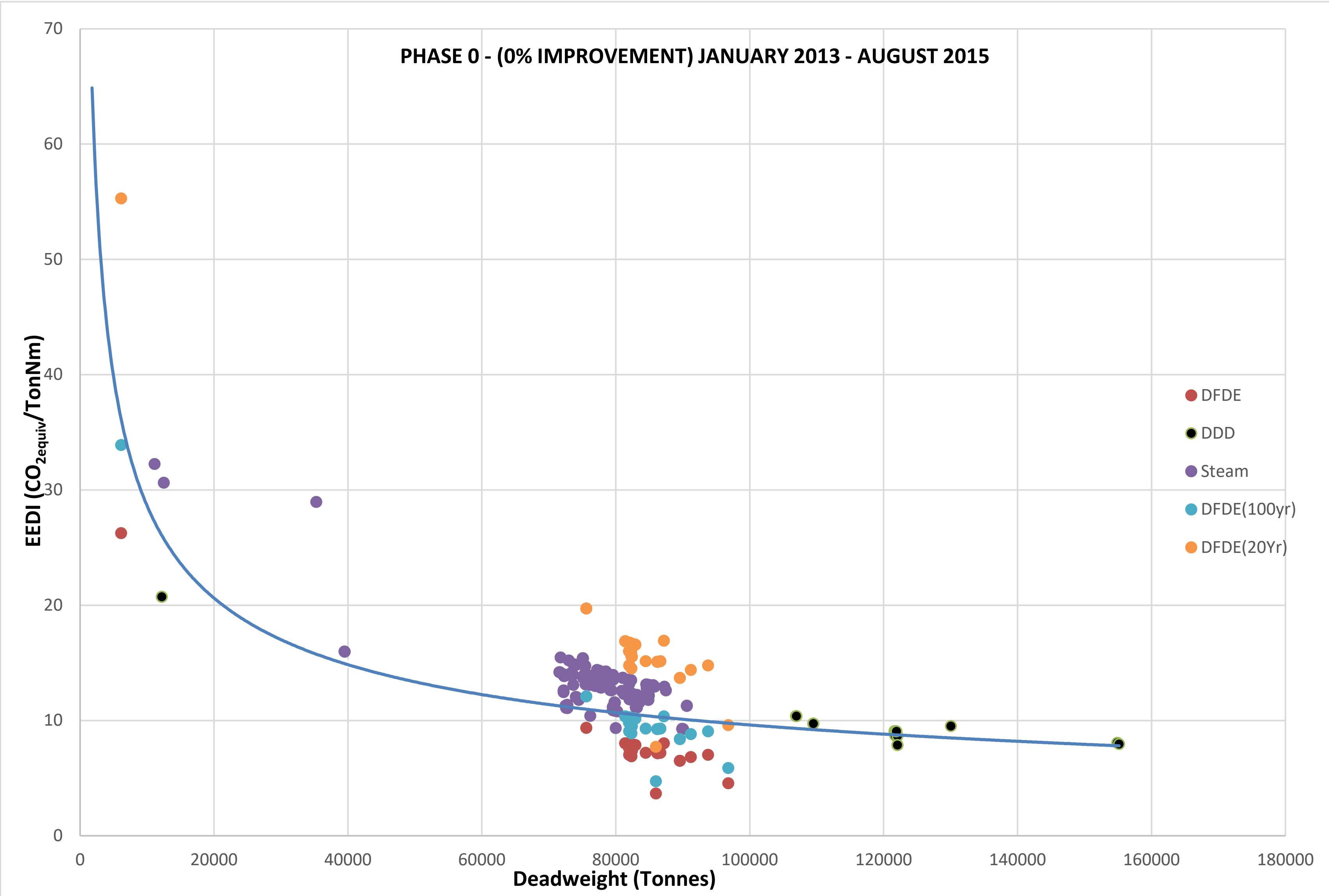
Al Daayen	LNG Carrier	99106	90617	2007	19.5	Steam Turbine		148853	27066	27066		22464.78	0	2.75	3.114	3.206	190	285	175	11.28292	10.07346	9.066115	8.058769	7.051423
Al Jassasiya	LNG Carrier	97496	84554	2007	19.5	Steam Turbine		145700	40260	29400		24402	0	2.75	3.114	3.206	190	285	175	13.1347	10.40961	9.36865	8.327689	7.286728
Celestine River	LNG Carrier	118571	75434	2007	19.5	Steam Turbine		147608	39437	29400		24402	0	2.75	3.114	3.206	190	285	175	14.72269	10.98827	9.889442	8.790615	7.691788
Cheikh El Mokrani	LNG Carrier	52855	39520	2007	17.5	Steam Turbine		74365	18240	15000		12450	0	2.75	3.114	3.206	190	285	175	15.97636	14.92811	13.4353	11.94249	10.44968
Clean Energy	LNG Carrier	100244	85813	2007	19.5	Steam Turbine		149700	40950	29400		24402	0	2.75	3.114	3.206	190	285	175	12.94199	10.33694	9.303245	8.269551	7.235857
Ejnan	LNG Carrier	95824	78403	2007	20	Steam Turbine		145000	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.81103	10.78903	9.710127	8.631224	7.552321
Grace Acacia	LNG Carrier	100341	85214	2007	19.5	Steam Turbine		149786	29420	29420		24418.6	0	2.75	3.114	3.206	190	285	175	13.04183	10.37132	9.334185	8.297054	7.259922
Grace Barleria	LNG Carrier	100450	84812	2007	19.5	Steam Turbine		149700	29420	29420		24418.6	0	2.75	3.114	3.206	190	285	175	13.10365	10.39459	9.355131	8.315672	7.276213
Grand Elena	LNG Carrier	122239	74127	2007	19.5	Steam Turbine		147200	23600	23600		19588	0	2.75	3.114	3.206	190	285	175	12.02659	11.07968	9.971713	8.863745	7.755777
LNG Borno	LNG Carrier	97874	82030	2007	19.8	Steam Turbine		149600	26074	26074		21641.42	0	2.75	3.114	3.206	190	285	175	11.82528	10.56022	9.5042	8.448177	7.392155
LNG Kano	LNG Carrier	98798	83961	2007	19.75	Steam Turbine		149600	38087	26728		22184.24	0	2.75	3.114	3.206	190	285	175	11.87308	10.4444	9.399956	8.355517	7.311077
LNG Ogun	LNG Carrier	97874	81997	2007	19.8	Steam Turbine		149600	29052	29052		24113.16	0	2.75	3.114	3.206	190	285	175	13.18118	10.56224	9.506012	8.449789	7.393565
LNG Ondo	LNG Carrier	98798	83688	2007	19.75	Steam Turbine		148300	38243	26728		22184.24	0	2.75	3.114	3.206	190	285	175	11.91181	10.46053	9.414478	8.368425	7.322372
Maran Gas Coronis	LNG Carrier	97491	84823	2007	19.5	Steam Turbine		145700	30338	26478		21976.74	0	2.75	3.114	3.206	190	285	175	11.79176	10.39395	9.354555	8.31516	7.275765
Methane Alison Victoria	LNG Carrier	95753	79058	2007	20.2	Steam Turbine		145127	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.561	10.74657	9.671911	8.597254	7.522597
Methane Heather Sally	LNG Carrier	95753	79054	2007	20.2	Steam Turbine		145127	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.56169	10.74683	9.672143	8.59746	7.522778
Methane Nile Eagle	LNG Carrier	97100	77766	2007	20.2	Steam Turbine		145144	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.7863	10.83083	9.747747	8.664664	7.581581
Methane Shirley Elisabeth	LNG Carrier	95753	78997	2007	20.2	Steam Turbine		145127	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.57147	10.7505	9.67545	8.6004	7.52535
Neo Energy	LNG Carrier	100253	85602	2007	19.5	Steam Turbine		149700	29600	29600		24568	0	2.75	3.114	3.206	190	285	175	13.06215	10.34901	9.314107	8.279207	7.244306
OB River	LNG Carrier	100244	84682	2007	19.5	Steam Turbine	HFO	149700	28684	28684		23807.72	0	2.75	3.114	3.206	190	285	175	12.79545	10.40215	9.361935	8.32172	7.281505
Seri Ayu	LNG Carrier	95729	83365	2007	19	Steam Turbine		145894	36019	24860		20633.8	0	2.75	3.114	3.206	190	285	175	11.56126	10.47972	9.431751	8.383778	7.335806
Seri Bakti	LNG Carrier	105335	90065	2007	19.5	Steam Turbine	HFO	152300	22065	22065		18313.95	0	2.75	3.114	3.206	190	285	175	9.25454	10.10268	9.092411	8.082143	7.071875
Seri Begawan	LNG Carrier	105335	89902	2007	19.5	Steam Turbine	HFO	152300	22065	22065		18313.95	0	2.75	3.114	3.206	190	285	175	9.271319	10.11136	9.100221	8.089085	7.07795
Sestao Knutsen	LNG Carrier	90478	77204	2007	19.5	Steam Turbine		138114	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	14.38515	10.86813	9.781317	8.694504	7.607691
Sun Arrows	LNG Carrier	20620	11142	2007	18.1	Steam Turbine		19100	8830	8830		7328.9	0	2.75	3.114	3.206	190	285	175	32.25229	27.20418	24.48376	21.76334	19.04292
Al Marrouna	LNG Carrier	99106	90617	2006	19.5	Steam Turbine		149539	30917	27057		22457.31	0	2.75	3.114	3.206	190	285	175	11.27916	10.07346	9.066115	8.058769	7.051423
Arctic Discoverer	LNG Carrier	118571	75485	2006	20	Steam Turbine		142612	30430	26900		22327	0	2.75	3.114	3.206	190	285	175	13.12512	10.98475	9.886274	8.787799	7.689325

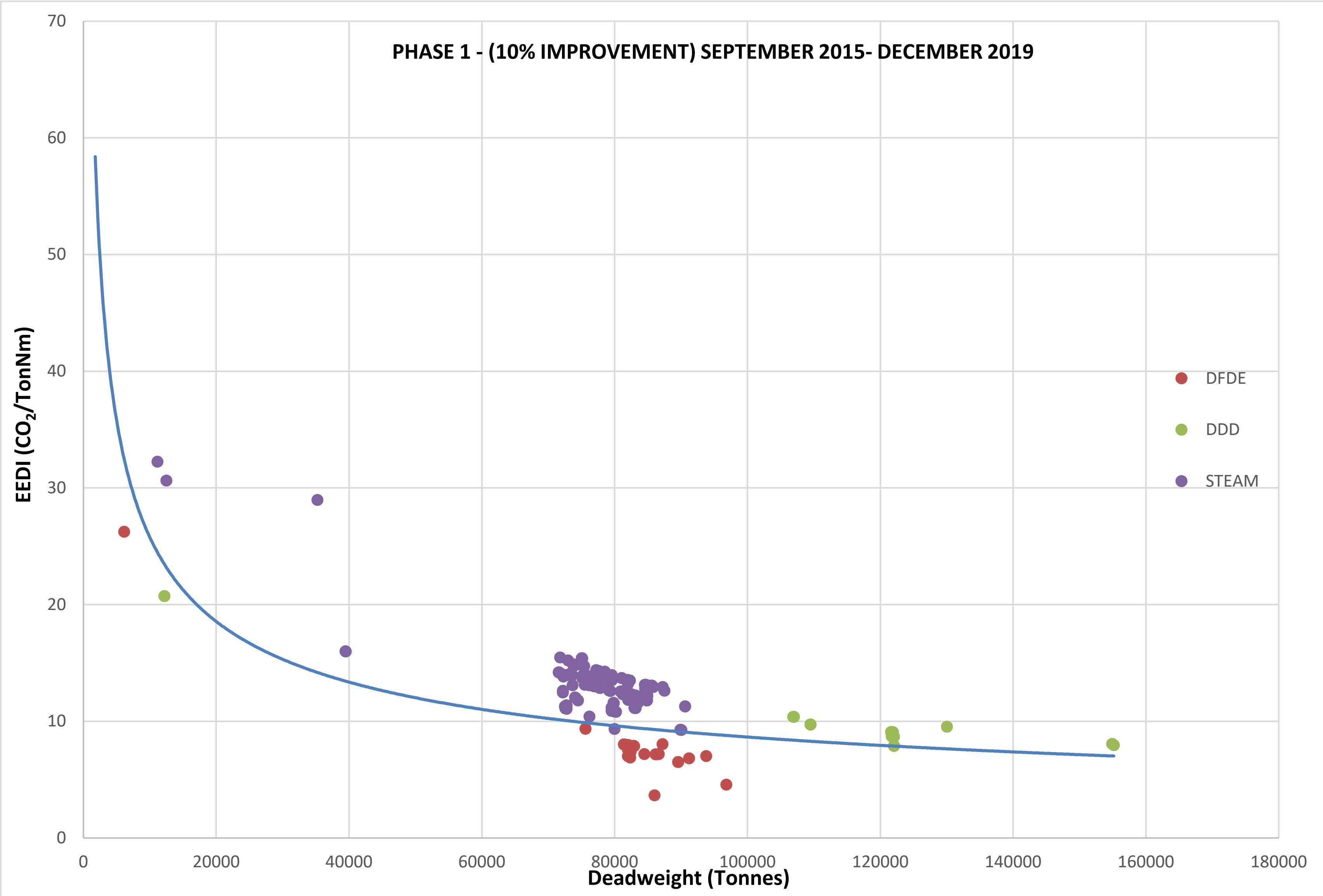
Arctic Lady	LNG Carrier	121597	84878	2006	19.5	Steam Turbine		147208	38590	27600		22908	0	2.75	3.114	3.206	190	285	175	12.28347	10.39076	9.351682	8.312606	7.27353
Arctic Princess	LNG Carrier	121597	84878	2006	19.5	Steam Turbine		147835	27600	27600		22908	0	2.75	3.114	3.206	190	285	175	12.28347	10.39076	9.351682	8.312606	7.27353
Arctic Voyager	LNG Carrier	118571	75434	2006	19.5	Steam Turbine		142929	34430	26900		22327	0	2.75	3.114	3.206	190	285	175	13.47076	10.98827	9.889442	8.790615	7.691788
Energy Progress	LNG Carrier	119100	79983	2006	19.5	Steam Turbine		147558	19785	19785		16421.55	0	2.75	3.114	3.206	190	285	175	9.344269	10.68748	9.618729	8.549982	7.481234
Excelerate	LNG/Regasification	93901	77623	2006	19.1	Steam Turbine		138074	26496	26496		21991.68	0	2.75	3.114	3.206	190	285	175	13.16431	10.84028	9.756255	8.672227	7.588199
Golar Grand	LNG Carrier	97491	84894	2006	19.5	Steam Turbine	HFO	145879	30338	26478		21976.74	0	2.75	3.114	3.206	190	285	175	11.78189	10.38983	9.350846	8.311863	7.27288
Iberica Knutsen	LNG Carrier	93915	77541	2006	19.5	Steam Turbine	HFO	138120	30115	29400		24402	0	2.75	3.114	3.206	190	285	175	14.32263	10.84572	9.761144	8.676573	7.592001
Ibra LNG	LNG Carrier	96671	81057	2006	19.5	Steam Turbine		147100	40650	29400		24402	0	2.75	3.114	3.206	190	285	175	13.70136	10.62012	9.558107	8.496095	7.434084
Ibri LNG	LNG Carrier	118608	71776	2006	19.5	Steam Turbine		147569	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	15.47302	11.25024	10.12522	9.000195	7.875171
LNG Benue	LNG Carrier	97561	82971	2006	19.75	Steam Turbine		145842	28646	24786		20572.38	0	2.75	3.114	3.206	190	285	175	11.14178	10.50328	9.452954	8.402626	7.352297
LNG Dream	LNG Carrier	118876	80889	2006	19.5	Steam Turbine		145000	26900	26900		22327	0	2.75	3.114	3.206	190	285	175	12.56232	10.63057	9.567512	8.504455	7.441398
LNG Lokoja	LNG Carrier	98798	83965	2006	19.75	Steam Turbine		149600	31087	26728		22184.24	0	2.75	3.114	3.206	190	285	175	11.87251	10.44416	9.399744	8.355328	7.310912
LNG River Niger	LNG Carrier	115993	79541	2006	19.7	Steam Turbine		141000	23184	23184		19242.72	0	2.75	3.114	3.206	190	285	175	10.89865	10.71559	9.644028	8.572469	7.500911
Methane Jane Elizabeth	LNG Carrier	95753	78984	2006	20.2	Steam Turbine	HFO	145000	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.5737	10.75134	9.676205	8.601071	7.525937
Methane Lydon Volney	LNG Carrier	95753	78957	2006	20.2	Steam Turbine		145000	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.57835	10.75308	9.677773	8.602465	7.527157
Methane Rita Andrea	LNG Carrier	95753	79046	2006	20.2	Steam Turbine		145000	39750	29400		24402	0	2.75	3.114	3.206	190	285	175	13.56306	10.74734	9.672607	8.597873	7.523139
Milaha Qatar	LNG Carrier	96508	77803	2006	20.6	Steam Turbine		145130	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	13.51218	10.82839	9.74555	8.662711	7.579872
Pacific Eurus	LNG Carrier	111539	72571	2006	19.5	Steam Turbine		136942	21320	21320		17695.6	0	2.75	3.114	3.206	190	285	175	11.09765	11.19166	10.07249	8.953326	7.83416
Seri Amanah	LNG Carrier	95729	83400	2006	19	Steam Turbine		145000	35227	24877		20647.91	0	2.75	3.114	3.206	190	285	175	11.56432	10.47764	9.429874	8.382111	7.334347
Seri Anggun	LNG Carrier	95729	83395	2006	19	Steam Turbine		145731	24877	24877		20647.91	0	2.75	3.114	3.206	190	285	175	11.56501	10.47794	9.430142	8.382349	7.334555
Seri Angkasa	LNG Carrier	95729	83395	2006	19	Steam Turbine		145000	36020	24860		20633.8	0	2.75	3.114	3.206	190	285	175	11.55711	10.47794	9.430142	8.382349	7.334555
Simaisma	LNG Carrier	97496	84863	2006	19.5	Steam Turbine		145700	40260	29400		24402	0	2.75	3.114	3.206	190	285	175	13.08687	10.39163	9.352465	8.313302	7.27414
Stena Blue Sky	LNG Carrier	97754	84363	2006	19.5	Steam Turbine	IFO	145819	30926	27066		22464.78	0	2.75	3.114	3.206	190	285	175	12.11934	10.42078	9.378698	8.336621	7.294543
Al Deebel	LNG Carrier	95824	78542	2005	19.5	Steam Turbine		145130	39950	29600		24568	0	2.75	3.114	3.206	190	285	175	14.23629	10.77998	9.701978	8.62398	7.545983
Al Thakhira	LNG Carrier	95824	78542	2005	19.5	Steam Turbine		145130	39950	29600		24568	0	2.75	3.114	3.206	190	285	175	14.23629	10.77998	9.701978	8.62398	7.545983
Energy Advance	LNG Carrier	119233	71586	2005	19.5	Steam Turbine		147624	26900	26900		22327	0	2.75	3.114	3.206	190	285	175	14.19486	11.26439	10.13795	9.01151	7.885071
Excellence	LNG/Regasification	93179	77349	2005	19.1	Steam Turbine	HFO	138120	38058	26478		21976.74	0	2.75	3.114	3.206	190	285	175	13.20197	10.85847	9.772622	8.686775	7.600928
Excelsior	LNG/Regasification	93179	35257	2005	19.1	Steam Turbine	HFO	138087	38058	26478		21976.74	0	2.75	3.114	3.206	190	285	175	28.9633	15.75803	14.18222	12.60642	11.03062

Golar Viking	LNG Carrier	93750	79950	2005	19.5	Steam Turbine		140208	12252			0	0	2.75	3.114	3.206	190	285	175					
LNG Adamawa	LNG Carrier	115993	79566	2005	19.7	Steam Turbine		142656	23184	23184		19242.72	0	2.75	3.114	3.206	190	285	175	10.89522	10.71399	9.642591	8.571192	7.499793
LNG Cross River	LNG Carrier	115993	79591	2005	19.7	Steam Turbine		141000	23184	23184		19242.72	0	2.75	3.114	3.206	190	285	175	10.8918	10.7124	9.641156	8.569916	7.498677
LNG Enugu	LNG Carrier	97561	83160	2005	19.75	Steam Turbine		145914	28646	24786		20572.38	0	2.75	3.114	3.206	190	285	175	11.11646	10.49196	9.442764	8.393568	7.344372
LNG Oyo	LNG Carrier	97561	83068	2005	19.75	Steam Turbine		145842	28646	24786		20572.38	0	2.75	3.114	3.206	190	285	175	11.12877	10.49747	9.44772	8.397973	7.348227
LNG Pioneer	LNG Carrier	90046	77712	2005	19.5	Steam Turbine	HFO	138000	30338	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.87076	10.8344	9.750957	8.667518	7.584078
Lusail	LNG Carrier	95824	78488	2005	19.5	Steam Turbine		145000	39950	29600		24568	0	2.75	3.114	3.206	190	285	175	14.24608	10.78349	9.705141	8.626792	7.548443
Maran Gas Asclepius	LNG Carrier	97496	84659	2005	19.5	Steam Turbine		145822	33260	29400		24402	0	2.75	3.114	3.206	190	285	175	13.11841	10.40349	9.363141	8.322792	7.282443
Nizwa LNG	LNG Carrier	118608	77252	2005	19.5	Steam Turbine		147684	26900	26900		22327	0	2.75	3.114	3.206	190	285	175	13.15375	10.86493	9.778436	8.691943	7.60545
Puteri Mutiara Satu	LNG Carrier	94446	76229	2005	19.5	Steam Turbine		137100	26800	26800		22244	0	2.75	3.114	3.206	190	285	175	13.28072	10.9338	9.84042	8.74704	7.65366
Salalah LNG	LNG Carrier	96671	81034	2005	19.5	Steam Turbine		145951	40650	29400		24402	0	2.75	3.114	3.206	190	285	175	13.70525	10.62155	9.559393	8.497238	7.435084
Seri Alam	LNG Carrier	95729	83482	2005	19	Steam Turbine	HFO	145572	24860	24860		20633.8	0	2.75	3.114	3.206	190	285	175	11.54506	10.47276	9.425483	8.378207	7.330931
Umm Bab	LNG Carrier	97496	84659	2005	19.5	Steam Turbine		145000	30926	27066		22464.78	0	2.75	3.114	3.206	190	285	175	12.07697	10.40349	9.363141	8.322792	7.282443
Berge Arzew	LNG Carrier	93844	77409	2004	19.5	Steam Turbine		138088	34544	26985		22397.55	0	2.75	3.114	3.206	190	285	175	13.16855	10.85448	9.76903	8.683583	7.598135
Bilbao Knutsen	LNG Carrier	90835	77217	2004	19.5	Steam Turbine		138000	28000	28000		23240	0	2.75	3.114	3.206	190	285	175	13.69784	10.86726	9.780537	8.69381	7.607084
Cadiz Knutsen	LNG Carrier	90835	77228	2004	19.5	Steam Turbine		138826	28000	28000		23240	0	2.75	3.114	3.206	190	285	175	13.69589	10.86653	9.779876	8.693223	7.606571
Disha	LNG Carrier	94058	81237	2004	19.5	Steam Turbine		136026	33378	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.31227	10.60896	9.548063	8.487167	7.426271
Dukhan	LNG Carrier	111162	72533	2004	19.5	Steam Turbine		137661	26800	26800		22244	0	2.75	3.114	3.206	190	285	175	13.95745	11.19444	10.07499	8.955549	7.836105
Fuji LNG	LNG Carrier	118219	77351	2004	19.5	Steam Turbine		149172	26900	26900		22327	0	2.75	3.114	3.206	190	285	175	13.13691	10.85834	9.772502	8.686668	7.600835
Fuwairit	LNG Carrier	93227	74067	2004	19.5	Steam Turbine		138000	35952	29052		24113.16	0	2.75	3.114	3.206	190	285	175	14.81693	11.08394	9.975542	8.867148	7.758755
Galicia Spirit	LNG Carrier	94822	79166	2004	19.5	Steam Turbine		140624	26478	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.63437	10.73962	9.665655	8.591693	7.517731
Gemmata	LNG Carrier	111459	72727	2004	19	Steam Turbine		136985	21320	21320		17695.6	0	2.75	3.114	3.206	190	285	175	11.36526	11.18027	10.06224	8.944217	7.82619
Lalla Fatma N'Soumer	LNG Carrier	118363	80920	2004	19.5	Steam Turbine		147845	26882	26882		22312.06	0	2.75	3.114	3.206	190	285	175	12.5491	10.62864	9.565774	8.50291	7.440047
LNG Akwa Ibom	LNG Carrier	115993	79633	2004	19.7	Steam Turbine		141038	23184	23184		19242.72	0	2.75	3.114	3.206	190	285	175	10.88606	10.70972	9.638745	8.567773	7.496802
LNG River Orashi	LNG Carrier	97561	83068	2004	19.75	Steam Turbine		145914	24786	24786		20572.38	0	2.75	3.114	3.206	190	285	175	11.12877	10.49747	9.44772	8.397973	7.348227
Madrid Spirit	LNG Carrier	90835	77213	2004	19.5	Steam Turbine		138000	27617	27617		22922.11	0	2.75	3.114	3.206	190	285	175	13.51117	10.86753	9.780777	8.694024	7.607271
Methane Kari Elin	LNG Carrier	93410	73989	2004	19.5	Steam Turbine		138209	29052	29052		24113.16	0	2.75	3.114	3.206	190	285	175	14.83255	11.08947	9.980525	8.871578	7.76263
Milaha Ras Laffan	LNG Carrier	93226	73705	2004	19.5	Steam Turbine		138270	29052	29052		24113.16	0	2.75	3.114	3.206	190	285	175	14.8897	11.10971	9.998735	8.887764	7.776794

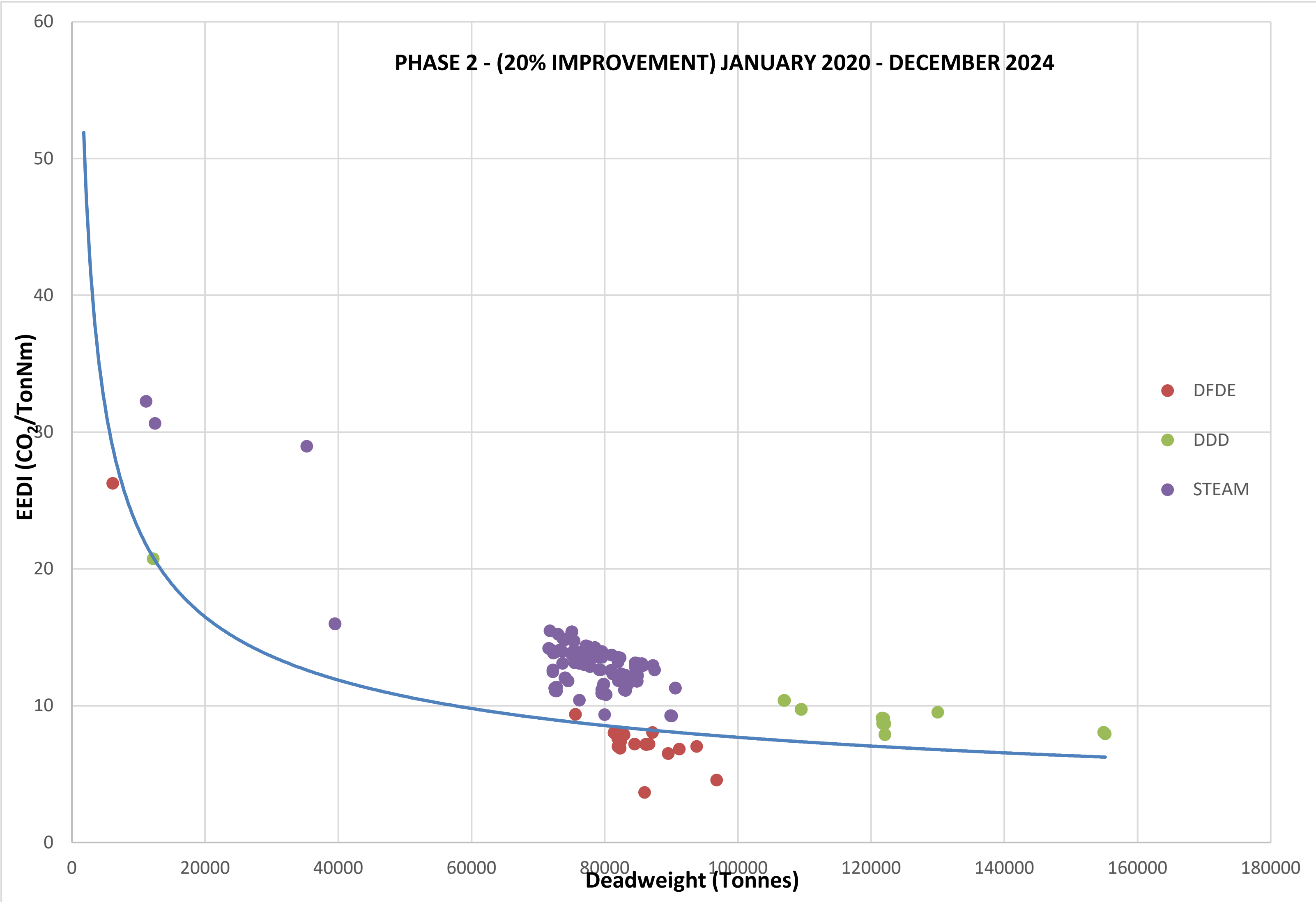
Northwest Swan	LNG Carrier	96165	73659	2004	19.2	Steam Turbine		138000	25135	25135		20862.05	0	2.75	3.114	3.206	190	285	175	13.09162	11.11299	10.00169	8.890395	7.779096
Puteri Firus Satu	LNG Carrier	94446	76197	2004	19.5	Steam Turbine		137617	26413	26413		21922.79	0	2.75	3.114	3.206	190	285	175	13.09444	10.93598	9.842379	8.748781	7.655183
Puteri Zamrud Satu	LNG Carrier	94446	76144	2004	19.5	Steam Turbine		137100	26413	26413		21922.79	0	2.75	3.114	3.206	190	285	175	13.10355	10.93958	9.845625	8.751667	7.657708
Raahi	LNG Carrier	94058	81237	2004	19.5	Steam Turbine		136026	26478	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.31227	10.60896	9.548063	8.487167	7.426271
British Innovator	LNG Carrier	93498	75074	2003	18.5	Steam Turbine		138287	29030	29030		24094.9	0	2.75	3.114	3.206	190	285	175	15.39669	11.01321	9.911892	8.810571	7.709249
British Merchant	LNG Carrier	93498	75059	2003	18.5	Steam Turbine		138283	29030	29030		24094.9	0	2.75	3.114	3.206	190	285	175	15.39977	11.01426	9.912831	8.811405	7.70998
BW GDF Suez Boston	LNG Carrier	93844	77410	2003	19.5	Steam Turbine		138059	34544	26985		22397.55	0	2.75	3.114	3.206	190	285	175	13.16838	10.85441	9.768971	8.683529	7.598088
BW GDF Suez Everett	LNG Carrier	93844	77410	2003	19.5	Steam Turbine		138028	34544	26985		22397.55	0	2.75	3.114	3.206	190	285	175	13.16838	10.85441	9.768971	8.683529	7.598088
Castillo de Villalba	LNG Carrier	90835	77217	2003	19.5	Steam Turbine		138000	31330	28000		23240	0	2.75	3.114	3.206	190	285	175	13.69784	10.86726	9.780537	8.69381	7.607084
Catalunya Spirit	LNG Carrier	90835	77204	2003	19.5	Steam Turbine		138000	27617	27617		22922.11	0	2.75	3.114	3.206	190	285	175	13.51275	10.86813	9.781317	8.694504	7.607691
Energy Frontier	LNG Carrier	119381	71642	2003	19.5	Steam Turbine		147599	26900	26900		22327	0	2.75	3.114	3.206	190	285	175	14.18377	11.26021	10.13419	9.008171	7.882149
Excel	LNG Carrier	93786	77773	2003	19.5	Steam Turbine	HFO	138106	26478	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.86066	10.83037	9.747332	8.664295	7.581258
Golar Arctic	LNG Carrier	94934	72199	2003	19.5	Steam Turbine		140648	23830	23830		19778.9	0	2.75	3.114	3.206	190	285	175	12.46809	11.21895	10.09706	8.975162	7.853267
LNG Bayelsa	LNG Carrier	114354	79822	2003	18.5	Steam Turbine		137500	23183	23183		19241.89	0	2.75	3.114	3.206	190	285	175	11.56423	10.69769	9.627921	8.558152	7.488383
Methane Princess	LNG Carrier	93899	77707	2003	19.5	Steam Turbine		138000	30897	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.87158	10.83473	9.751255	8.667782	7.584309
Pacific Notus	LNG Carrier	111533	72490	2003	19.2	Steam Turbine		137006	21321	21321		17696.43	0	2.75	3.114	3.206	190	285	175	11.28417	11.19758	10.07782	8.958066	7.838308
Puteri Nilam Satu	LNG Carrier	94446	76124	2003	19.5	Steam Turbine		137585	26413	26413		21922.79	0	2.75	3.114	3.206	190	285	175	13.10699	10.94095	9.846851	8.752757	7.658662
SK Sunrise	LNG Carrier	92927	75249	2003	19.5	Steam Turbine		138306	39930	29400		24402	0	2.75	3.114	3.206	190	285	175	14.75888	11.00107	9.900959	8.800853	7.700746
Abadi	LNG Carrier	111461	72758	2002	19.5	Steam Turbine	HFO	136912	21318	21318		17693.94	0	2.75	3.114	3.206	190	285	175	11.06809	11.17801	10.06021	8.942411	7.824609
British Trader	LNG Carrier	93498	75109	2002	18.5	Steam Turbine		138000	29030	29030		24094.9	0	2.75	3.114	3.206	190	285	175	15.38951	11.01078	9.909702	8.808624	7.707546
Excalibur	LNG Carrier	95800	77822	2002	19.5	Steam Turbine	HFO	138034	37328	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.85256	10.82714	9.744422	8.661708	7.578995
Galea	LNG Carrier	111459	72781	2002	19	Steam Turbine		136967	21320	21320		17695.6	0	2.75	3.114	3.206	190	285	175	11.35683	11.17634	10.05871	8.941071	7.823437
Gallina	LNG Carrier	111459	72781	2002	19	Steam Turbine		137001	21320	21320		17695.6	0	2.75	3.114	3.206	190	285	175	11.35683	11.17634	10.05871	8.941071	7.823437
Hispania Spirit	LNG Carrier	94822	79363	2002	19.5	Steam Turbine		140500	26478	26478		21976.74	0	2.75	3.114	3.206	190	285	175	12.603	10.72697	9.654275	8.581577	7.50888
LNG Rivers	LNG Carrier	114354	79866	2002	18.5	Steam Turbine		137231	23183	23183		19241.89	0	2.75	3.114	3.206	190	285	175	11.55786	10.6949	9.625406	8.555916	7.486427
LNG Sokoto	LNG Carrier	114354	79822	2002	18.5	Steam Turbine		137231	23183	23183		19241.89	0	2.75	3.114	3.206	190	285	175	11.56423	10.69769	9.627921	8.558152	7.488383
Puteri Delima Satu	LNG Carrier	94430	75929	2002	19.5	Steam Turbine		137100	26413	26413		21922.79	0	2.75	3.114	3.206	190	285	175	13.14065	10.95426	9.85883	8.763404	7.667979
Puteri Intan Satu	LNG Carrier	94430	75849	2002	19.5	Steam Turbine		137489	26413	26413		21922.79	0	2.75	3.114	3.206	190	285	175	13.15451	10.95973	9.863757	8.767784	7.671811

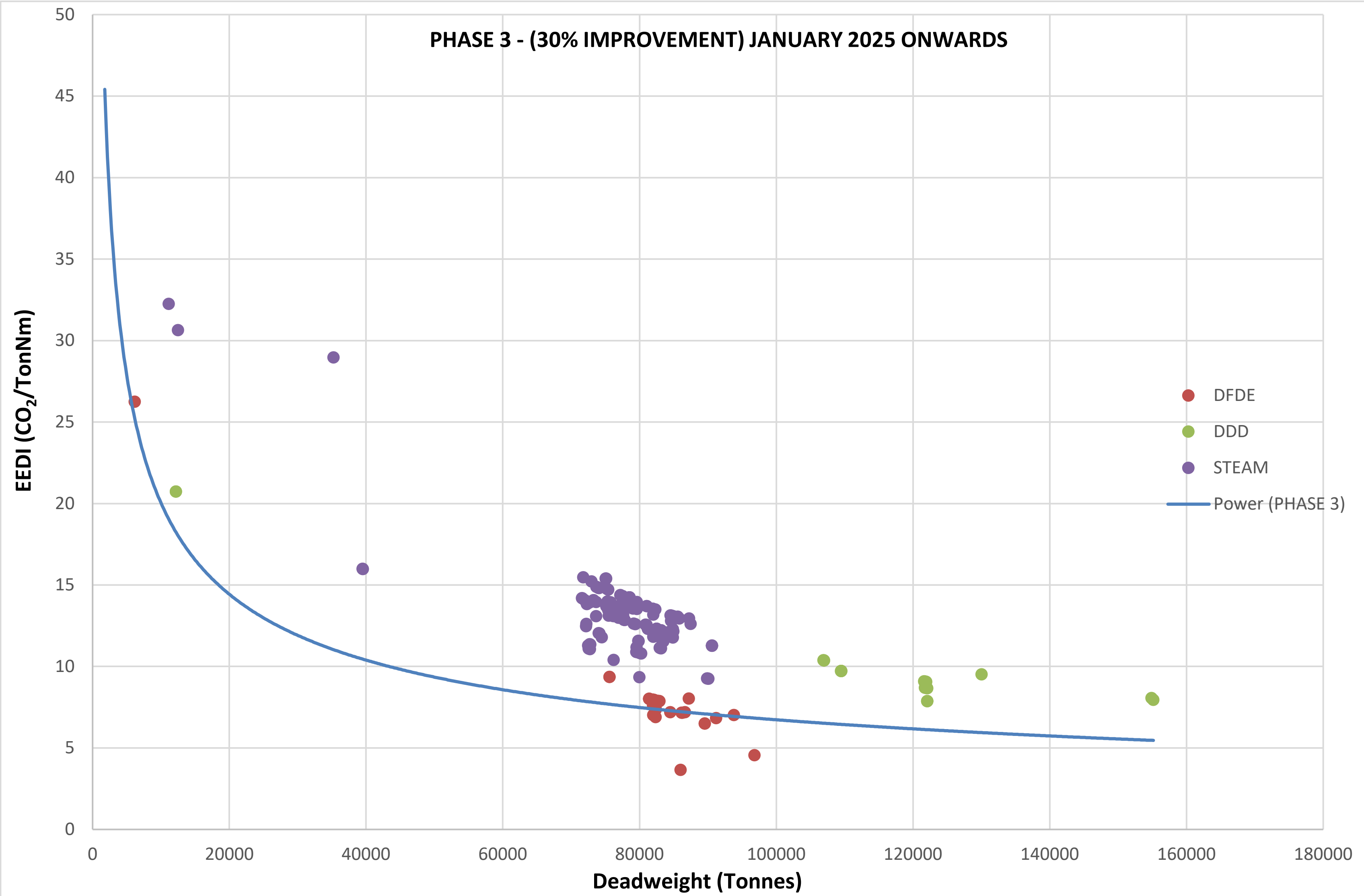
Sohar LNG	LNG Carrier	111203	71997	2001	19.5	Steam Turbine	HFO	137248	26802	26802		22245.66	0	2.75	3.114	3.206	190	285	175	14.06241	11.23386	10.11048	8.987089	7.863703
Al Jasra	LNG Carrier	111168	72218	2000	19.5	Steam Turbine		137100	24117	24117		20017.11	0	2.75	3.114	3.206	190	285	175	12.61493	11.21755	10.0958	8.974043	7.852288
Golar Mazo	LNG Carrier	111835	76210	2000	19.8	Steam Turbine		136867	21318	21318		17693.94	0	2.75	3.114	3.206	190	285	175	10.40665	10.93509	9.841583	8.748073	7.654564
Hanjin Ras Laffan	LNG Carrier	93769	75079	2000	20.3	Steam Turbine		138214	28611	28611		23747.13	0	2.75	3.114	3.206	190	285	175	13.82802	11.01287	9.911579	8.810293	7.709006
Hanjin Sur	LNG Carrier	93769	75159	2000	20.3	Steam Turbine		138333	28611	28611		23747.13	0	2.75	3.114	3.206	190	285	175	13.8133	11.00731	9.906577	8.805846	7.705116
Hyundai Aquapia	LNG Carrier	113998	77564	2000	20.3	Steam Turbine		135000	28662	28662		23789.46	0	2.75	3.114	3.206	190	285	175	13.40886	10.84419	9.759772	8.675353	7.590934
Hyundai Cosmopia	LNG Carrier	113998	77591	2000	20.3	Steam Turbine		135000	28684	28684		23807.72	0	2.75	3.114	3.206	190	285	175	13.41448	10.8424	9.758162	8.673922	7.589682
Hyundai Oceanpia	LNG Carrier	113998	77564	2000	20.3	Steam Turbine		135000	28684	28684		23807.72	0	2.75	3.114	3.206	190	285	175	13.41915	10.84419	9.759772	8.675353	7.590934
K. Acacia	LNG Carrier	95376	75768	2000	20.5	Steam Turbine	HFO	138017	29401	29401		24402.83	0	2.75	3.114	3.206	190	285	175	13.94325	10.96528	9.868754	8.772226	7.675698
K. Freesia	LNG Carrier	95381	77022	2000	20.5	Steam Turbine	HFO	135256	29400	29400		24402	0	2.75	3.114	3.206	190	285	175	13.71577	10.8803	9.792266	8.704236	7.616207
LNG Jamal	LNG Carrier	112069	72674	2000	19.5	Steam Turbine		135333	26802	26802		22245.66	0	2.75	3.114	3.206	190	285	175	13.93141	11.18414	10.06572	8.947309	7.828895
SK Splendor	LNG Carrier	92866	75154	2000	20.8	Steam Turbine		138375	29052	29052		24113.16	0	2.75	3.114	3.206	190	285	175	13.68996	11.00765	9.906889	8.806124	7.705358
SK Stellar	LNG Carrier	92866	75154	2000	20.8	Steam Turbine		138375	29052	29052		24113.16	0	2.75	3.114	3.206	190	285	175	13.68996	11.00765	9.906889	8.806124	7.705358
SK Supreme	LNG Carrier	92866	75319	2000	20.3	Steam Turbine		138200	29052	29052		24113.16	0	2.75	3.114	3.206	190	285	175	13.99642	10.99622	9.896596	8.796975	7.697353
Surya Satsuma	LNG Carrier	20017	12498	2000	15	Steam Turbine	HFO	23096	7796	7796		6470.68	0	2.75	3.114	3.206	190	285	175	30.63244	25.76284	23.18655	20.61027	18.03399


PHASE 0 - (0% IMPROVEMENT) JANUARY 2013 - AUGUST 2015
EEDI (CO_{2equiv}/TonNm)
Deadweight (Tonnes)
70
60
50
40
30
20
10
0
0
20000
40000
60000
80000
100000
120000
140000
160000
180000
DFDE
DDD
Steam
DFDE(100yr)
DFDE(20Yr)



PHASE 1 - (10% IMPROVEMENT) SEPTEMBER 2015- DECEMBER 2019
EEDI (CO_2/TonNm)
Deadweight (Tonnes)
0
10
20
30
40
50
60
70
0
20000
40000
60000
80000
100000
120000
140000
160000
180000
DFDE
DDD
STEAM


PHASE 2 - (20% IMPROVEMENT) JANUARY 2020 - DECEMBER 2024
EEDI (CO_2/TonNm)
Deadweight (Tonnes)
60
50
40
30
20
10
0
0
20000
40000
60000
80000
100000
120000
140000
160000
180000
DFDE
DDD
STEAM


PHASE 3 - (30% IMPROVEMENT) JANUARY 2025 ONWARDS
EEDI (CO2/TonNm)
50
45
40
35
30
25
20
15
10
5
0
0
20000
40000
60000
80000
100000
120000
140000
160000
180000
Deadweight (Tonnes)
DFDE
DDD
STEAM
Power (PHASE 3)

Including the Effects of Methane Slip

Vessel Name	Type	GT	Dwt	Built	Speed (knots)	Power Type	Fuel Type	Capacity (cu m)	Total Generated Power KW	Propulsion Power KW	Prop PWR	PME	PAE	CFME (LNG)	CFME (HFO)	CFME (MDO)	SFC (DDD)	SFC (STEAM)	SFC (DFDE)	EEDI (A)	EEDI (B)	PHASE 1	PHASE 2	PHASE 3
Abdelkader	LNG Carrier	114277	87194	2010	19.5	Diesel Electric	LNG - MDO	155000	39507	38500	28450	25863.64	1413.864	3.5837	3.114	3.206	190	285	175	10.36988	10.25901	9.233109	8.207208	7.181307
Amali	LNG Carrier	98490	82000	2011	19.5	Diesel Electric	LNG - MDO	148000	34900	34200	23340	21218.18	1204.818	3.5837	3.114	3.206	190	285	175	9.064326	10.56205	9.505848	8.449642	7.393437
Arctic Aurora	LNG Carrier	100236	84604	2013	19.5	Diesel Electric	LNG - MDO	154899	33000	33000		0	250	3.5837	3.114	3.206	190	285	175					
Arkat	LNG Carrier	98490	82000	2011	19.5	Diesel Electric	LNG - MDO	147228	34900	34200	23340	21218.18	1204.818	3.5837	3.114	3.206	190	285	175	9.064326	10.56205	9.505848	8.449642	7.393437
Arwa Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	3.5837	3.114	3.206	190	285	175	10.35362	10.59888	9.538996	8.479107	7.419219
Aseem	LNG Carrier	97874	86655	2009	19.5	Diesel Electric	LNG - MDO	155000	30000	30000	25300	23000	1285	3.5837	3.114	3.206	190	285	175	9.289667	10.28921	9.260287	8.231366	7.202445
Asia Vision	LNG Carrier	101427	82487	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
British Diamond	LNG Carrier	102064	84553	2008	20	Diesel Electric	LNG - MDO	155046	39900	39900		0	250	3.5837	3.114	3.206	190	285	175					
British Emerald	LNG Carrier	102064	84303	2007	20	Diesel Electric	LNG - MDO	154983	39900	39900		0	250	3.5837	3.114	3.206	190	285	175					
British Ruby	LNG Carrier	102064	84491	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	3.5837	3.114	3.206	190	285	175					
British Sapphire	LNG Carrier	102064	84455	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	3.5837	3.114	3.206	190	285	175					
BW GDF Suez Brussels	LNG Carrier	103670	89556	2009	19.5	Diesel Electric	LNG - MDO	162400	33392	33000	23600	21454.55	1215.455	3.5837	3.114	3.206	190	285	175	8.390976	10.12985	9.116869	8.103884	7.090898
BW GDF Suez Paris	LNG Carrier	103670	89556	2009	19.5	Diesel Electric	LNG - MDO	162400	33392	33000	23600	21454.55	1215.455	3.5837	3.114	3.206	190	285	175	8.390976	10.12985	9.116869	8.103884	7.090898
Castillo de Santisteban	LNG Carrier	111665	93796	2010	19.7	Diesel Electric	LNG - MDO	173673	40116	40000	27000	24545.45	1354.545	3.5837	3.114	3.206	190	285	175	9.060235	9.910162	8.919145	7.928129	6.937113
Cool Runner	LNG Carrier	102097	81891	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
Cool Voyager	LNG Carrier	102097	81890	2013	19.5	Diesel Electric	LNG - MDO	160372	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
Coral Methane	LNG/Ethylene/LPG	7833	6150	2009	15.5	Diesel Electric	LNG - IFO	7500	13100	12900	5000	4545.455	454.5455	3.5837	3.114	3.206	190	285	175	33.9042	36.05532	32.44978	28.84425	25.23872

Cubal	LNG Carrier	100723	82857	2012	20	Diesel Electric	LNG - MDO	160534	39900	39900	27200	24727.27	1362.727	3.5837	3.114	3.206	190	285	175	10.17666	10.51013	9.459116	8.408103	7.357091
Experience	LNG/Regasification	116486	95105	2014	18	Diesel Electric		173660	35750	35100		0	250	3.5837	3.114	3.206	190	285	175					
Gaselys	LNG Carrier	97741	75600	2007	19	Diesel Electric	LNG - MDO	154472	39900	39900	28000	25454.55	1395.455	3.5837	3.114	3.206	190	285	175	12.08257	10.97683	9.879143	8.781461	7.683778
GasLog Santiago	LNG Carrier	98075	82178	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
GasLog Savannah	LNG Carrier	97818	82291	2010	19.5	Diesel Electric	LNG - MDO	155000	39900	39900	25300	23000	1285	3.5837	3.114	3.206	190	285	175	9.78231	10.54433	9.489899	8.435466	7.381033
GasLog Seattle	LNG Carrier	98075	81982	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500	25300	23000	1285	3.5837	3.114	3.206	190	285	175	9.819181	10.56315	9.506837	8.450522	7.394206
GasLog Shanghai	LNG Carrier	98075	82104	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
GasLog Singapore	LNG Carrier	97818	82339	2010	19.5	Diesel Electric	LNG - MDO	155000	39900	39900	23000	20909.09	1190.909	3.5837	3.114	3.206	190	285	175	8.896974	10.54142	9.487277	8.433135	7.378993
GasLog Skagen	LNG Carrier	98075	81847	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
GasLog Sydney	LNG Carrier	98075	82010	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
GDF Suez Global Energy	LNG Carrier	49700	36145	2006	17.5	Diesel Electric	LNG - MDO	74130	22800	22800		0	250	3.5837	3.114	3.206	190	285	175					
Golar Celsius	LNG Carrier	102100	82048	2013	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
Golar Crystal	LNG Carrier	102100	82058	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
Golar Seal	LNG Carrier	102100	82048	2013	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	3.5837	3.114	3.206	190	285	175					
Independence	LNG/Regasification	110303	80305	2014	18	Diesel Electric	LNG - MDO	170000	29042	28650		0	250	3.5837	3.114	3.206	190	285	175					
Lena River	LNG Carrier	100236	84565	2013	19.5	Diesel Electric	LNG - MDO	155165	33000	33000		0	250	3.5837	3.114	3.206	190	285	175					
Lobito	LNG Carrier	100723	82929	2011	20	Diesel Electric	LNG - MDO	161337	39900	39900	27200	24727.27	1362.727	3.5837	3.114	3.206	190	285	175	10.16782	10.5058	9.455223	8.404642	7.354062
Magellan Spirit	LNG Carrier	104169	82187	2009	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	3.5837	3.114	3.206	190	285	175	10.25448	10.55065	9.495589	8.440524	7.385458
Malanje	LNG Carrier	100723	82728	2011	20	Diesel Electric	LNG - MDO	160400	39900	39900	27200	24727.27	1362.727	3.5837	3.114	3.206	190	285	175	10.19253	10.51789	9.466105	8.414316	7.362526
Marib Spirit	LNG Carrier	104169	8140	2008	19.5	Diesel Electri	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	3.5837	3.114	3.206	190	285	175	10.35362	10.59888	9.538996	8.479107	7.419219

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Meridian Spirit	LNG Carrier	104169	81929	2010	19.5	Diesel Electric	LNG - MDO	165772	38500	38500	26500	24090.91	1334.091	3.5837	3.114	3.206	190	285	175	10.28677	10.56639	9.509751	8.453112	7.396473
Methane Becki Anne	LNG Carrier	109004	86269	2010	19.75	Diesel Electric	LNG - MDO	170678	39900	39900	25400	23090.91	1289.091	3.5837	3.114	3.206	190	285	175	9.249156	10.311	9.279903	8.248803	7.217703
Methane Mickie Harper	LNG Carrier	109004	86170	2010	19.75	Diesel Electric	LNG - MDO	170000	39900	39900	25400	23090.91	1289.091	3.5837	3.114	3.206	190	285	175	9.259782	10.31662	9.284955	8.253294	7.221632
Methane Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	3.5837	3.114	3.206	190	285	175	10.35362	10.59888	9.538996	8.479107	7.419219
Provalys	LNG Carrier	97741	75600	2006	19	Diesel Electric	LNG - MDO	154472	38500	38500	28000	25454.55	1395.455	3.5837	3.114	3.206	190	285	175	12.08257	10.97683	9.879143	8.781461	7.683778
Seri Balhaf	LNG Carrier	105000	85999	2008	19.5	Diesel Electric	LNG - MDO	152300	40206	39820	12650	11500	767.5	3.5837	3.114	3.206	190	285	175	4.728445	10.32634	9.293702	8.261068	7.228435
Seri Balqis	LNG Carrier	107633	91198	2009	19.5	Diesel Electric	LNG - MDO	157611	40206	39820	25300	23000	1285	3.5837	3.114	3.206	190	285	175	8.826905	10.04299	9.038692	8.034393	7.030094
Soyo	LNG Carrier	100723	82857	2011	20	Diesel Electric	LNG - MDO	161337	39900	39900	27200	24727.27	1362.727	3.5837	3.114	3.206	190	285	175	10.17666	10.51013	9.459116	8.408103	7.357091
Stena Clear Sky	LNG Carrier	109949	96811	2011	20.4	Diesel Electric	LNG - MDO	173593	42100	41250	18667	16970	1013.65	3.5837	3.114	3.206	190	285	175	5.885905	9.762652	8.786387	7.810121	6.833856
Stena Crystal Sky	LNG Carrier	109949	96889	2011	20.4	Diesel Electric	LNG - MDO	173611	42100	41250		0	250	3.5837	3.114	3.206	190	285	175					
Tangguh Foja	LNG Carrier	97897	82338	2008	20	Diesel Electric	LNG - MDO	155641	39900	39900	25300	23000	1285	3.5837	3.114	3.206	190	285	175	9.532308	10.54148	9.487331	8.433183	7.379035
Tangguh Hiri	LNG Carrier	101957	84467	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	3.5837	3.114	3.206	190	285	175					
Tangguh Jaya	LNG Carrier	97897	82338	2008	20	Diesel Electric	LNG - MDO	155641	39900	39900	25300	23000	1285	3.5837	3.114	3.206	190	285	175	9.532308	10.54148	9.487331	8.433183	7.379035
Tangguh Palung	LNG Carrier	97897	82407	2009	20	Diesel Electric	LNG - MDO	155642	39900	39900	25300	23000	1285	3.5837	3.114	3.206	190	285	175	9.524326	10.53729	9.483565	8.429836	7.376106
Tangguh Sago	LNG Carrier	101957	84484	2009	20	Diesel Electric	LNG - MDO	154971	39900	39900	25300	23000	1285	3.5837	3.114	3.206	190	285	175	9.290175	10.4137	9.372329	8.330959	7.289589
Velikiy Novgorod	LNG Carrier	113876	93486	2014	19.5	Diesel Electric	LNG - MDO	170567	34000	34000		0	250	3.5837	3.114	3.206	190	285	175					
Woodside Donaldson	LNG Carrier	104169	82085	2009	19.5	Diesel Electric	LNG - MDO	165936	38500	38500	26500	24090.91	1334.091	3.5837	3.114	3.206	190	285	175	10.26722	10.55687	9.501181	8.445494	7.389807
Woodside Rogers	LNG Carrier	103928	90327	2013	19.9	Diesel Electric	LNG - MDO - HFO	160668	35852	35460			250	3.5837	3.114	3.206	190	285	175					
Yenisei River	LNG Carrier	100236	84604	2013	19.5	Diesel Electric	LNG - MDO	155000	33000	33000			250	3.5837	3.114	3.206	190	285	175					

Abdelkader	LNG Carrier	114277	87194	2010	19.5	Diesel Electric	LNG - MDO	155000	39507	38500	28450	25863.64	1413.864	5.9144	3.114	3.206	190	285	175	16.91334	10.25901	9.233109	8.207208	7.181307
Amali	LNG Carrier	98490	82000	2011	19.5	Diesel Electric	LNG - MDO	148000	34900	34200	23340	21218.18	1204.818	5.9144	3.114	3.206	190	285	175	14.78398	10.56205	9.505848	8.449642	7.393437
Arctic Aurora	LNG Carrier	100236	84604	2013	19.5	Diesel Electric	LNG - MDO	154899	33000	33000		0	250	5.9144	3.114	3.206	190	285	175					
Arkat	LNG Carrier	98490	82000	2011	19.5	Diesel Electric	LNG - MDO	147228	34900	34200	23340	21218.18	1204.818	5.9144	3.114	3.206	190	285	175	14.78398	10.56205	9.505848	8.449642	7.393437
Arwa Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	5.9144	3.114	3.206	190	285	175	16.88683	10.59888	9.538996	8.479107	7.419219
Aseem	LNG Carrier	97874	86655	2009	19.5	Diesel Electric	LNG - MDO	155000	30000	30000	25300	23000	1285	5.9144	3.114	3.206	190	285	175	15.15151	10.28921	9.260287	8.231366	7.202445
Asia Vision	LNG Carrier	101427	82487	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
British Diamond	LNG Carrier	102064	84553	2008	20	Diesel Electric	LNG - MDO	155046	39900	39900		0	250	5.9144	3.114	3.206	190	285	175					
British Emerald	LNG Carrier	102064	84303	2007	20	Diesel Electric	LNG - MDO	154983	39900	39900		0	250	5.9144	3.114	3.206	190	285	175					
British Ruby	LNG Carrier	102064	84491	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	5.9144	3.114	3.206	190	285	175					
British Sapphire	LNG Carrier	102064	84455	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	5.9144	3.114	3.206	190	285	175					
BW GDF Suez Brussels	LNG Carrier	103670	89556	2009	19.5	Diesel Electric	LNG - MDO	162400	33392	33000	23600	21454.55	1215.455	5.9144	3.114	3.206	190	285	175	13.68574	10.12985	9.116869	8.103884	7.090898
BW GDF Suez Paris	LNG Carrier	103670	89556	2009	19.5	Diesel Electric	LNG - MDO	162400	33392	33000	23600	21454.55	1215.455	5.9144	3.114	3.206	190	285	175	13.68574	10.12985	9.116869	8.103884	7.090898
Castillo de Santisteban	LNG Carrier	111665	93796	2010	19.7	Diesel Electric	LNG - MDO	173673	40116	40000	27000	24545.45	1354.545	5.9144	3.114	3.206	190	285	175	14.77731	9.910162	8.919145	7.928129	6.937113
Cool Runner	LNG Carrier	102097	81891	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
Cool Voyager	LNG Carrier	102097	81890	2013	19.5	Diesel Electric	LNG - MDO	160372	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
Coral Methane	LNG/Ethylene/LPG	7833	6150	2009	15.5	Diesel Electric	LNG - IFO	7500	13100	12900	5000	4545.455	454.5455	5.9144	3.114	3.206	190	285	175	55.29798	36.05532	32.44978	28.84425	25.23872
Cubal	LNG Carrier	100723	82857	2012	20	Diesel Electric	LNG - MDO	160534	39900	39900	27200	24727.27	1362.727	5.9144	3.114	3.206	190	285	175	16.5982	10.51013	9.459116	8.408103	7.357091

Experience	LNG/Regasification	116486	95105	2014	18	Diesel Electric		173660	35750	35100		0	250	5.9144	3.114	3.206	190	285	175					
Gaselys	LNG Carrier	97741	75600	2007	19	Diesel Electric	LNG - MDO	154472	39900	39900	28000	25454.55	1395.455	5.9144	3.114	3.206	190	285	175	19.70675	10.97683	9.879143	8.781461	7.683778
GasLog Santiago	LNG Carrier	98075	82178	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
GasLog Savannah	LNG Carrier	97818	82291	2010	19.5	Diesel Electric	LNG - MDO	155000	39900	39900	25300	23000	1285	5.9144	3.114	3.206	190	285	175	15.95502	10.54433	9.489899	8.435466	7.381033
GasLog Seattle	LNG Carrier	98075	81982	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500	25300	23000	1285	5.9144	3.114	3.206	190	285	175	16.01515	10.56315	9.506837	8.450522	7.394206
GasLog Shanghai	LNG Carrier	98075	82104	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
GasLog Singapore	LNG Carrier	97818	82339	2010	19.5	Diesel Electric	LNG - MDO	155000	39900	39900	23000	20909.09	1190.909	5.9144	3.114	3.206	190	285	175	14.51103	10.54142	9.487277	8.433135	7.378993
GasLog Skagen	LNG Carrier	98075	81847	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
GasLog Sydney	LNG Carrier	98075	82010	2013	19.5	Diesel Electric	LNG - MDO	155000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
GDF Suez Global Energy	LNG Carrier	49700	36145	2006	17.5	Diesel Electric	LNG - MDO	74130	22800	22800		0	250	5.9144	3.114	3.206	190	285	175					
Golar Celsius	LNG Carrier	102100	82048	2013	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
Golar Crystal	LNG Carrier	102100	82058	2014	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
Golar Seal	LNG Carrier	102100	82048	2013	19.5	Diesel Electric	LNG - MDO	160000	38500	38500		0	250	5.9144	3.114	3.206	190	285	175					
Independence	LNG/Regasification	110303	80305	2014	18	Diesel Electric	LNG - MDO	170000	29042	28650		0	250	5.9144	3.114	3.206	190	285	175					
Lena River	LNG Carrier	100236	84565	2013	19.5	Diesel Electric	LNG - MDO	155165	33000	33000		0	250	5.9144	3.114	3.206	190	285	175					
Lobito	LNG Carrier	100723	82929	2011	20	Diesel Electric	LNG - MDO	161337	39900	39900	27200	24727.27	1362.727	5.9144	3.114	3.206	190	285	175	16.58379	10.5058	9.455223	8.404642	7.354062
Magellan Spirit	LNG Carrier	104169	82187	2009	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	5.9144	3.114	3.206	190	285	175	16.72512	10.55065	9.495589	8.440524	7.385458
Malanje	LNG Carrier	100723	82728	2011	20	Diesel Electric	LNG - MDO	160400	39900	39900	27200	24727.27	1362.727	5.9144	3.114	3.206	190	285	175	16.62408	10.51789	9.466105	8.414316	7.362526
Marib Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	5.9144	3.114	3.206	190	285	175	16.88683	10.59888	9.538996	8.479107	7.419219
Meridian Spirit	LNG Carrier	104169	8192	2010	19.5	Diesel Electri	LNG - MDO	165772	38500	38500	26500	24090.91	1334.091	5.9144	3.114	3.206	190	285	175	16.77779	10.56639	9.509751	8.453112	7.396473

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Methane Becki Anne	LNG Carrier	109004	86269	2010	19.75	Diesel Electric	LNG - MDO	170678	39900	39900	25400	23090.91	1289.091	5.9144	3.114	3.206	190	285	175	15.08544	10.311	9.279903	8.248803	7.217703
Methane Mickie Harper	LNG Carrier	109004	86170	2010	19.75	Diesel Electric	LNG - MDO	170000	39900	39900	25400	23090.91	1289.091	5.9144	3.114	3.206	190	285	175	15.10277	10.31662	9.284955	8.253294	7.221632
Methane Spirit	LNG Carrier	104169	81400	2008	19.5	Diesel Electric	LNG - MDO	165500	39900	39900	26500	24090.91	1334.091	5.9144	3.114	3.206	190	285	175	16.88683	10.59888	9.538996	8.479107	7.419219
Provalys	LNG Carrier	97741	75600	2006	19	Diesel Electric	LNG - MDO	154472	38500	38500	28000	25454.55	1395.455	5.9144	3.114	3.206	190	285	175	19.70675	10.97683	9.879143	8.781461	7.683778
Seri Balhaf	LNG Carrier	105000	85999	2008	19.5	Diesel Electric	LNG - MDO	152300	40206	39820	12650	11500	767.5	5.9144	3.114	3.206	190	285	175	7.712126	10.32634	9.293702	8.261068	7.228435
Seri Balqis	LNG Carrier	107633	91198	2009	19.5	Diesel Electric	LNG - MDO	157611	40206	39820	25300	23000	1285	5.9144	3.114	3.206	190	285	175	14.39674	10.04299	9.038692	8.034393	7.030094
Soyo	LNG Carrier	100723	82857	2011	20	Diesel Electric	LNG - MDO	161337	39900	39900	27200	24727.27	1362.727	5.9144	3.114	3.206	190	285	175	16.5982	10.51013	9.459116	8.408103	7.357091
Stena Clear Sky	LNG Carrier	109949	96811	2011	20.4	Diesel Electric	LNG - MDO	173593	42100	41250	18667	16970	1013.65	5.9144	3.114	3.206	190	285	175	9.599952	9.762652	8.786387	7.810121	6.833856
Stena Crystal Sky	LNG Carrier	109949	96889	2011	20.4	Diesel Electric	LNG - MDO	173611	42100	41250		0	250	5.9144	3.114	3.206	190	285	175					
Tangguh Foja	LNG Carrier	97897	82338	2008	20	Diesel Electric	LNG - MDO	155641	39900	39900	25300	23000	1285	5.9144	3.114	3.206	190	285	175	15.54726	10.54148	9.487331	8.433183	7.379035
Tangguh Hiri	LNG Carrier	101957	84467	2008	20	Diesel Electric	LNG - MDO	155000	39900	39900		0	250	5.9144	3.114	3.206	190	285	175					
Tangguh Jaya	LNG Carrier	97897	82338	2008	20	Diesel Electric	LNG - MDO	155641	39900	39900	25300	23000	1285	5.9144	3.114	3.206	190	285	175	15.54726	10.54148	9.487331	8.433183	7.379035
Tangguh Palung	LNG Carrier	97897	82407	2009	20	Diesel Electric	LNG - MDO	155642	39900	39900	25300	23000	1285	5.9144	3.114	3.206	190	285	175	15.53424	10.53729	9.483565	8.429836	7.376106
Tangguh Sago	LNG Carrier	101957	84484	2009	20	Diesel Electric	LNG - MDO	154971	39900	39900	25300	23000	1285	5.9144	3.114	3.206	190	285	175	15.15234	10.4137	9.372329	8.330959	7.289589
Velikiy Novgorod	LNG Carrier	113876	93486	2014	19.5	Diesel Electric	LNG - MDO	170567	34000	34000		0	250	5.9144	3.114	3.206	190	285	175					
Woodside Donaldson	LNG Carrier	104169	82085	2009	19.5	Diesel Electric	LNG - MDO	165936	38500	38500	26500	24090.91	1334.091	5.9144	3.114	3.206	190	285	175	16.74591	10.55687	9.501181	8.445494	7.389807
Woodside Rogers	LNG Carrier	103928	90327	2013	19.9	Diesel Electric	LNG - MDO - HFO	160668	35852	35460			250	5.9144	3.114	3.206	190	285	175					
Yenisei River	LNG Carrier	100236	84604	2013	19.5	Diesel Electric	LNG - MDO	155000	33000	33000			250	5.9144	3.114	3.206	190	285	175					

Appendix 2- Full Dataset for Vessel case study

Date	Passage	Time	Speed A	Speed B	Cargo usd	FO usd	LNG FOE	RPM	Prop KW	Notes
18/06/2012 (12:00)	Ballast Passage	24:00:00	16.1	13.9	82.3	82.8	38.3	67.79	12200	Vessel in Bonny waiting area
19/06/2012 (12:00)	Ballast Passage	24:00:00	11.2	9.2	73.2	26.5	55.6	47.25	3317	ETA revised to 19th June/1400Lt (GMT+)
19/06/2012 (13:00)	Ballast Passage	01:00	11	8		1.4	3.1	50.52	0	
19/06/2012 (20:39)	Manoeuvering (B)	07:39								
20/06/2012 (12:00)	In Port Loading	15:00	0	0	0	29.3	35.8	0	0	
21/06/2012 (01:10)	In Port Loading	13:10								
21/06/2012 (03:30)	Manoeuvering (L)	02:20	3	2		19.6	24.5	0	0	FAOP
21/06/2012 (12:00)	Loaded Passage	08:30	18	16.1	0	87.4	37.2	79.24	20014	
22/06/2012 (12:00)	Loaded Passage	24:00:00	34.5	32.1	208.4	38.6	130.9	77.95	20500	Disharge port and ETA revised to Futtsu,Japan,18/97/2010@ 00:01LT.
23/06/2012 (12:00)	Loaded Passage	24:00:00	36	33.1	263.4	22	151.4	78.79	20925	
24/06/2012 (12:00)	Loaded Passage	23:00:00	17.9	16		0	169.2	78.88	21028	Wind>F5 in the last 24hrs. Clocks advanced to G.M.T +2
25/06/2012 (12:00)	Loaded Passage	24:00:00	18	16.3		0	178.7	79.2	20438	Wind>F5 in the last 24Hrs
26/06/2012 (12:00)	Loaded Passage	24:00:00	18.2	16.4		0	169.4	77.8	20665	Wind >F5 in the last 8hrs
27/06/2012 (12:00)	Loaded Passage	24:00:00	17.5	15.7			172.2	78.06	20622	Wind >F5 in the last 24 hrs
28/06/2012 (12:00)	Loaded Passage	23:00:00	17.1	16.3		0	161.3	77.83	20516	Wind>F5 in the last 24hrs. Clocks advanced to GMT +3
29/06/2012 (12:00)	Loaded Passage	24:00:00	18.5	16.9		0	173.4	78.94	20417	
30/06/2012 (12:00)	Loaded Passage	23:00:00	18.7	17		0	168.3	80	20360	Wind>F5 in the last 8hrs. Clocks advanced to GMT+4
01/07/2012 (12:00)	Loaded Passage	24:00:00	19	17.3		0	174.5	80.36	20624	Wind >F5 in the last 24hrs
02/07/2012 (12:00)	Loaded Passage	24:00:00	19.3	17.3		0	173.2	80.25	20245	wind >F5 in the last 24 hrs
03/07/2012 (12:00)	Loaded Passage	23:00	19.1	17.4		0	167.2	80.24	21010	Clocks advanced to GMT+5
04/07/2012 (12:00)	Loaded Passage	24:00:00	18.9	17.2		0	173.8	79.6	21076	E.T.A revised to 09:45LT / 18th July.clocks advanced to GMT +5
05/07/2012 (12:00)	Loaded Passage	23:00	18.8	16.9		0	167.2	78.4	19921	
06/07/2012 (12:00)	Loaded Passage	24:00:00	18.2	16.3		0	175.2	77.68	19599	Wind>F5 in the last 12hrs
07/07/2012 (12:00)	Loaded Passage	24:00:00	17.5	15.5		0	170.1	76.52	20293	Remarks: Wind>F5 in the last 8hrs.
08/07/2012 (12:00)	Loaded Passage	23:00	17	15.3		2.3	161.1	76.42	20223	Ships clock advanced to GMT+7. wind >F5 in the last 24hrs
09/07/2012 (12:00)	Loaded Passage	24:00:00	16.5	15.4		48.9	99.9	73.11	18832	

10/07/2012 (12:00)	Loaded Passage	23:00	18.7	16.8	201.8	25.3	125.1	76.55	15417	Ships clock advanced to GMT+8
11/07/2012 (12:00)	Loaded Passage	24:00:00	16.5	15.4		48.9	99.9	73.11	18832	Vessel transiting piracy area
12/07/2012 (12:00)	Loaded Passage	24:00:00	17.7	16.1	184.4	24.2	120.4	73.25	13805	
13/07/2012 (12:00)	Loaded Passage	24:00:00	16.4	14.4	179.8	20.5	90.6	65.5	10923	
14/07/2012 (12:00)	Loaded Passage	24:00:00	16.3	14.4	172.2	4.8	112.7	65.81	11265	
15/07/2012 (12:00)	Loaded Passage	24:00:00	16.2	13.1	161.9	3.3	106.7	62.11	11326	Remarks: Wind>F5 in the last 8hrs.
16/07/2012 (12:00)	Loaded Passage	23:00	16	14.1	173.7	8.6	107.1	65.64	11330	
17/07/2012 (12:00)	Loaded Passage	24:00:00	15.6	12.9	179.8	0	120.1	63.98	11398	Wind>F5 in the last 12 hours
18/07/2012 (07:30)	Loaded Passage	19:30	14.7	11.7		18.4	19.6	59.8	6300	
18/07/2012 (12:00)	Manoeuvering (L)	04:30	0	0		4	13.1	0	0	
18/07/2012 (12:44)	Manoeuvering (L)	00:44								
19/07/2012 (10:00)	In Port Discharging	21:16								
19/07/2012 (12:00)	Manoeuvering (B)	02:00	0	0	0	49.3	12.4	0	0	
19/07/2012 (12:30)	Manoeuvering (B)	00:30	10	8						
20/07/2012 (12:00)	Ballast Passage	23:30	17.7	16.1		97.1	57.8	79.67	21145	Wind >F5 in the last 16hrs
21/07/2012 (12:00)	Ballast Passage	24:00:00	18.4	16.4	78.4	119.4	51.2	79.37	19854	
22/07/2012 (12:00)	Ballast Passage	24:00:00	17.8	15.8	244.7	82.7	88.9	77.81	20370	Wind>F5 in the last 8hrs
23/07/2012 (12:00)	Ballast Passage	24:00:00	14.2	12.7	206.2	83	81.1	73.78	18374	Wind>F5 in the last 24hrs
24/07/2012 (12:00)	Ballast Passage	25:00:00	14.7	12.6		83.4	83.3	73.46	20914	Wind >F5 in the last 24 hrs. Clocks retarded to GMT+8
25/07/2012 (12:00)	Ballast Passage	24:00:00	17.1	15.2	35.2	99.7	66	77.4	20777	Wind >F5 in the last 24 hrs
26/07/2012 (12:00)	Ballast Passage	24:00:00	17	15.5	127.3	92.7	72.6	79.52	19505	Wind>F5 in the last 8hrs
26/07/2012 (18:30)	Ballast Passage	06:30	5.6	4.8		17.7	18.3	66.98		
27/07/2012 (12:00)	OPL	17:30	0	0		16.6	30.7	0	0	Bunkering Singapore
27/07/2012 (12:30)	OPL	00:30	24	14	2.5	0.7	0.9	26.4	0	Resume
28/07/2012 (12:00)	Ballast Passage	23:30	18.8	16.7	178.7	89.6	78.9	75.52	20354	Vsl on Security level 2
29/07/2012 (12:00)	Ballast Passage	25:00:00	17.8	16.4	238.1	90.4	82.1	78.83	20846	Ships clock retarded to GMT+7
30/07/2012 (12:00)	Ballast Passage	24:00:00	17.8	16.3	160.1	92	78.3	80.22	20780	Wind >F5 in the last 8hrs
31/07/2012 (12:00)	Ballast Passage	24:00:00	18.9	16.5	33.7	106	63.9	79.29	21220	Wind>F5 in the last 12hrs
01/08/2012 (12:00)	Ballast Passage	25:00:00	17.6	15.1	360.8	72.6	100.4	77.97	19217	Wind >F5 in the last 24 hrs.ships clock retarded to GMT+6

02/08/2012 (12:00)	Ballast Passage	24:00:00	16.7	14.3	33.3	83.6	78.7	75.64	16111	Wind >F5 in the last 24hrs. ETA revised to 21/08/2012@08:30hrs.
03/08/2012 (12:00)	Ballast Passage	24:00:00	15.5	13.3		71.5	56.1	65.11	3831	Wind>F5 in the last 12hrs
04/08/2012 (12:00)	Ballast Passage	25:00:00	16.5	14.5	214.1	71.7	75.8	69.92	14886	Sips clock retarded to GMT+5.
05/08/2012 (12:00)	Ballast Passage	24:00:00	15.9	13.8	158.7	72.5	72.4	69.55	14555	
06/08/2012 (08:30)	Ballast Passage	20:30	15.7	13.4		72.5	45.1	67.8		SOP for essential maintenance to steam plant
06/08/2012 (12:00)	OPL	03:30	92.3	78.6	4.7	1.8	0.7	0	0	
06/08/2012 (18:00)	OPL	06:00	0.6	0.3		5.1	1	1.18	9000	Resume
07/08/2012 (12:00)	Ballast Passage	19:00	16.3	13.2	104.7	55.5	48.2	68.42	15222	Clocks retarded to GMT +4
08/08/2012 (12:00)	Ballast Passage	24:00:00	16.5	14	308.7	54.7	83	70.21	14672	Wind>F5 in the last 16 hrs.
09/08/2012 (12:00)	Ballast Passage	24:00:00	14.5	12.5	21.9	51.7	85.4	68.01	15927	Wind > F5 in the last 24hrs
10/08/2012 (12:00)	Ballast Passage	25:00:00	14.4	12.2	29.8	91.8	52.6	68.52	13045	Clocks retarded to GMT+3. Wind>F5 in the last 16hrs
11/08/2012 (12:00)	Ballast Passage	24:00:00	12.4	9.8	117.9	67.5	46	61.22	11035	Wind > F5 in the last 24hrs. ETA revised to 23/08/12@ 17:00LT
12/08/2012 (12:00)	Ballast Passage	24:00:00	9.8	7.1	119.1	49.2	64.8	59.94	13490	Wind >f5 in thwe last 24 hrs
13/08/2012 (12:00)	Ballast Passage	25:00:00	14.8	12.4	130.4	60.4	69.3	67.22	12916	Clocks retarded to GMT+2
14/08/2012 (12:00)	Ballast Passage	24:00:00	13.3	10.9	35.3	39.2	58.2	59.29	8393	Wind >F5 in the last 12hrs
15/08/2012 (12:00)	Ballast Passage	24:00:00	10.5	7.9	91.9	31.6	53.4	45.79	6065	Wind >F5 in the last 16hrs
16/08/2012 (12:00)	Ballast Passage	24:00:00	12.8	10.5	33.1	42.2	46.2	53.51	6500	Wind >F5 in the last 24hrs
17/08/2012 (12:00)	Ballast Passage	24:00:00	10.3	8.4	42.1	23.2	40.1	44.81	3725	Wind > F5 in the last 8hrs
18/08/2012 (12:00)	Ballast Passage	25:00:00	10.2	8.3	134.2	30.7	37.9	43.8	3510	ETA REVISED TO 23/08/2012 .GMT +1
19/08/2012 (12:00)	Ballast Passage	24:00:00	8.3	6.3	22.7	21	28	35.41	1536	
20/08/2012 (12:00)	Ballast Passage	24:00:00	7.6	5.8	61.8	20	26.1	33.97	1507	
21/08/2012 (12:00)	Ballast Passage	24:00:00	7.7	5.9	6.1	17.7	33.8	32.67	1510	
22/08/2012 (12:00)	Ballast Passage	25:00:00	7.1	5	64.4	17	31.3	33.27	1419	ETA revised to 23/08/12@17:00 GMT+1
23/08/2012 (12:00)	Ballast Passage	24:00:00	8.8	6.5		28.8	29.8	37.2	2353	ETA revised to 24/08/2012@ 02:00 GMT +2
24/08/2012 (00:48)	Ballast Passage	12:48	8.6	6.4		24.9	9.7	37.24	1490	EOSP @ 24/08/2012 @00:48hrs
24/08/2012 (00:48)	Manoeuvering (B)	05:00								
24/08/2012 (05:48)	In Port Loading	06:12	0	0		24.7	3.6	0	0	
25/08/2012 (12:00)	In Port Loading	24:00:00	0	0		23.6	34	0	0	
25/08/2012 (12:30)	In Port Loading	00:30								

25/08/2012 (16:30)	Manoeuvering (L)	04:00	0	0		7	8	0	0	
26/08/2012 (12:00)	Loaded Passage	19:30	17.6	15.8	162.9	18	113	77.2	20942	GMT+1
27/08/2012 (12:00)	Loaded Passage	24:00:00	17.5	15.8	244.2	20	154	78.4	19404	GMT+1
28/08/2012 (12:00)	Loaded Passage	24:00:00	16.9	14.8	289.9	3	167	75.6	21065	GMT+1 100% gas burn from 15:00 hrs
29/08/2012 (12:00)	Loaded Passage	23:00:00	17.8	15.5	329.9	0	171	78.6	21312	Wind > F5 8 hours
30/08/2012 (12:00)	Loaded Passage	24:00:00	17	15	320.5	0	170	76.6	19641	GMT+2 Wind >F5 12 hours
31/08/2012 (12:00)	Loaded Passage	24:00:00	17.8	15.9	288	0	168.8	77	20800	GMT+2 Wind >F5 12 hours
01/09/2012 (12:00)	Loaded Passage	23:00:00	16.5	14.7	144.7	0	161	75.4	19223	GMT+3 Wind F>5 over the last 23hrs
02/09/2012 (12:00)	Loaded Passage	24:00:00	17.2	15.3	273.1	0	162	75.8	19671	GMT+3. Winds >F5 for 12 hours
03/09/2012 (12:00)	Loaded Passage	24:00:00	17.7	15.9	319.6	0	165	77.5	20811	GMT+3 Wind above F5 24 hours
04/09/2012 (12:00)	Loaded Passage	23:00	19.1	16.8	295.9	0	162	78.7	20249	Wind above F5 23 hours
05/09/2012 (12:00)	Loaded Passage	24:00:00	19.4	17	294	0	162	79	20099	Wind above F5 20 hours
06/09/2012 (06:30)	Loaded Passage	18:30	17.8	16.1	200.4	15	124	75.6	19671	OPL port call Mauritius, Dual fuel HRA
06/09/2012 (09:00)	OPL	02:30	3.2	2.1	2.5	5	3	60	19671	
06/09/2012 (12:00)	Loaded Passage	03:00	16.7	14.7	13.6	4	16	74.7	20295	
07/09/2012 (12:00)	Loaded Passage	23:00:00	17.4	15.7	249.1	18	144	77.3	20013	Wind above F5 20 hours
08/09/2012 (12:00)	Loaded Passage	24:00:00	17	15	204.6	19	147	76.1	19825	Wind above F5 24 hours
09/09/2012 (12:00)	Loaded Passage	24:00:00	16.6	15.1	252.4	19	148	75.6	19948	Wind abopve F5 24 hours
10/09/2012 (12:00)	Loaded Passage	24:00:00	17.6	16.2	266.5	19	150	77.4	20913	Wind above F5 16 hours
11/09/2012 (12:00)	Loaded Passage	24:00:00	19	17.1	297.1	19	152	79.8	21150	
12/09/2012 (12:00)	Loaded Passage	24:00:00	18.8	16.5	240.3	22	153	79.75	20772	
13/09/2012 (12:00)	Loaded Passage	24:00:00	18.3	16.3	274.5	19	155	79.2	21111	
14/09/2012 (02:48)	Loaded Passage	14:48	15.8	13.6	134.8	17	60	66.5	7806	
14/09/2012 (09:30)	Manoeuvering (L)	06:42								
14/09/2012 (12:00)	In Port Discharging	02:30	0	0	48.2	9	27	0	0	
15/09/2012 (08:26)	In Port Discharging	20:26								
15/09/2012 (09:18)	Manoeuvering (B)	00:52	0	0	0	41	5	0	0	Forced vapour mini fuel FOAP
15/09/2012 (12:00)	Ballast Passage	02:42	12.6	11.5	16	6	6	61.8	14955	
16/09/2012 (12:00)	Ballast Passage	24:00:00	17.9	17	377.5	21	150	76.4	20873	Wind>f5 24 hours

17/09/2012 (12:00)	Ballast Passage	24:00:00	19.1	16.9	141.5	22	149	78.4	15488	Wind above F5 20 hours
18/09/2012 (12:00)	Ballast Passage	24:00:00	17.4	14.9	239.1	20	124	71.6	15369	Wind above F5 20 hours
19/09/2012 (12:00)	Ballast Passage	24:00:00	17	14.9	164.7	18	131	71.7	16487	
20/09/2012 (12:00)	Ballast Passage	24:00:00	16.8	13.8	442	20	135	73.1	20114	Wind >F5 in last 12 hours
21/09/2012 (12:00)	Ballast Passage	24:00:00	17	14.3	287	19	142	75	1487	Wind above F5 24 hours
22/09/2012 (12:00)	Ballast Passage	25:00:00	18.2	15.4	107.6	20	144	76.1	14658	Wind above f5 25 hours
23/09/2012 (07:30)	Ballast Passage	19:30	14.5	12.4	0	20.4	67	72.3	1465	Suspend
23/09/2012 (10:30)	OPL	3:00:00	2	0.7	0	6	4	0	0	Resume
23/09/2012 (12:00)	Ballast Passage	01:30	17.7	12	0	3	5	56.5	19459	
24/09/2012 (12:00)	Ballast Passage	24:00:00	19.5	16.9	342.3	0	170	79.4	20907	Wind above F5 16 Hours 100% gas burn
25/09/2012 (12:00)	Ballast Passage	24:00:00	18.8	16.3	413.9	3	180	78.3	20932	Wind above F5 6 hours
26/09/2012 (12:00)	Ballast Passage	24:00:00	15.3	13.1	274	3	160	73.4	20403	Wind above F5 8 hours
27/09/2012 (12:00)	Ballast Passage	24:00:00	17	14.6	241.3	0	167	79.4	19497	winds >F5 24hrs
28/09/2012 (12:00)	Ballast Passage	25:00:00	16.7	14	423.3	8	1610	75.6	17637	Wind avove F5 25 hours
29/09/2012 (01:00)	Ballast Passage	13:00	15.5	12.9	0	2	86	73.4	17637	wind above f5 13 hours SUSPEND
29/09/2012 (03:30)	OPL	02:30	3.2	1.2	0	4	4	0	0	100% gas burn RESUME
29/09/2012 (12:00)	Ballast Passage	08:30	18.9	0	69.9	4	55	77.6	20554	
30/09/2012 (12:00)	Ballast Passage	24:00:00	19.3	16.8	308.8	2	159	78.64	20095	
01/10/2012 (07:36)	Ballast Passage	19:36	23	20	135.3	5	133	78.8	20095	Suspend passage for plant shutdown
01/10/2012 (12:00)	Maintenance	04:24	0	0	0	0	0	0	0	plant shut down
02/10/2012 (00:48)	Maintenance	12:48	1.7	0	0	5	30	0	0	PLANT STARTED
02/10/2012 (12:00)	Ballast Passage	11:12	10.6	8.8	0	6	25	44.8	3976	Wind above F5 8 hours
03/10/2012 (12:00)	Ballast Passage	24:00:00	16.7	14.6	286.9	1	121	68.1	13162	
04/10/2012 (12:00)	Ballast Passage	24:00:00	16.4	14.4	204.7	0	128	67.8	12863	
05/10/2012 (07:30)	Ballast Passage	19:30	16.7	14.7	96.5	2	98	67.5	12963	Suspend passage for bunker loading
05/10/2012 (12:00)	OPL	04:30	3.1	1.1	5.6	4	12	22.2	690	
06/10/2012 (00:00)	OPL	12:00	2.8	1.8	94.3	9	32	21.37	690	
06/10/2012 (12:00)	Ballast Passage	12:00	13.8	11.1	123.1	26	64	70.61	14446	
07/10/2012 (12:00)	Ballast Passage	24:00:00	14.3	12.2	207.3	30	93	61.8	13661	

08/10/2012 (04:30)	Ballast Passage	16:30	16.1	13.8	114.6	25	74	68.8	1647	
08/10/2012 (09:57)	Manoeuvering (B)	05:27								
08/10/2012 (12:00)	In Port Loading	03:03	0	0	0	12	13	0	0	
09/10/2012 (09:13)	In Port Loading	21:13								
09/10/2012 (11:00)	Manoeuvering (L)	01:47	1.2	1.2	0	31	30	0	0	Mini Fuel
09/10/2012 (12:00)	Loaded Passage	01:00	13.8	13.8	0	2	2	56	19532	
10/10/2012 (12:00)	Loaded Passage	24:00:00	18.5	16.8	221.3	21	160	79.5	20296	
11/10/2012 (12:00)	Loaded Passage	24:00:00	16.9	16.2	234.9	22	151	78.3	19350	
12/10/2012 (12:00)	Loaded Passage	24:00:00	17.3	16.2	314	2	172	77.9	19708	100% gas burn from 14:00 Wind above F5 12 hours
13/10/2012 (12:00)	Loaded Passage	24:00:00	18.7	16.8	317.6	0	177	79	20669	
14/10/2012 (12:00)	Loaded Passage	24:00:00	18.2	16.2	299.2	0	176	77.7	20353	
15/10/2012 (12:00)	Loaded Passage	24:00:00	16.7	15	333.2	0	176	76.2	20470	Wind abovev F5 24 hours
16/10/2012 (07:00)	Loaded Passage	19:00	12	10.4	166.6	5	98	67	7234	Suspend passage for bunkering LSDO
16/10/2012 (12:00)	OPL	05:00	2.1	1.3	16.7	4	11	0	0	
16/10/2012 (15:42)	OPL	03:32	0.5	0.3	6.3	4	7	56	1898	
17/10/2012 (12:00)	Loaded Passage	20:18	15.8	13.5	205.4	1	125	70.38	14606	
18/10/2012 (12:00)	Loaded Passage	23:00	14.3	12	139.1	18	91	58.6	6120	
18/10/2012 (15:00)	Loaded Passage	03:00	10.3	8	68.7	2	11	49.3	6120	
18/10/2012 (18:22)	Manoeuvering (L)	03:22								
19/10/2012 (12:00)	In Port Discharging	15:38	0	0	0	3	20	0	0	
19/10/2012 (17:05)	In Port Discharging	05:05								
19/10/2012 (18:00)	Manoeuvering (B)	00:55	0.9	0.9	0	4	6	54	13528	100% gas burn
20/10/2012 (12:00)	Ballast Passage	18:00	18.6	14.9	411	3	120	74	18395	
21/10/2012 (12:00)	Ballast Passage	25:00:00	18.2	15.9	95.7	0	175	75.28	18451	
22/10/2012 (12:00)	Ballast Passage	24:00:00	18.6	16.3	267.7	0	167	76.5	18129	
23/10/2012 (12:00)	Ballast Passage	24:00:00	19.2	17	298.4	0	178	78.5	18139	
24/10/2012 (12:00)	Ballast Passage	24:00:00	16.8	14.8	172.3	10	148	78.3	18139	
25/10/2012 (12:00)	Ballast Passage	24:00:00	15.8	13.8	183.7	31	114	68.2	18471	
26/10/2012 (12:00)	Ballast Passage	24:00:00	17.7	15	259.1	25	136	73.5	1549	

27/10/2012 (12:00)	Ballast Passage	24:00:00	15.8	14.2	318.8	20	128	69.9	14965	
28/10/2012 (12:00)	Ballast Passage	24:00:00	16.6	14.1	61.1	20	120	68.2	14965	
28/10/2012 (20:00)	Ballast Passage	08:00	14.3	11.4	88.3	7	28	57.1	6385	
29/10/2012 (01:07)	Manoeuvering (B)	05:07								
29/10/2012 (12:00)	In Port Loading	10:53	1.8	1.3	0	15	29	0	0	
29/10/2012 (23:09)	In Port Loading	11:09								
30/10/2012 (01:12)	Manoeuvering (L)	02:03	1.2	1.1	0	17	17	50	6385	Mini fuel
30/10/2012 (12:00)	Loaded Passage	10:48	17.3	15.4	63.8	10	64	76.4	19764	
31/10/2012 (12:00)	Loaded Passage	24:00:00	17.4	15.9	215.6	25	142	77.5	19919	
01/11/2012 (12:00)	Loaded Passage	24:00:00	18.3	16	264.6	2	165	77.4	18239	100% gas burn, IGG plant in use areating
02/11/2012 (12:00)	Loaded Passage	23:00	17.3	15.5	286	0	160	77.2	19716	
03/11/2012 (12:00)	Loaded Passage	24:00:00	18.4	15.9	299.5	0	166	77.5	21272	
04/11/2012 (12:00)	Loaded Passage	24:00:00	18.6	16.7	307.8	0	171	79.3	20714	
05/11/2012 (12:00)	Loaded Passage	24:00:00	18.5	16.5	284.2	0	169	79.2	20405	
06/11/2012 (12:00)	Loaded Passage	23:00	19.1	15.7	273.4	0	160	77.4	20609	
07/11/2012 (12:00)	Loaded Passage	24:00:00	17.7	15.6	305.4	0	172	78.8	21292	
08/11/2012 (12:00)	Loaded Passage	24:00:00	17.3	15.1	325.1	0	170	78	20857	
09/11/2012 (12:00)	Loaded Passage	23:00	16.9	15	294.5	0	165	77.9	20875	Wind above F5 12 hours
10/11/2012 (12:00)	Loaded Passage	24:00:00	18.5	16.2	336.5	0	165	78.2	20993	Wind above F5 24 hours
11/11/2012 (12:00)	Loaded Passage	23:00	18.2	16.2	302.3	2	158	81.6	21033	
12/11/2012 (12:00)	Loaded Passage	24:00:00	18	16.4	303	1	171	78.34	21012	
13/11/2012 (12:00)	Loaded Passage	24:00:00	17.6	16	308.2	0	173	77.9	20540	
14/11/2012 (12:00)	Loaded Passage	23:00	17.2	15.7	300.4	0	164	77.1	20903	
15/11/2012 (12:00)	Loaded Passage	24:00:00	17	15.5	301.2	0	173	77.2	20907	Wind >F5 16 hours
16/11/2012 (12:00)	Loaded Passage	24:00:00	17	15.5	313.8	0	169	76.7	20907	
17/11/2012 (12:00)	Loaded Passage	23:00	15.3	14.1	206.7	26	103	67.8	16325	
18/11/2012 (12:00)	Loaded Passage	24:00:00	17.5	16.3	233.9	22	140	75.4	18652	
19/11/2012 (12:00)	Loaded Passage	23:00	17.8	16.3	225.7	19	134	75.52	16247	
20/11/2012 (12:00)	Loaded Passage	24:00:00	17.5	15.5	232.9	23	125	72.9	15969	

21/11/2012 (12:00)	Loaded Passage	24:00:00	16	13.8	172.1	25	99	66.2	11347	
22/11/2012 (12:00)	Loaded Passage	23:00	16.1	14.4	222.5	0	139.5	68.7	11988	
23/11/2012 (12:00)	Loaded Passage	24:00:00	16.2	13.6	204.2	3	115	65.6	11474	
24/11/2012 (12:00)	Loaded Passage	24:00:00	12.8	9.9	129.9	22	100	62	11358	
25/11/2012 (12:00)	Loaded Passage	24:00:00	14.3	11.7	228.4	21	101	63.9	11599	
26/11/2012 (12:00)	Loaded Passage	24:00:00	14.5	12.3	196	20	101	63.9	11491	
27/11/2012 (05:30)	Loaded Passage	17:30	11.9	10.2	169	14	87	64.7	11491	
27/11/2012 (09:30)	Manoeuvering (L)	04:00								
27/11/2012 (12:00)	In Port Discharging	02:30	7.7	6.2	0	6	20	0	0	
28/11/2012 (06:30)	In Port Discharging	18:30								
28/11/2012 (12:00)	Manoeuvering (B)	05:30	0	0	4.2	48	18.3	0	0	
29/11/2012 (12:00)	Ballast Passage	24:00:00	18.5	16.3	154.7	102.9	59.2	78.21	21700	
30/11/2012 (12:00)	Ballast Passage	24:00:00	18.8	16.5	157.8	94.4	71	78.87	21173	
01/12/2012 (12:00)	Ballast Passage	24:00:00	19.2	17.4	69.3	90.6	75.2	79.54	20915	
02/12/2012 (12:00)	Ballast Passage	25:00:00	18.8	17.6	123.2	104.6	65.3	79.36	21030	
03/12/2012 (12:00)	Ballast Passage	24:00:00	19.1	17.5		93.1	70.9	79.51	20743	
04/12/2012 (12:00)	Ballast Passage	24:00:00	19.2	16.6	7.3	86.5	65.1	75.6	16504	
04/12/2012 (18:42)	Ballast Passage	06:42	13.6	12.7	12	13.2	16.7	60.27	0	
05/12/2012 (11:12)	OPL	16:30	0	0	16.8	26.3	19.5	4	6727	
05/12/2012 (12:00)	Ballast Passage	00:48	15.5	12.5		2.4	1.2	60.25	12725	
06/12/2012 (12:00)	Ballast Passage	24:00:00	18.5	16.5	241.2	85.2	70	75.2	20359	
07/12/2012 (12:00)	Ballast Passage	25:00:00	18.4	17.2	187.9	98.1	70.7	78.82	20224	
08/12/2012 (12:00)	Ballast Passage	24:00:00	18.6	16.8	171.8	100.4	70.5	78.1	20562	
09/12/2012 (12:00)	Ballast Passage	24:00:00	17.5	15.7	78.7	98.6	74.5	76.98	21316	
10/12/2012 (12:00)	Ballast Passage	25:00:00	18.4	16.1	33	96.4	79.6	77.9	19844	
11/12/2012 (12:00)	Ballast Passage	24:00:00	17.9	15.5	300.6	88.9	75.7	77.33	21011	Vessel experiencing adverse weather conditions and winds in excess of F5 over the pas
12/12/2012 (12:00)	Ballast Passage	24:00:00	17.4	15.4	74.2	81.6	81.6	75.78	18923	Vessel experiencing adverse weather conditions and winds in excess of F5 for the past
13/12/2012 (12:00)	Ballast Passage	25:00:00	17.7	15.5	109.1	106.3	62.3	76.03	18880	
14/12/2012 (12:00)	Ballast Passage	24:00:00	8	5.8	132.6	22.3	56.7	45.67	3622	Boiler shutdown operations.

15/12/2012 (12:00)	Ballast Passage	24:00:00	9.2	7	18.1	23.4	45.1	42.75	7599	
16/12/2012 (12:00)	Ballast Passage	25:00:00	16.6	14.4	204.3	88.6	75.3	75.76	20259	
17/12/2012 (12:00)	Ballast Passage	24:00:00	18.1	15.4	108.9	94.4	67.6	78	21344	
18/12/2012 (12:00)	Ballast Passage	25:00:00	17.4	15	72.6	90.6	70.1	75.76	21409	
19/12/2012 (12:00)	Ballast Passage	24:00:00	19	18.7	210	105.4	60.2	78.93	19343	
20/12/2012 (12:00)	Ballast Passage	25:00:00	18.3	17.9	97	94.6	70.2	77.05	20471	
21/12/2012 (12:00)	Ballast Passage	24:00:00	19.2	19.1	52.4	93.8	63.9	78.76	20859	
22/12/2012 (12:00)	Ballast Passage	24:00:00	11.8	11.9	1	23.3	56.1	49.45	1472	
23/12/2012 (12:00)	Ballast Passage	24:00:00	11.5	11.5	165.2	22.3	55.7	48.12	13408	
24/12/2012 (12:00)	Ballast Passage	25:00:00	14.3	14.4	100.2	42.8	60	56.31	6199	
25/12/2012 (12:00)	Ballast Passage	24:00:00	15.4	15.6	110	54.4	58.5	63.53	11850	
26/12/2012 (12:00)	Ballast Passage	24:00:00	15.8	15.8	161.8	36	83.4	64.99	12001	
27/12/2012 (08:30)	Ballast Passage	20:30	0	0	75.4	23	104.4	62	7066	
27/12/2012 (12:00)	Manoeuvering (B)	03:30	0	0	1.2	5.5	6.9	0	0	
27/12/2012 (13:24)	Manoeuvering (B)	01:24								
28/12/2012 (12:00)	In Port Loading	24:00:00	0	0	0	21.6	35	0	0	
28/12/2012 (13:19)	In Port Loading	01:19								
28/12/2012 (15:30)	Manoeuvering (L)	02:11	0	0	0	5.8	4.6	0	0	
29/12/2012 (12:00)	Loaded Passage	20:30	17.9	17.9	172.1	26.7	119.7	77.84	19907	
30/12/2012 (12:00)	Loaded Passage	24:00:00	17.9	17.8	235.5	19.6	148.7	77.16	20651	
31/12/2012 (12:00)	Loaded Passage	23:00	17.5	17.5	284.6	0	162.5	76.34	20906	
01/01/2013 (12:00)	Loaded Passage	24:00:00	17	17.2	302	0	173.2	77.11	19266	Vessel experiencing adverse weather conditions and head winds in excess of F5 for the
02/01/2013 (12:00)	Loaded Passage	24:00:00	15.4	15.5	275.5	0	162.9	73.65	20620	Vessel experiencing adverse weather conditions and head-on winds in excess of F5 for
03/01/2013 (12:00)	Loaded Passage	23:00	16.7	16.5	289.5	0	162	75.82	20330	Vessel experiencing adverse weather conditions and head winds in excess of F5 for the
04/01/2013 (12:00)	Loaded Passage	24:00:00	15.8	16.4	291.1	0	167.6	74.86	21185	Vessel experiencing adverse weather conditions and winds in excess of F5 for the past
05/01/2013 (12:00)	Loaded Passage	24:00:00	16.6	17.9	328.6	0	176.8	77.63	20858	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24
06/01/2013 (12:00)	Loaded Passage	23:00	17.6	18	317.3	0	168.6	78.28	21038	
07/01/2013 (12:00)	Loaded Passage	24:00:00	18.2	18.2	314.4	0	175.3	78.4	21175	
08/01/2013 (12:00)	Loaded Passage	24:00:00	17.8	18	332.5	0	175.1	78.3	20997	

09/01/2013 (12:00)	Loaded Passage	24:00:00	17.1	17.4	327.1	0	173.7	76.5	19916	Vessel experiencing strong winds in excess of F5 for the past 18 hours.
10/01/2013 (12:00)	Loaded Passage	23:00	17.1	17.3	306.1	0	167.1	76.89	20669	Vessel experienced strongs winds in excess of F5 for 20 hours in the past 24 hours.
11/01/2013 (12:00)	Loaded Passage	24:00:00	17.3	17.6	324.9	0	174.3	77.5	20852	Vessel experiencing strong winds >F5 for 12 hours in the past 24 hours.
12/01/2013 (12:00)	Loaded Passage	24:00:00	16.4	16.5	303.6	0	174.5	75.53	20966	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24 ho
13/01/2013 (12:00)	Loaded Passage	23:00	16.5	16.4	298.5	0	166.9	75.02	20836	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24 ho
14/01/2013 (12:00)	Loaded Passage	24:00:00	16.8	17	338.4	0	174.4	76.08	20866	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24 ho
15/01/2013 (12:00)	Loaded Passage	23:00	17.9	18.1	315.1	0	166.9	77.71	20876	
16/01/2013 (12:00)	Loaded Passage	24:00:00	17.6	17.9	282.1	8.4	160.4	76.48	19910	
17/01/2013 (12:00)	Loaded Passage	24:00:00	16.6	16.6	214.9	32.4	126.5	73.41	19847	Vessel was on SBE condition on 16/01/13 from 12:45LT to 18:45 LT for passage through
18/01/2013 (12:00)	Loaded Passage	24:00:00	16.9	17.3	211.69	28.2	142.9	77.23	21115	Vessel experienced winds in excess of F5 for 16 hours in the past 24 hours.
19/01/2013 (12:00)	Loaded Passage	23:00	16	15.4	225.9	24	141.9	75.68	20657	Vessel experiencing strong head winds in excess of F5, rough seas and heavy swell for t
20/01/2013 (12:00)	Loaded Passage	24:00:00	16.2	15.8	276.5	21.6	149.8	75.59	20776	Vessel experiencing strong head winds in excess of F5, rough seas and heavy swell for t
21/01/2013 (12:00)	Loaded Passage	24:00:00	17.7	17.6	273.5	21.5	149.5	77.5	20571	
22/01/2013 (12:00)	Loaded Passage	23:00:00	18.4	18	303.4	5.4	161.3	77.5	21085	Vessel experienced strong winds in excess of F5 for 12 hours in the past 24 hours.
23/01/2013 (12:00)	Loaded Passage	24:00:00	17.6	17.5	300.2	4.6	171.2	78.5	21277	Vessel experiecing winds if excess of F5 for the past 24 hours.
24/01/2013 (12:00)	Loaded Passage	24:00:00	15.6	15.8	256.8	0	142.8	70.58	15196	Vessel experiencing winds in excess of F5 for the past 24 hours.
25/01/2013 (09:00)	Loaded Passage	21:00	9	9	148.1	16.9	84.1	47.3	6500	
25/01/2013 (12:00)	Manoeuvering (L)	03:00								
25/01/2013 (15:24)	Manoeuvering (L)	03:24								
26/01/2013 (10:40)	In Port Discharging	19:12								
26/01/2013 (12:00)	Manoeuvering (B)	01:20	0	0	0	60.8	31.5	0	0	
26/01/2013 (13:00)	Manoeuvering (B)	01:00	0	0	0	3	1.5	0	0	
27/01/2013 (12:00)	Ballast Passage	23:00	18.1	18.2	55.7	116.9	36.1	77	20239	
28/01/2013 (12:00)	Ballast Passage	24:00:00	18.5	19	29.6	126.6	42.7	77.63	20802	
29/01/2013 (12:00)	Ballast Passage	24:00:00	18.3	18.8	158.9	100.6	68.9	78.51	21152	
30/01/2013 (12:00)	Ballast Passage	24:00:00	19.3	19.4	193.2	91.2	76.6	79.4	21267	
31/01/2013 (12:00)	Ballast Passage	25:00:00	18.1	19.1	73.3	104.6	66.5	77.7	21210	
01/02/2013 (12:00)	Ballast Passage	24:00:00	19.1	19	11.2	109.5	50.7	76.93	19294	
01/02/2013 (17:30)	Ballast Passage	05:30	16.5	16.7	6.3	24.2	6.4	66.77	0	

02/02/2013 (12:00)	OPL	18:30	0	0	17.6	25	22	0	0	
02/02/2013 (14:30)	OPL	02:30	1.6	1.6	0	3	3	0	0	
03/02/2013 (12:00)	Ballast Passage	21:30	18.1	18.3	123	106	36	75.6	21552	
04/02/2013 (12:00)	Ballast Passage	24:00:00	19.4	19.6	132.1	98	67	79.67	21194	
05/02/2013 (12:00)	Ballast Passage	25:00:00	17.6	17.8	181.3	72	100	76.7	21149	
06/02/2013 (12:00)	Ballast Passage	24:00:00	17.8	18	225	94	72	78.09	21320	
07/02/2013 (12:00)	Ballast Passage	25:00:00	18.7	18.8	159.1	91	84	0	0	
08/02/2013 (12:00)	Ballast Passage	24:00:00	18.9	19	141.2	89.6	79	0	0	
09/02/2013 (12:00)	Ballast Passage	24:00:00	18.1	18.4	55	93	74	74.2	1777	Vessel reduced speed due to force magjour
10/02/2013 (12:00)	Ballast Passage	24:00:00	7	7.2	4.1	25	30	32.87	1610	
11/02/2013 (12:00)	Ballast Passage	24:00:00	6.6	7	72	26	31	32.7	14615	
12/02/2013 (12:00)	Ballast Passage	24:00:00	7.1	7.3	243.7	24	38	34.3	4637	Single boiler steaming from 09:00
13/02/2013 (12:00)	Ballast Passage	24:00:00	9.4	9.9	20	13	66	49.4	4214	
14/02/2013 (12:00)	Ballast Passage	24:00:00	10.5	10.9	146	20	58	46.6	4603	
15/02/2013 (12:00)	Ballast Passage	24:00:00	10.5	11	88.3	15	65	46.3	4530	Change over boilers Stbd boiler now in use
16/02/2013 (12:00)	Ballast Passage	24:00:00	10.3	11	120.6	16	62	46.5	4675	
17/02/2013 (12:00)	Ballast Passage	25:00:00	10.1	10.3	144.4	14	69	46.4	4676	
18/02/2013 (12:00)	Ballast Passage	24:00:00	10	10.3	100.1	15	66	46.5	4524	
19/02/2013 (12:00)	Ballast Passage	24:00:00	10.7	10.6	254.8	23	58	46.5	4931	Both boilers in use from 11:30
20/02/2013 (12:00)	Ballast Passage	24:00:00	12	11.4	127.4	62	77	62.7	17034	Vessel experiencing gale force winds with rough seas and heavy swells for the past 24 h
21/02/2013 (12:00)	Ballast Passage	24:00:00	14.2	14.6	14	85	75	70	16800	Vessel experienced rough seas, heavy swell and winds in excess of F5 for 18 hours in th
22/02/2013 (12:00)	Ballast Passage	24:00:00	10.8	10.7	90.5	19	59	45.3	3695	
23/02/2013 (12:00)	Ballast Passage	24:00:00	10.4	10.3	95.6	16	49	42.6	3461	
24/02/2013 (12:00)	Ballast Passage	24:00:00	10.1	10.2	46.9	15	50	42.7	3333	
25/02/2013 (07:00)	Ballast Passage	19:00	10.3	7	29.7	12	40	42.07	3333	Plant shut down at sea for Essential Maintenance
25/02/2013 (12:00)	Maintenance	05:00	1.2	1.2	4.8	0	0	0	0	
26/02/2013 (01:00)	Maintenance	13:00	0	0	0	3	3	3	3333	
26/02/2013 (12:00)	Ballast Passage	11:00	9.1	9.1	52.4	8	20	39.2	1577	
27/02/2013 (12:00)	Ballast Passage	24:00:00	8	8	0.5	14	35	33	1702	

28/02/2013 (12:00)	Ballast Passage	25:00:00	9.4	9.2	92.2	14	46	38.8	1600	
01/03/2013 (12:00)	Ballast Passage	24:00:00	7.7	7.7	107.7	19	33	33	3239	
02/03/2013 (12:00)	Ballast Passage	24:00:00	9.9	10	10.2	24	39	41.8	3118	
03/03/2013 (12:00)	Ballast Passage	24:00:00	8.9	8.9	78.3	26	31	39	2723	
04/03/2013 (12:00)	Ballast Passage	24:00:00	9	9.3	0.3	35	27	39.4	1862	
05/03/2013 (12:00)	Ballast Passage	24:00:00	8	8.1	59.6	31	27	36.7	2418	
06/03/2013 (12:00)	Ballast Passage	24:00:00	8.5	8.3	72.9	30	29	37.4	2491	
07/03/2013 (12:00)	Ballast Passage	24:00:00	8.3	8.4	60.6	24	33	37.4	2471	
08/03/2013 (12:00)	Ballast Passage	24:00:00	8.7	8.8	59.9	26	34	38.3	2296	
09/03/2013 (12:00)	Ballast Passage	24:00:00	6.8	6.5	10.7	52	7	33.4	1605	
10/03/2013 (12:00)	Ballast Passage	24:00:00	7.5	7.7	0	56	4	33	6430	
10/03/2013 (21:00)	Ballast Passage	09:00	5.3	5.3	0	25	13	52.7	6414	
11/03/2013 (02:50)	Manoeuvering (B)	05:50								
11/03/2013 (12:00)	In Port Loading	21:10:00	0	0	0	35	2	0	0	
12/03/2013 (12:00)	In Port Loading	24:00:00								
12/03/2013 (13:06)	In Port Loading	01:06								
12/03/2013 (15:30)	Manoeuvering (L)	02:24	6	5.5	6	6	3	60	6414	
13/03/2013 (12:00)	Loaded Passage	20:30	17.2	17.3	204.4	19	130	77.6	21458	
14/03/2013 (12:00)	Loaded Passage	24:00:00	18.2	18.3	253.2	19	155	78.2	21190	
15/03/2013 (12:00)	Loaded Passage	24:00:00	18	18.2	302.1	9	168	78.2	20310	
16/03/2013 (12:00)	Loaded Passage	23:00	17.1	17.3	281.1	0	162	76.5	20332	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 20HR
17/03/2013 (12:00)	Loaded Passage	24:00:00	16.5	16.5	314.5	0	170	76.1	20333	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24HR
18/03/2013 (12:00)	Loaded Passage	24:00:00	17.4	17.8	317.7	0	167	77.1	207176	V/L experienced wind > F5 for 16HRS in the past 24HRS
19/03/2013 (12:00)	Loaded Passage	23:00	17	18.1	287.1	0	162	77.8	20765	Wind above F5 6 hours Agulhas current against vessel, having effect on speed/distance
20/03/2013 (12:00)	Loaded Passage	24:00:00	17.5	18.3	303.8	0	168	77.5	20118	
21/03/2013 (12:00)	Loaded Passage	24:00:00	17.5	18.1	307.3	0	168	77.1	20464	
22/03/2013 (12:00)	Loaded Passage	23:00	17.4	17.7	375	0	160	76.3	20387	V/L experienced wind >F5 for 16HRS in the past 24HRS
23/03/2013 (12:00)	Loaded Passage	24:00:00	17.4	17.8	321.8	0	168	76.3	20302	V/L experienced wind >F5 for 16HRS in the last 24HRS
24/03/2013 (12:00)	Loaded Passage	24:00:00	17.5	17.3	308.9	0	169	76.9	20514	V/L experienced wind >F5 for 4HRS in the last 24HRS

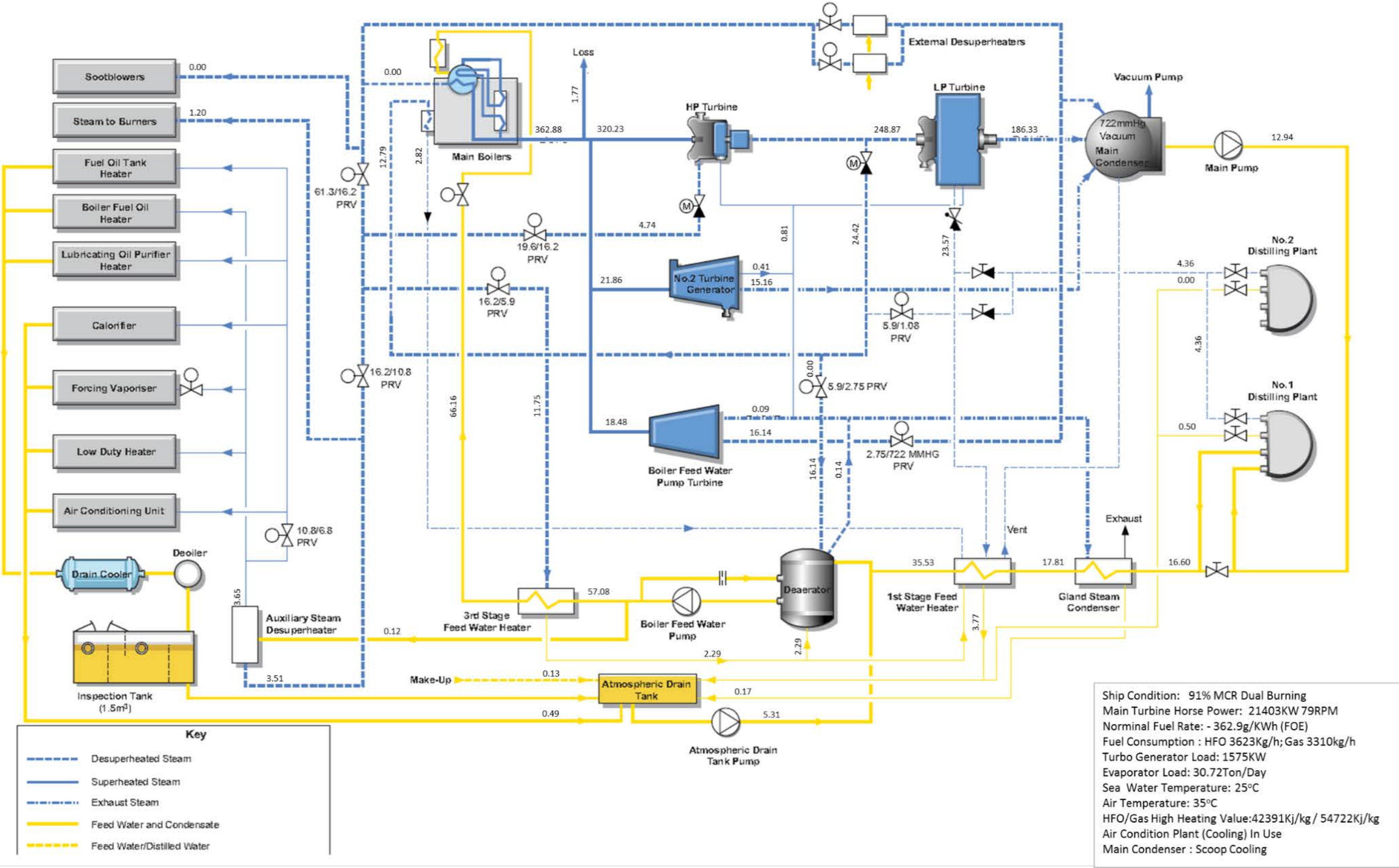
25/03/2013 (12:00)	Loaded Passage	23:00	16.1	16.3	313.9	0	163	74.9	20488	V/L experiencing wind >F5 for the past 24HRS
26/03/2013 (12:00)	Loaded Passage	24:00:00	14.8	14.8	343.8	0	163	72.5	19910	V/L experienced wind >F5 for 20HRS in the past 24HRS. IGG plant in use producing dry a
27/03/2013 (12:00)	Loaded Passage	24:00:00	15.6	16	299.1	0	170	74.4	19541	V/L experiencing wind >F5 for the past 24HRS
28/03/2013 (12:00)	Loaded Passage	23:00	15.6	16	320.7	0	169	73.9	20081	V/L experiencing wind >F5 for the past 24HRS
29/03/2013 (12:00)	Loaded Passage	24:00:00	16.7	16.7	330	0	172	74.7	21607	V/L experiencing wind >F5 for the past 24HRS
30/03/2013 (12:00)	Loaded Passage	23:00	17.2	17.4	307	0	168	73.8	20861	V/L experienced wind >F5 for 20HRS in the past 24HRS
31/03/2013 (12:00)	Loaded Passage	24:00:00	16.9	17.5	336.5	10	164	76.1	18074	
01/04/2013 (12:00)	Loaded Passage	24:00:00	17.4	17.4	121.5	20	142	73.64	20088	
02/04/2013 (12:00)	Loaded Passage	24:00:00	17.5	17.4	254.7	21	151	77.3	20067	
03/04/2013 (12:00)	Loaded Passage	23:00	17.7	17.7	233.2	20	142	77.15	19933	
04/04/2013 (12:00)	Loaded Passage	24:00:00	18.1	18.4	241.6	21	151	77.5	20076	
05/04/2013 (12:00)	Loaded Passage	24:00:00	18.4	18.6	228.2	21	145	77.8	19966	
06/04/2013 (12:00)	Loaded Passage	23:00	18.6	18.3	233.7	0	160	77.5	19901	V/L experienced wind >F5 for 4HRS in the past 24HRS
07/04/2013 (12:00)	Loaded Passage	24:00:00	11.4	11	299.4	0	163	68.8	16784	V/L experiencing wind >F5 for the past 24HRS.
08/04/2013 (12:00)	Loaded Passage	24:00:00	14.7	14.6	291.6	0	151	70.15	11748	V/L experienced wind>F5 for 20HRS in the past 24HRS
09/04/2013 (12:00)	Loaded Passage	24:00:00	11.4	11.3	188.7	26	69	48.7	455	EOP
09/04/2013 (15:58)	Manoeuvering (L)	03:58								
10/04/2013 (12:00)	In Port Discharging	16:02	7.8	6.8	0	26	0	0	0	
11/04/2013 (12:00)	In Port Discharging	24:00:00	0	0	0	52	15	0	0	
11/04/2013 (13:20)	In Port Discharging	01:20								
11/04/2013 (16:24)	Manoeuvering (B)	03:04	10.3	9.7	0	12	8	70	10586	
12/04/2013 (12:00)	Ballast Passage	19:36	18.4	18.2	33.5	95	42	76.8	15341	
13/04/2013 (12:00)	Ballast Passage	24:00:00	16.8	16.9	41.2	96	43	69.6	11222	
14/04/2013 (12:00)	Ballast Passage	25:00:00	14.1	14.6	112	92	34	0	0	
15/04/2013 (12:00)	Ballast Passage	24:00:00	15	15.5	23.1	84	38	63.6	11089	
16/04/2013 (12:00)	Ballast Passage	24:00:00	15.3	15.3	33.6	85	34	63.7	8409	
17/04/2013 (12:00)	Ballast Passage	24:00:00	11.9	12	140.3	52	48	49.8	18682	
18/04/2013 (12:00)	Ballast Passage	24:00:00	15.4	15.3	202.6	39	104	66.2	11061	
19/04/2013 (05:48)	Ballast Passage	17:48	14.7	14.6	8.4	44	45	60	11061	Bunkering Singapore

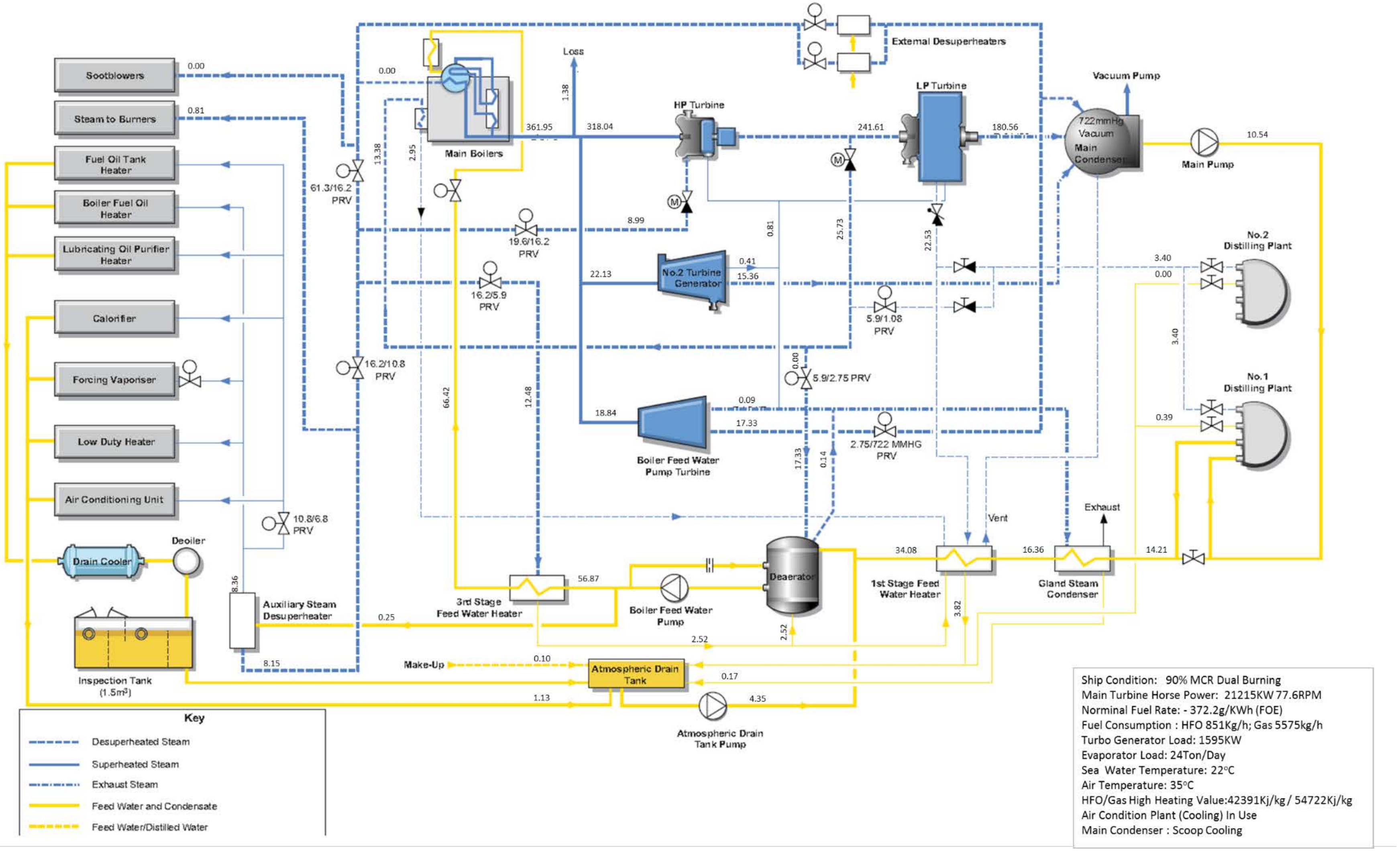
19/04/2013 (12:00)	OPL	06:12	2.3	1.8	4.4	12	7.4	0	0	
20/04/2013 (06:30)	OPL	16:30	3.8	3.8	19.3	19.6	25.6	0	0	
20/04/2013 (12:00)	Ballast Passage	05:30	18	17.8	7.1	31.7	7.2	73.59	20211	
21/04/2013 (12:00)	Ballast Passage	24:00:00	16.9	16.8	115.3	115.8	37.7	71.62	15886	
22/04/2013 (12:00)	Ballast Passage	24:00:00	16.2	16.1	138.3	78.2	68.3	69.73	11170	
23/04/2013 (12:00)	Ballast Passage	25:00:00	15	14.9	81.4	55.9	71.6	63.59	11223	
24/04/2013 (07:00)	Ballast Passage	19:00	14.4	14.3	95.4	58.1	35	61.43	0	
24/04/2013 (12:00)	Maintenance	05:00	0.8	0.2	17.8	0.5	0	0	0	
25/04/2013 (00:00)	Maintenance	12:00	1.8	0.8	0	3.8	0.9	0.64	4387	Resume
25/04/2013 (12:00)	Ballast Passage	12:00	9	9	0	17	23.8	43.3	3721	
26/04/2013 (12:00)	Ballast Passage	24:00:00	12.6	12.7	133.8	33.6	73.6	54.96	13011	
27/04/2013 (12:00)	Ballast Passage	25:00:00	15	14.9	0	69	99.7	65.95	13526	
28/04/2013 (12:00)	Ballast Passage	24:00:00	15	15.1	0	60.8	45.7	65.97	12896	
29/04/2013 (12:00)	Ballast Passage	24:00:00	15.1	15.1	98.4	61.3	72.5	65.82	12721	
30/04/2013 (12:00)	Ballast Passage	25:00:00	14.9	15	120.4	64.5	75.5	65.88	13130	
01/05/2013 (12:00)	Ballast Passage	24:00:00	15.1	15.4	0	96.9	35.5	65.81	12736	
02/05/2013 (12:00)	Ballast Passage	24:00:00	14.5	14.4	266.3	114.4	21.7	65.78	15805	V/L experiencing wind >F5 for the past 24HRS
03/05/2013 (12:00)	Ballast Passage	25:00:00	15.7	16	0	73.2	89.5	70.61	16007	
04/05/2013 (10:18)	Ballast Passage	22:18	16.5	16.6	0	55.2	88.7	70.2	14642	Immobilization and main engine shut down for repairs
04/05/2013 (12:00)	Maintenance	01:42	1.2	0.6	118	1.4	2.1	0	0	
04/05/2013 (12:42)	Maintenance	00:42	1.4	0	0	0.8	1.2	0	0	
05/05/2013 (12:00)	Ballast Passage	24:18:00	13.1	12.8	445.4	39.4	102.6	66.01	18116	Vessel experienced rough seas, heavy swell and winds in excess of F5 for 20 hours in th
06/05/2013 (12:00)	Ballast Passage	24:00:00	16.9	16.2	122.4	84	81.9	72.86	17693	
07/05/2013 (12:00)	Ballast Passage	24:00:00	16.8	16.7	11.6	79.5	78.1	72.38	13486	
08/05/2013 (12:00)	Ballast Passage	25:00:00	11.1	10.8	0	33	40.2	44.94	3493	
09/05/2013 (12:00)	Ballast Passage	24:00:00	10.1	10.2	11.8	33.2	29.6	41.9	2522	
10/05/2013 (12:00)	Ballast Passage	25:00:00	8.6	8.7	26	29.7	23.6	35.39	1800	
11/05/2013 (12:00)	Ballast Passage	24:00:00	8.8	8.8	57.9	23.9	26.7	35.53	2213	
12/05/2013 (12:00)	Ballast Passage	24:00:00	8.8	9.1	6	31.3	26.3	37.47	2422	

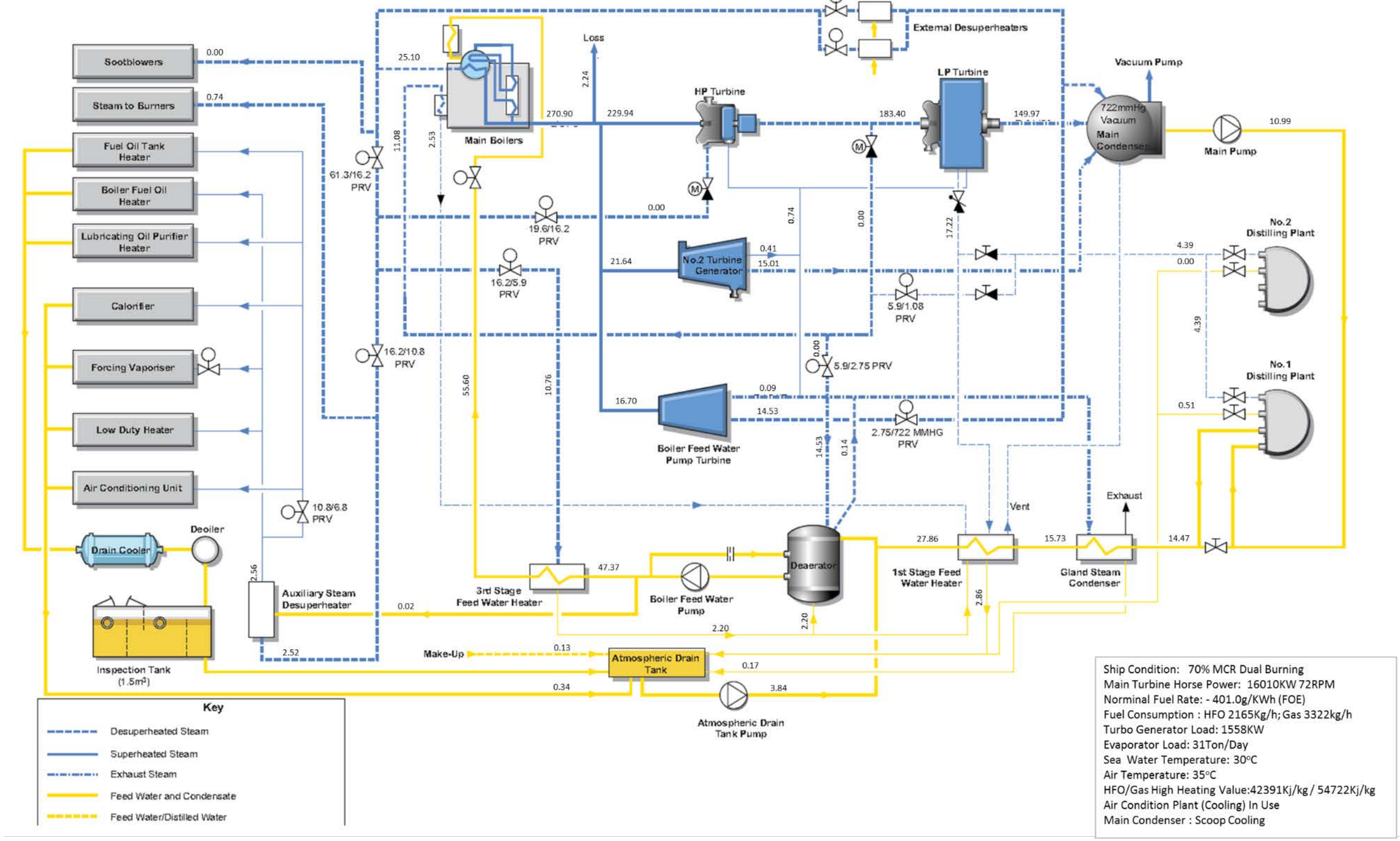
13/05/2013 (12:00)	Ballast Passage	24:00:00	8.8	8.9	28.4	32.1	23.5	36.1	1621	
14/05/2013 (12:00)	Ballast Passage	24:00:00	7.6	7.8	63.7	19.6	33	33.59	1627	
15/05/2013 (12:00)	Ballast Passage	24:00:00	7.8	7.8	22.6	31.4	22.9	33.04	1593	
16/05/2013 (12:00)	Ballast Passage	24:00:00	7.8	7.8	83.7	27.8	26.3	33.14	1644	
17/05/2013 (12:00)	Ballast Passage	24:00:00	8	8.5	25.5	22	31	31.35	1645	
18/05/2013 (12:00)	Ballast Passage	24:00:00	7.2	7.3	80.7	27.8	27.1	32.59	1615	
19/05/2013 (12:00)	Ballast Passage	24:00:00	7.3	7.2	65.1	21.4	30.3	32.83	1474	
20/05/2013 (12:00)	Ballast Passage	24:00:00	7	7	49.9	19.3	30.8	32.77	1635	
21/05/2013 (12:00)	Ballast Passage	24:00:00	7	6.9	56.9	17.1	32.4	32.97	1515	
22/05/2013 (12:00)	Ballast Passage	24:00:00	7	7	13.6	13.9	33.8	32.04	1680	
23/05/2013 (12:00)	Ballast Passage	24:00:00	7.5	7.5	81.5	10.7	38.7	34.34	3512	
24/05/2013 (12:00)	Ballast Passage	24:00:00	10.5	10.6	123.7	15.1	58.1	46.57	5167	
25/05/2013 (12:00)	Ballast Passage	24:00:00	10.7	10.7	132.9	13.9	64.9	46.74	4689	
26/05/2013 (12:00)	Ballast Passage	24:00:00	12.4	12.5	156.5	23.3	76.9	54.88	6821	
27/05/2013 (12:00)	Ballast Passage	24:00:00	12.4	12.4	0	26.2	70.5	52.86	7981	
27/05/2013 (14:00)	Ballast Passage	02:00	13	12.5	0	5.7	4.1	59.16	6308	
27/05/2013 (19:23)	Manoeuvering (B)	05:23								
28/05/2013 (12:00)	In Port Loading	16:37	0	0	0	31.2	27.7	0	0	
29/05/2013 (06:41)	In Port Loading	18:41								
29/05/2013 (08:42)	Manoeuvering (L)	02:01	6.4	6.4	0	68	31.4	0	0	
29/05/2013 (12:00)	Loaded Passage	03:18	16.4	16.1	0	8.4	14.7	72.99	19813	
30/05/2013 (12:00)	Loaded Passage	24:00:00	17.6	17.4	239.2	20.4	156.7	75.24	20179	
31/05/2013 (12:00)	Loaded Passage	24:00:00	17.2	17.3	237.8	20.2	157.2	76.45	19735	
01/06/2013 (12:00)	Loaded Passage	23:00	16.3	16.4	235.2	19.7	152.1	75.34	20237	Vessel experienced wind > F5 for 12 hours in the past 24 hours.
02/06/2013 (12:00)	Loaded Passage	24:00:00	15.9	16.2	285.8	21.1	159.8	75.19	19388	Vessel experienced wind > F5 for the past 24 hours.
03/06/2013 (12:00)	Loaded Passage	24:00:00	14.9	15	256.6	20.3	155.5	73.03	20519	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24 h
04/06/2013 (12:00)	Loaded Passage	24:00:00	14	14.3	259.7	28	146.6	71.94	19423	Vessel experienced rough seas, heavy swell and winds in excess of F5 for 16 hours in th
05/06/2013 (12:00)	Loaded Passage	23:00	15	15.5	61.8	31.8	132.6	72.4	20519	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24 h
06/06/2013 (12:00)	Loaded Passage	24:00:00	16.8	17.8	457.8	35.8	143	76.93	19799	V/L experiencing wind >F5 for the past 24HRS

07/06/2013 (12:00)	Loaded Passage	24:00:00	17.5	18.2	234.4	36.4	142.3	77.5	20552	Vessel experienced rough seas, heavy swell and winds in excess of F5 for 12 hours in th
08/06/2013 (12:00)	Loaded Passage	23:00	17.7	18	227.9	34.9	136.5	77.66	20366	Vessel experiencing rough seas, heavy swell and winds in excess of F5 for the past 24 ho
09/06/2013 (12:00)	Loaded Passage	24:00:00	17.8	17.8	237.3	36.2	142.9	77.62	18224	V/L experiencing wind >F5 for the past 24HRS
10/06/2013 (12:00)	Loaded Passage	24:00:00	17.3	17.5	253.1	27.5	137	75.17	20122	
11/06/2013 (12:00)	Loaded Passage	23:00	15.9	16	144	31.5	107.6	68.76	13538	
12/06/2013 (12:00)	Loaded Passage	24:00:00	15.5	15.4	167.3	35.8	108.1	67.42	13618	
13/06/2013 (12:00)	Loaded Passage	24:00:00	14.5	14.4	166.5	35.5	107.6	65.32	13230	Vessel experienced wind > F5 for 20 hours in the past 24 hours.
14/06/2013 (12:00)	Loaded Passage	23:00	13.7	13.8	202.2	20.6	109.2	63.31	11545	V/L experiencing wind >F5 for the past 24HRS
15/06/2013 (12:00)	Loaded Passage	24:00:00	12.8	13.1	167.6	25.3	101	61.61	12253	V/L experiencing wind >F5 for the past 24HRS

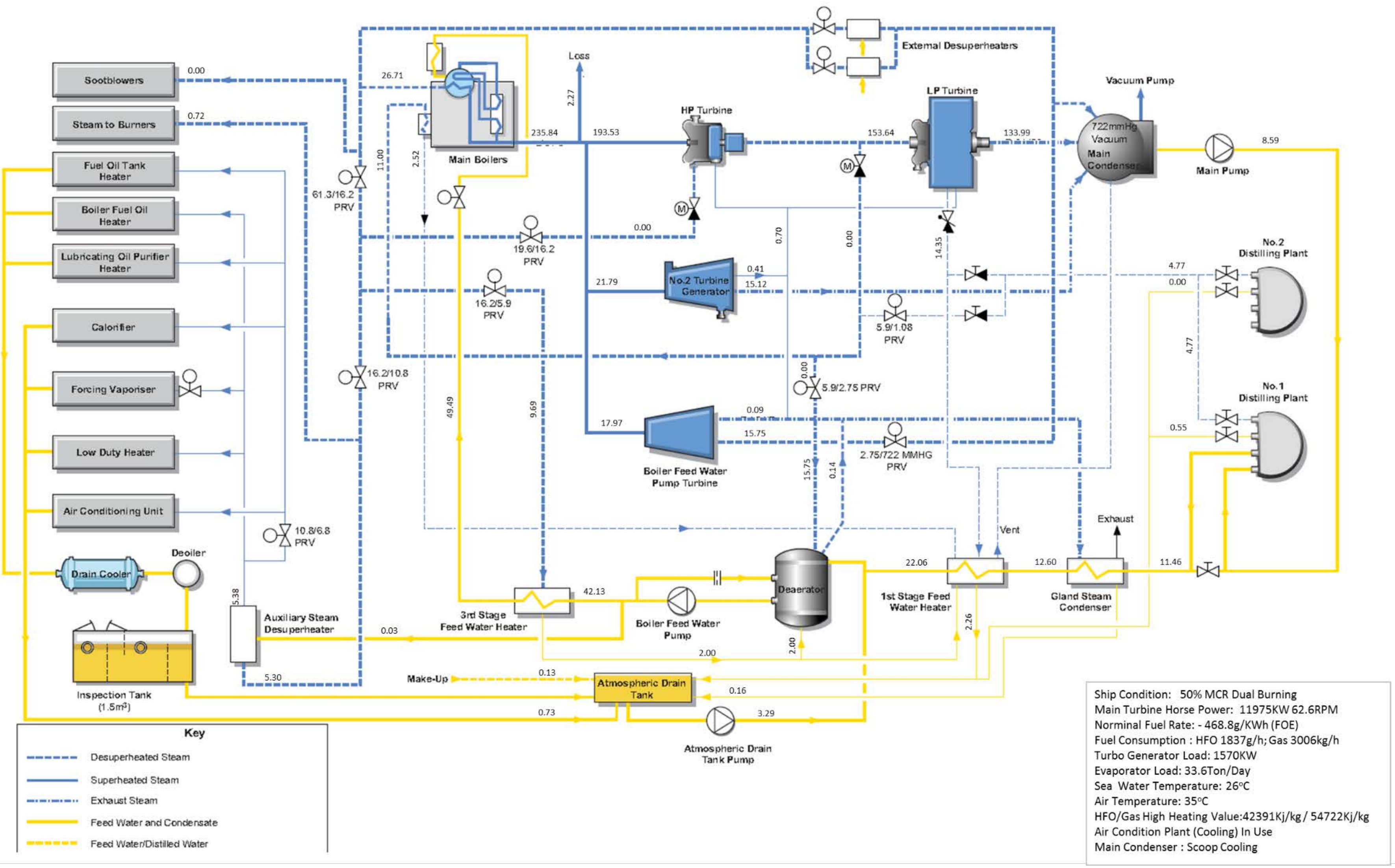
Appendix 3- Energy Flow Diagrams for the different conditions



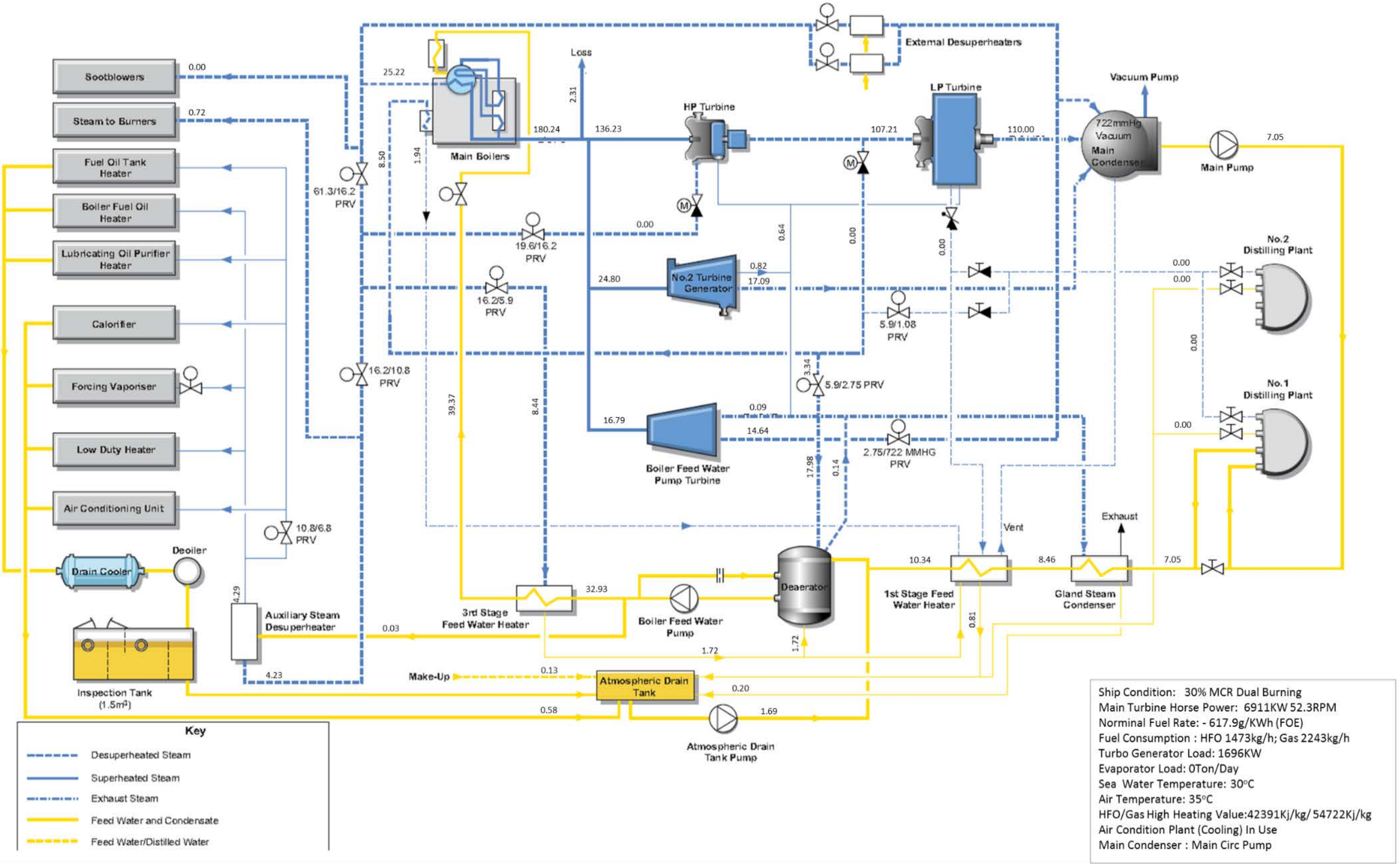

Sootblowers
Steam to Burners
Fuel Oil Tank Heater
Boiler Fuel Oil Heater
Lubricating Oil Purifier Heater
Calorifier
Forcing Vaporiser
Low Duty Heater
Air Conditioning Unit
Drain Cooler
Deoiler
Inspection Tank (1.5m³)
Auxiliary Steam Desuperheater
Main Boilers
Loss
External Desuperheaters
HP Turbine
LP Turbine
Vacuum Pump
722mmHg Vacuum Main Condenser
Main Pump
No.2 Distilling Plant
No.1 Distilling Plant
No.2 Turbine Generator
Boiler Feed Water Pump Turbine
61.3/16.2 PRV
19.6/16.2 PRV
16.2/5.9 PRV
16.2/10.8 PRV
10.8/6.8 PRV
5.9/1.08 PRV
5.9/2.75 PRV
2.75/722 MMHG PRV
3rd Stage Feed Water Heater
Boiler Feed Water Pump
Deaerator
1st Stage Feed Water Heater
Gland Steam Condenser
Exhaust
Vent
Make-Up
Atmospheric Drain Tank
Atmospheric Drain Tank Pump
Key
Desuperheated Steam
Superheated Steam
Exhaust Steam
Feed Water and Condensate
Feed Water/Distilled Water
Ship Condition: 90% MCR Dual Burning
Main Turbine Horse Power: 21215KW 77.6RPM
Norminal Fuel Rate: - 372.2g/KWh (FOE)
Fuel Consumption : HFO 851Kg/h; Gas 5575kg/h
Turbo Generator Load: 1595KW
Evaporator Load: 24Ton/Day
Sea Water Temperature: 22°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg / 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Scoop Cooling

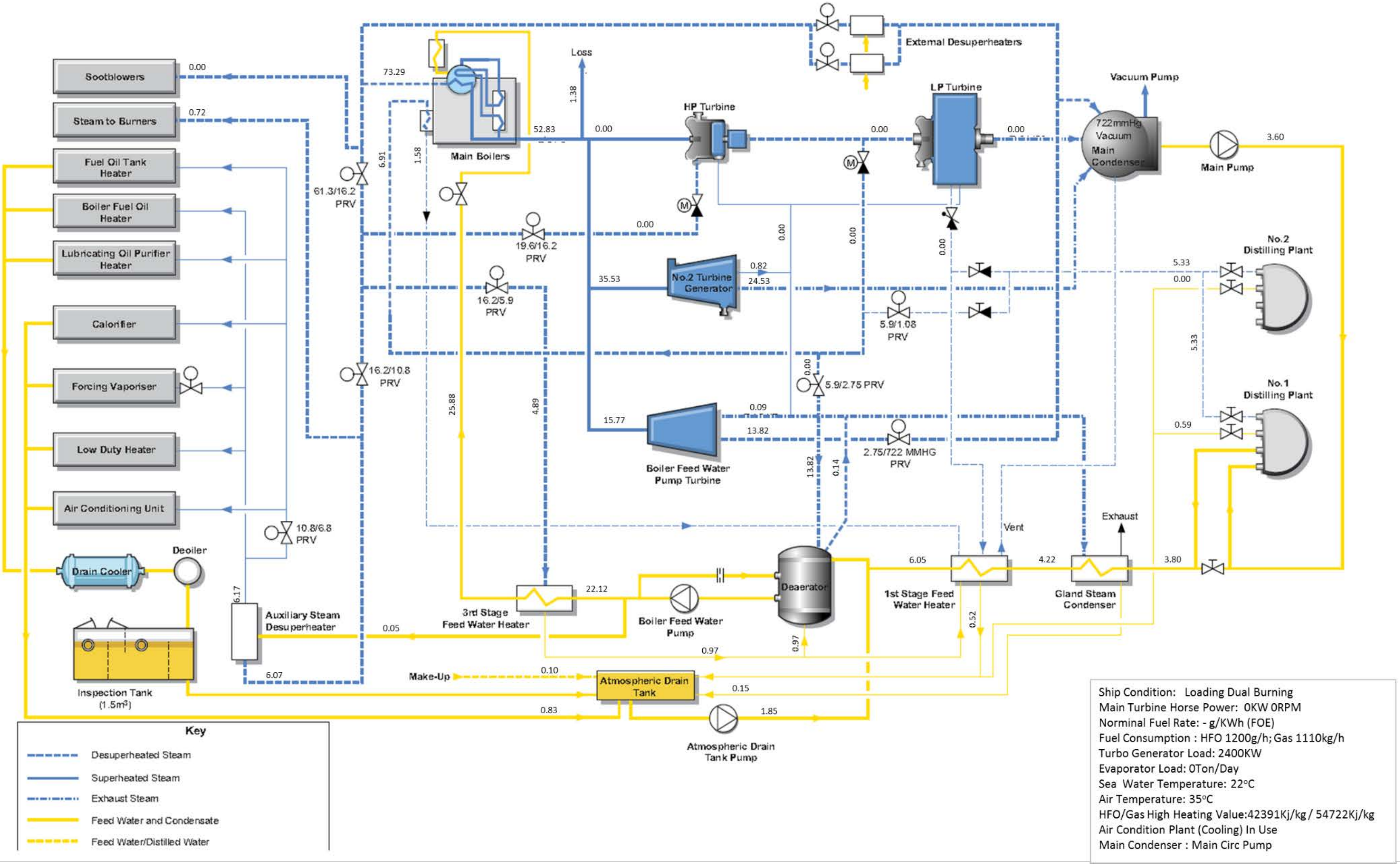


Sootblowers
Steam to Burners
Fuel Oil Tank Heater
Boiler Fuel Oil Heater
Lubricating Oil Purifier Heater
Calorifier
Forcing Vaporiser
Low Duty Heater
Air Conditioning Unit
Drain Cooler
Deoiler
Inspection Tank (1.5m³)
Auxiliary Steam Desuperheater
3rd Stage Feed Water Heater
Boiler Feed Water Pump
Deaerator
1st Stage Feed Water Heater
Gland Steam Condenser
Exhaust
Vent
Atmospheric Drain Tank
Atmospheric Drain Tank Pump
Make-Up
Main Boilers
Loss
HP Turbine
LP Turbine
External Desuperheaters
Vacuum Pump
722mmHg Vacuum Main Condenser
Main Pump
No.2 Turbine Generator
Boiler Feed Water Pump Turbine
No.2 Distilling Plant
No.1 Distilling Plant
61.3/16.2 PRV
19.6/16.2 PRV
16.2/5.9 PRV
16.2/10.8 PRV
10.8/6.8 PRV
5.9/1.08 PRV
5.9/2.75 PRV
2.75/722 MMHG PRV
0.00
0.74
25.10
270.90
229.94
183.40
149.97
10.99
2.24
11.08
2.53
0.00
0.74
0.00
17.22
21.64
0.41
15.01
4.39
0.00
4.39
0.51
55.60
10.76
0.00
16.70
0.09
14.53
14.53
0.14
27.86
15.73
14.47
47.37
2.56
0.02
2.52
2.20
2.20
2.86
0.13
0.17
0.34
3.84
Key
Desuperheated Steam
Superheated Steam
Exhaust Steam
Feed Water and Condensate
Feed Water/Distilled Water
Ship Condition: 70% MCR Dual Burning
Main Turbine Horse Power: 16010KW 72RPM
Norminal Fuel Rate: - 401.0g/KWh (FOE)
Fuel Consumption : HFO 2165Kg/h; Gas 3322kg/h
Turbo Generator Load: 1558KW
Evaporator Load: 31Ton/Day
Sea Water Temperature: 30°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg / 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Scoop Cooling

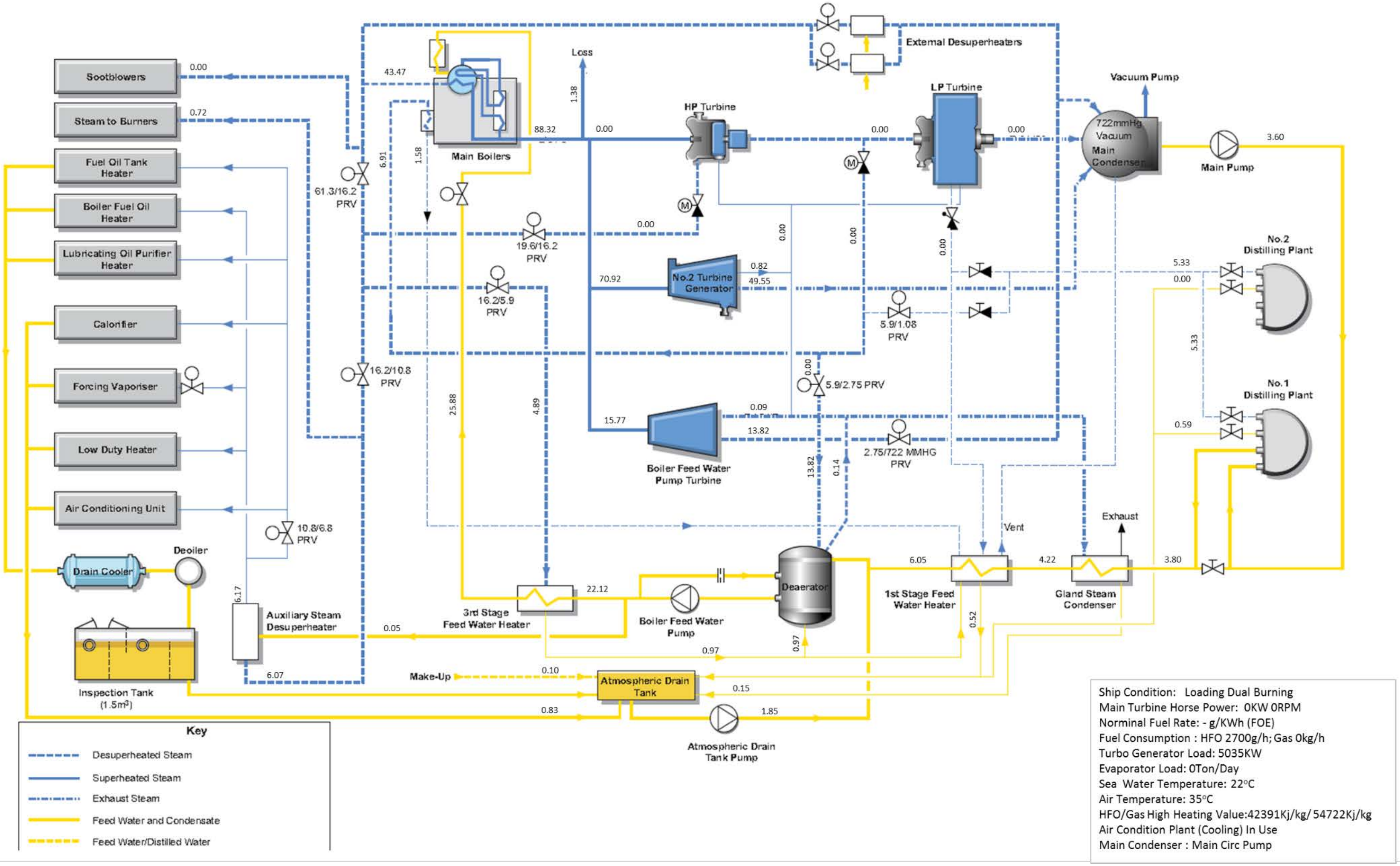


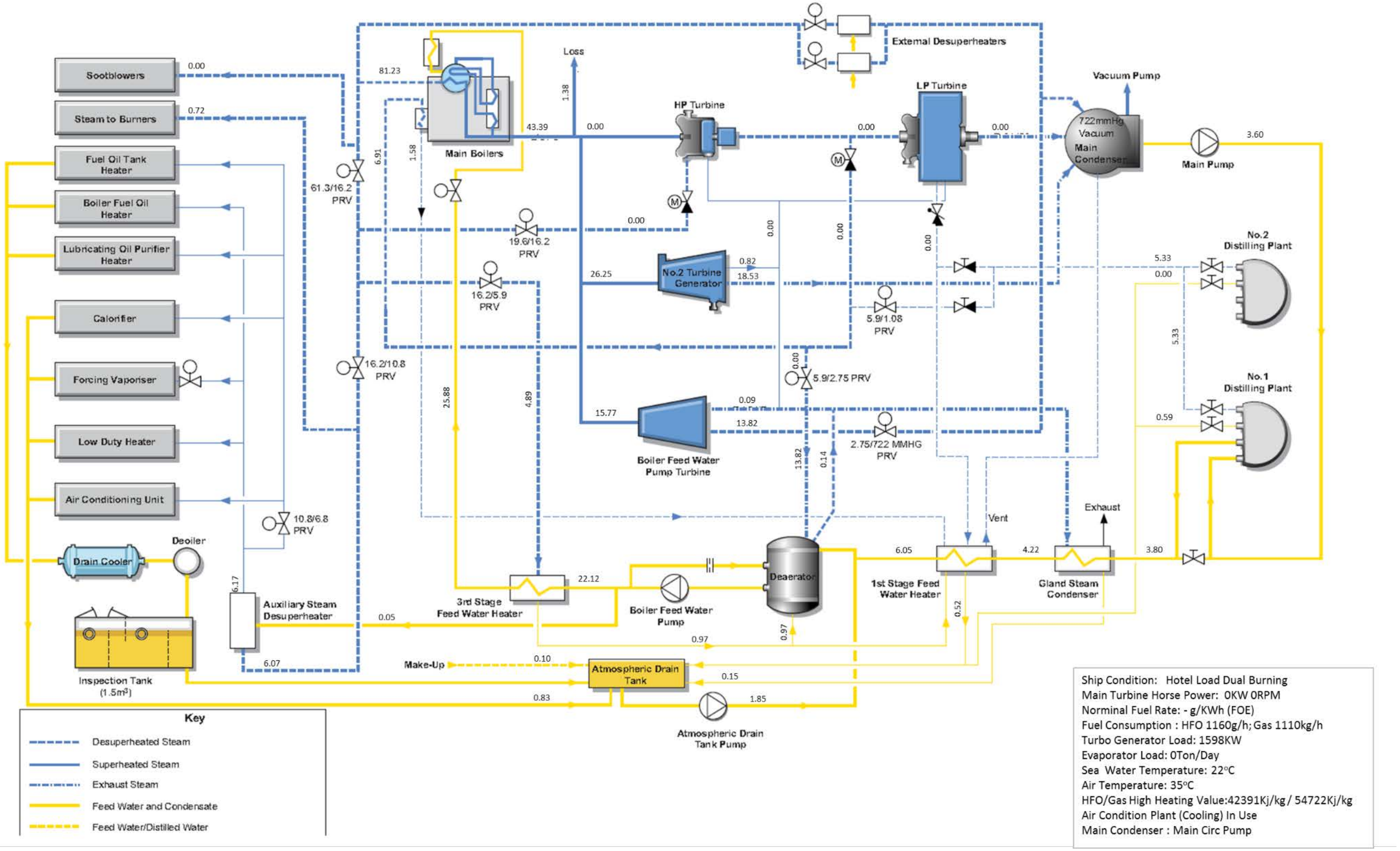
Sootblowers
Steam to Burners
Fuel Oil Tank Heater
Boiler Fuel Oil Heater
Lubricating Oil Purifier Heater
Calorifier
Forcing Vaporiser
Low Duty Heater
Air Conditioning Unit
Drain Cooler
Deoiler
Inspection Tank (1.5m³)
Auxiliary Steam Desuperheater
Main Boilers
Loss
HP Turbine
LP Turbine
External Desuperheaters
Vacuum Pump
722mmHg Vacuum Main Condenser
Main Pump
No.2 Distilling Plant
No.1 Distilling Plant
No.2 Turbine Generator
Boiler Feed Water Pump Turbine
3rd Stage Feed Water Heater
Boiler Feed Water Pump
Deaerator
1st Stage Feed Water Heater
Gland Steam Condenser
Vent
Exhaust
Make-Up
Atmospheric Drain Tank
Atmospheric Drain Tank Pump
61.3/16.2 PRV
19.6/16.2 PRV
16.2/5.9 PRV
16.2/10.8 PRV
10.8/6.8 PRV
5.9/1.08 PRV
5.9/2.75 PRV
2.75/722 MMHG PRV
Key
Desuperheated Steam
Superheated Steam
Exhaust Steam
Feed Water and Condensate
Feed Water/Distilled Water
Ship Condition: 50% MCR Dual Burning
Main Turbine Horse Power: 11975KW 62.6RPM
Norminal Fuel Rate: - 468.8g/KWh (FOE)
Fuel Consumption : HFO 1837g/h; Gas 3006kg/h
Turbo Generator Load: 1570KW
Evaporator Load: 33.6Ton/Day
Sea Water Temperature: 26°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg / 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Scoop Cooling


Sootblowers
Steam to Burners
Fuel Oil Tank Heater
Boiler Fuel Oil Heater
Lubricating Oil Purifier Heater
Calorifier
Forcing Vaporiser
Low Duty Heater
Air Conditioning Unit
Drain Cooler
Deoiler
Inspection Tank (1.5m³)
Auxiliary Steam Desuperheater
Main Boilers
Loss
HP Turbine
LP Turbine
External Desuperheaters
Vacuum Pump
722mmHg Vacuum
Main Condenser
Main Pump
No.2 Turbine Generator
No.2 Distilling Plant
No.1 Distilling Plant
Boiler Feed Water Pump Turbine
61.3/16.2 PRV
19.6/16.2 PRV
16.2/5.9 PRV
16.2/10.8 PRV
10.8/6.8 PRV
5.9/1.08 PRV
5.9/2.75 PRV
2.75/722 MMHG PRV
3rd Stage Feed Water Heater
Boiler Feed Water Pump
Deaerator
1st Stage Feed Water Heater
Gland Steam Condenser
Exhaust
Vent
Make-Up
Atmospheric Drain Tank
Atmospheric Drain Tank Pump
0.00
0.72
25.22
8.50
1.94
2.31
180.24
136.23
107.21
110.00
7.05
0.00
0.64
0.00
0.00
24.80
0.82
17.09
0.00
0.00
0.00
0.00
3.34
39.37
8.44
16.79
0.09
14.64
17.98
0.14
32.93
10.34
8.46
7.05
0.03
4.29
4.23
0.13
0.20
0.58
1.69
1.72
1.72
0.81
Key
Desuperheated Steam
Superheated Steam
Exhaust Steam
Feed Water and Condensate
Feed Water/Distilled Water
Ship Condition: 30% MCR Dual Burning
Main Turbine Horse Power: 6911KW 52.3RPM
Norminal Fuel Rate: - 617.9g/KWh (FOE)
Fuel Consumption : HFO 1473kg/h; Gas 2243kg/h
Turbo Generator Load: 1696KW
Evaporator Load: 0Ton/Day
Sea Water Temperature: 30°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg/ 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Main Circ Pump

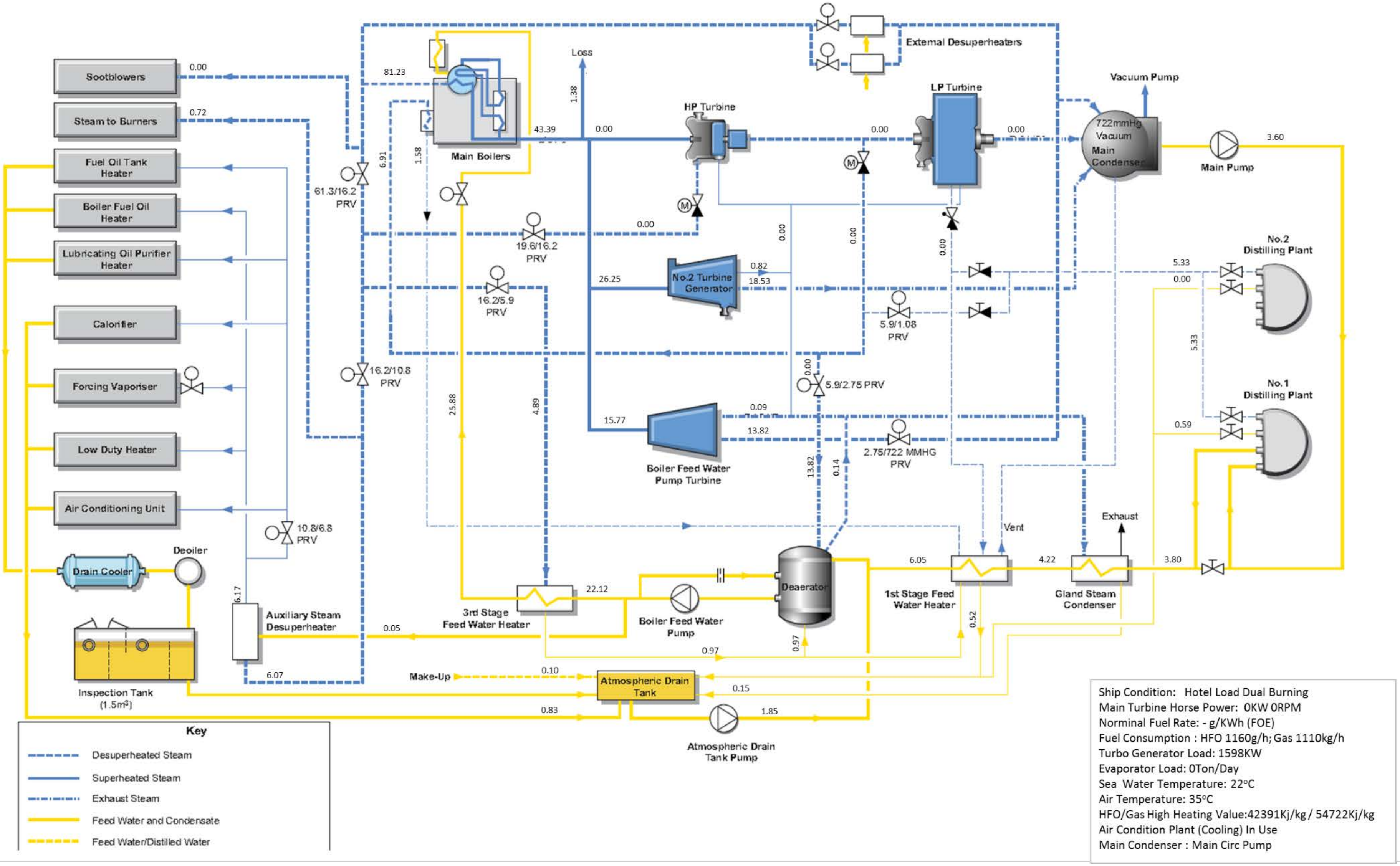


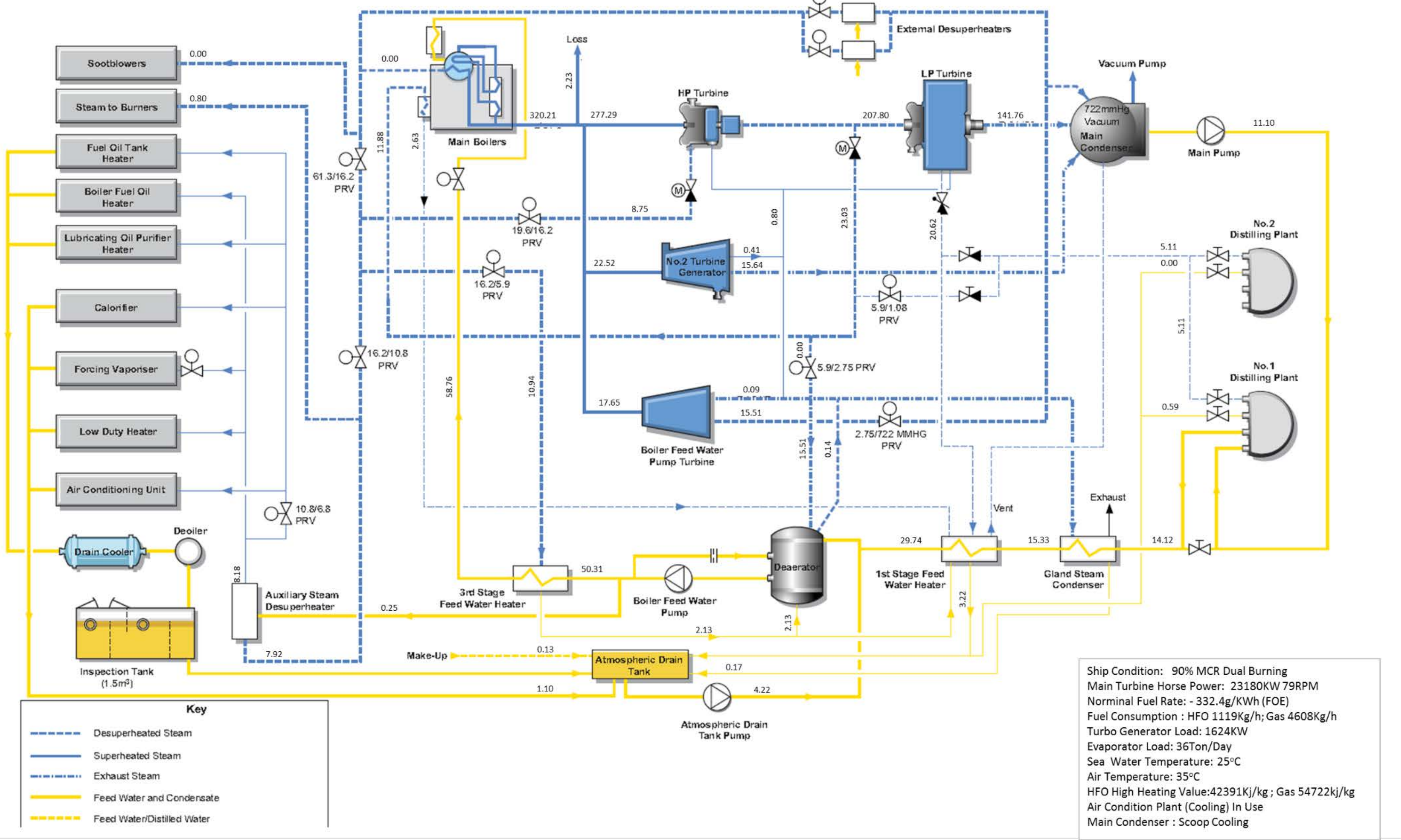
Sootblowers
0.00
Steam to Burners
0.72
Fuel Oil Tank Heater
Boiler Fuel Oil Heater
Lubricating Oil Purifier Heater
Calorifier
Forcing Vaporiser
Low Duty Heater
Air Conditioning Unit
Drain Cooler
Deoiler
Inspection Tank (1.5m³)
Auxiliary Steam Desuperheater
6.17
6.07
0.05
10.8/6.8 PRV
61.3/16.2 PRV
16.2/10.8 PRV
73.29
6.91
1.58
Main Boilers
Loss
1.38
52.83
0.00
HP Turbine
LP Turbine
External Desuperheaters
Vacuum Pump
722mmHg Vacuum Main Condenser
Main Pump
3.60
19.6/16.2 PRV
16.2/5.9 PRV
35.53
No.2 Turbine Generator
0.82
24.53
5.9/1.08 PRV
5.9/2.75 PRV
25.88
4.89
15.77
Boiler Feed Water Pump Turbine
0.09
13.82
2.75/722 MMHG PRV
13.82
0.14
No.2 Distilling Plant
5.33
0.00
5.33
No.1 Distilling Plant
0.59
3rd Stage Feed Water Heater
22.12
Boiler Feed Water Pump
Deaerator
6.05
1st Stage Feed Water Heater
Vent
4.22
Gland Steam Condenser
Exhaust
3.80
0.52
0.97
0.97
Make-Up
0.10
Atmospheric Drain Tank
0.15
0.83
1.85
Atmospheric Drain Tank Pump
Key
Desuperheated Steam
Superheated Steam
Exhaust Steam
Feed Water and Condensate
Feed Water/Distilled Water
Ship Condition: Loading Dual Burning
Main Turbine Horse Power: 0KW 0RPM
Norminal Fuel Rate: - g/KWh (FOE)
Fuel Consumption : HFO 1200g/h; Gas 1110kg/h
Turbo Generator Load: 2400KW
Evaporator Load: 0Ton/Day
Sea Water Temperature: 22°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg / 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Main Circ Pump


Sootblowers
Steam to Burners
Fuel Oil Tank Heater
Boiler Fuel Oil Heater
Lubricating Oil Purifier Heater
Calorifier
Forcing Vaporiser
Low Duty Heater
Air Conditioning Unit
Drain Cooler
Deoiler
Inspection Tank (1.5m³)
Auxiliary Steam Desuperheater
Main Boilers
Loss
HP Turbine
LP Turbine
External Desuperheaters
Vacuum Pump
722mmHg Vacuum Main Condenser
Main Pump
No.2 Turbine Generator
No.2 Distilling Plant
No.1 Distilling Plant
Boiler Feed Water Pump Turbine
3rd Stage Feed Water Heater
Boiler Feed Water Pump
Deaerator
1st Stage Feed Water Heater
Gland Steam Condenser
Exhaust
Vent
Make-Up
Atmospheric Drain Tank
Atmospheric Drain Tank Pump
61.3/16.2 PRV
19.6/16.2 PRV
16.2/5.9 PRV
16.2/10.8 PRV
10.8/6.8 PRV
5.9/1.08 PRV
5.9/2.75 PRV
2.75/722 MMHG PRV
Key
Desuperheated Steam
Superheated Steam
Exhaust Steam
Feed Water and Condensate
Feed Water/Distilled Water
Ship Condition: Loading Dual Burning
Main Turbine Horse Power: 0KW 0RPM
Norminal Fuel Rate: - g/KWh (FOE)
Fuel Consumption : HFO 2700g/h; Gas 0kg/h
Turbo Generator Load: 5035KW
Evaporator Load: 0Ton/Day
Sea Water Temperature: 22°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg/ 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Main Circ Pump



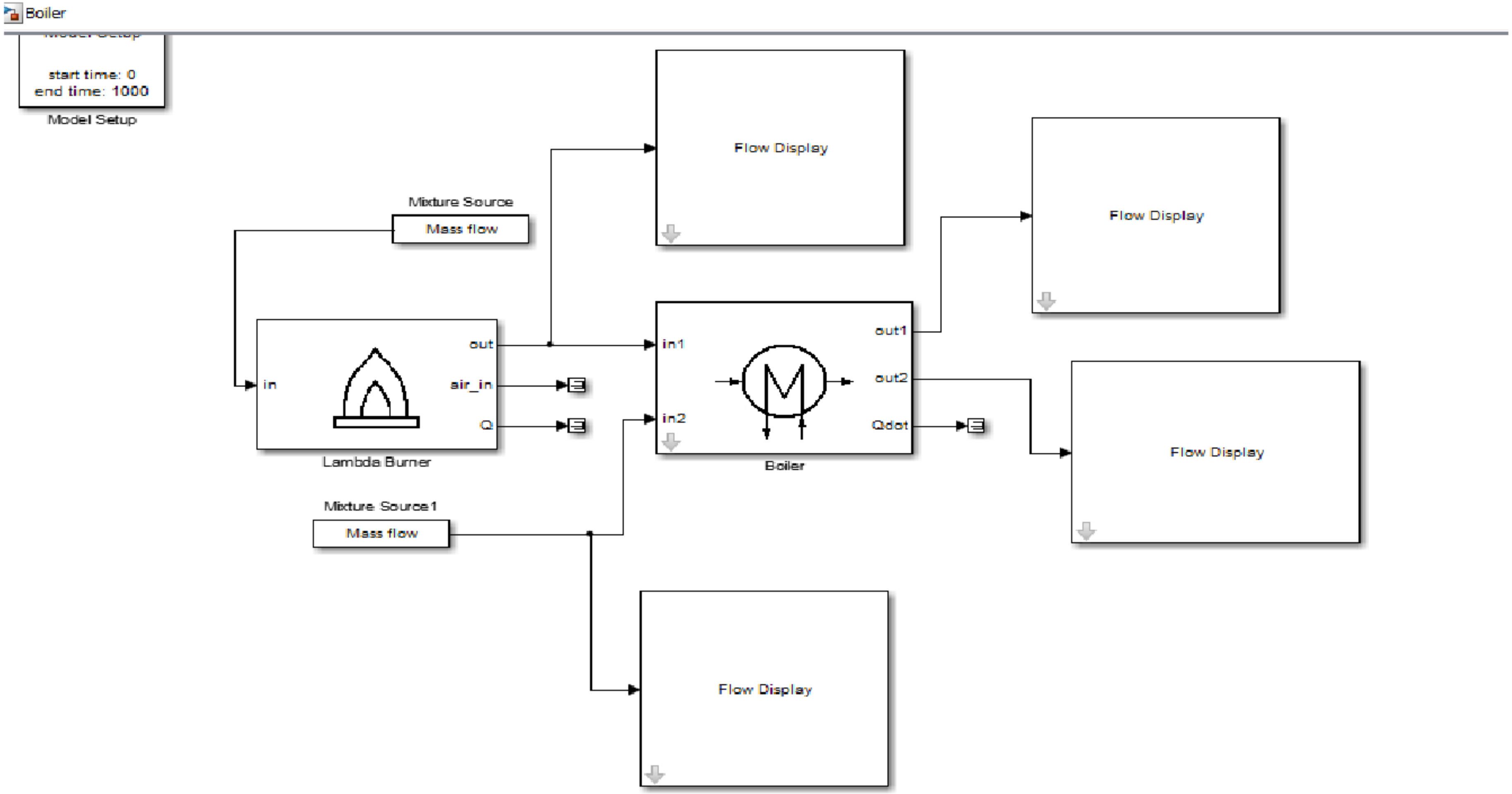
Ship Condition: Hotel Load Dual Burning
Main Turbine Horse Power: 0KW 0RPM
Norminal Fuel Rate: - g/KWh (FOE)
Fuel Consumption : HFO 1160g/h; Gas 1110kg/h
Turbo Generator Load: 1598KW
Evaporator Load: 0Ton/Day
Sea Water Temperature: 22°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg / 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Main Circ Pump

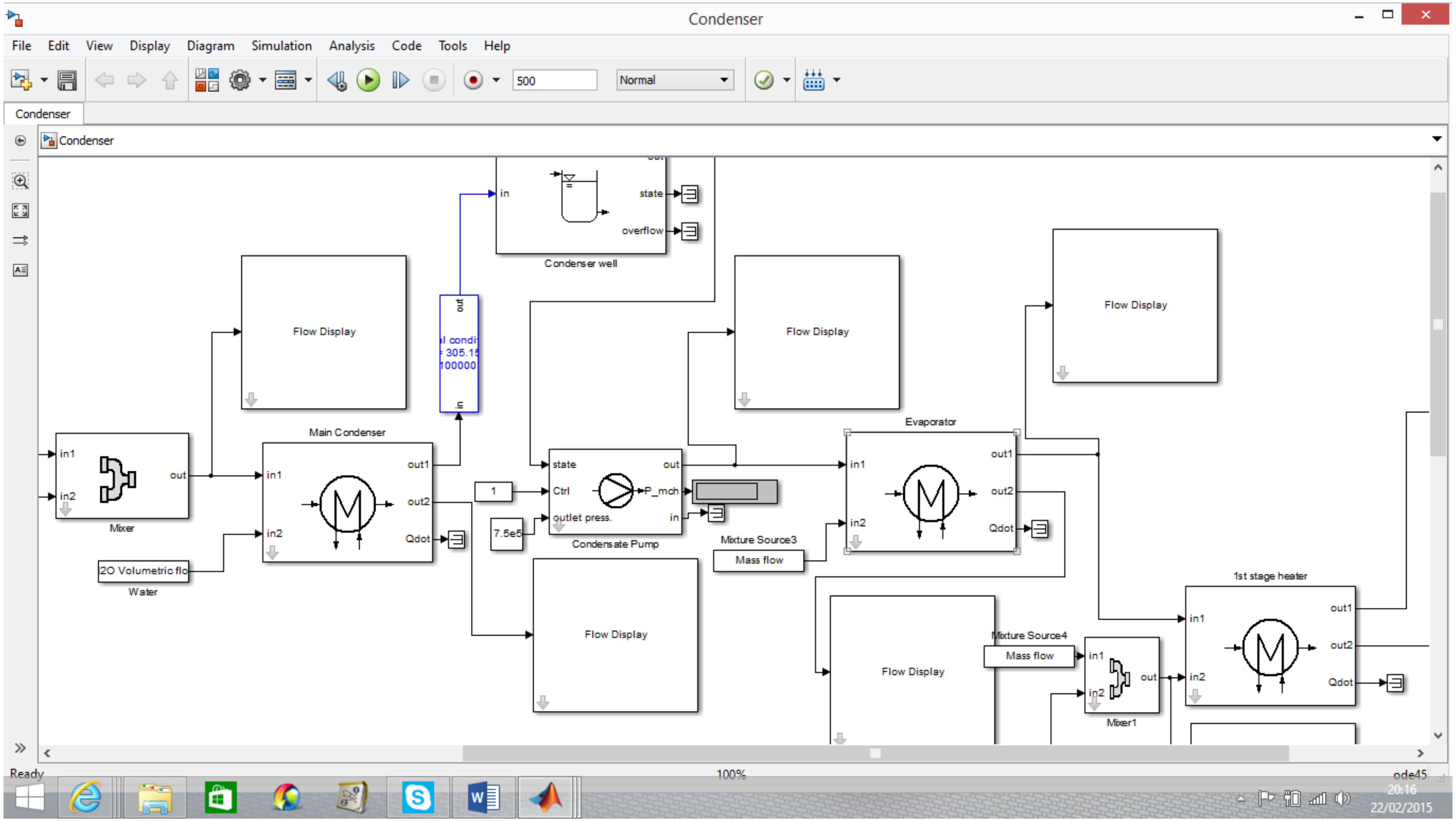

Sootblowers
0.00
Steam to Burners
0.72
Fuel Oil Tank Heater
Boiler Fuel Oil Heater
Lubricating Oil Purifier Heater
Calorifier
Forcing Vaporiser
Low Duty Heater
Air Conditioning Unit
Drain Cooler
Deoiler
Inspection Tank
(1.5m³)
81.23
Main Boilers
Loss
1.38
43.39
0.00
6.91
1.58
61.3/16.2
PRV
19.6/16.2
PRV
16.2/5.9
PRV
16.2/10.8
PRV
10.8/6.8
PRV
HP Turbine
LP Turbine
External Desuperheaters
Vacuum Pump
722mmHg
Vacuum
Main
Condenser
Main Pump
3.60
0.00
No.2 Turbine Generator
26.25
0.82
18.53
5.9/1.08
PRV
5.9/2.75 PRV
No.2
Distilling Plant
No.1
Distilling Plant
5.33
0.59
15.77
0.09
13.82
2.75/722 MMHG
PRV
Boiler Feed Water Pump Turbine
25.88
4.89
0.14
6.17
Auxiliary Steam Desuperheater
0.05
3rd Stage Feed Water Heater
22.12
Boiler Feed Water Pump
Deaerator
0.97
6.05
1st Stage Feed Water Heater
0.52
Vent
4.22
Gland Steam Condenser
Exhaust
3.80
6.07
Make-Up
0.10
Atmospheric Drain Tank
0.15
0.83
1.85
Atmospheric Drain Tank Pump
Key
Desuperheated Steam
Superheated Steam
Exhaust Steam
Feed Water and Condensate
Feed Water/Distilled Water
Ship Condition: Hotel Load Dual Burning
Main Turbine Horse Power: 0KW 0RPM
Norminal Fuel Rate: - g/KWh (FOE)
Fuel Consumption : HFO 1160g/h; Gas 1110kg/h
Turbo Generator Load: 1598KW
Evaporator Load: 0Ton/Day
Sea Water Temperature: 22°C
Air Temperature: 35°C
HFO/Gas High Heating Value:42391Kj/kg / 54722Kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Main Circ Pump

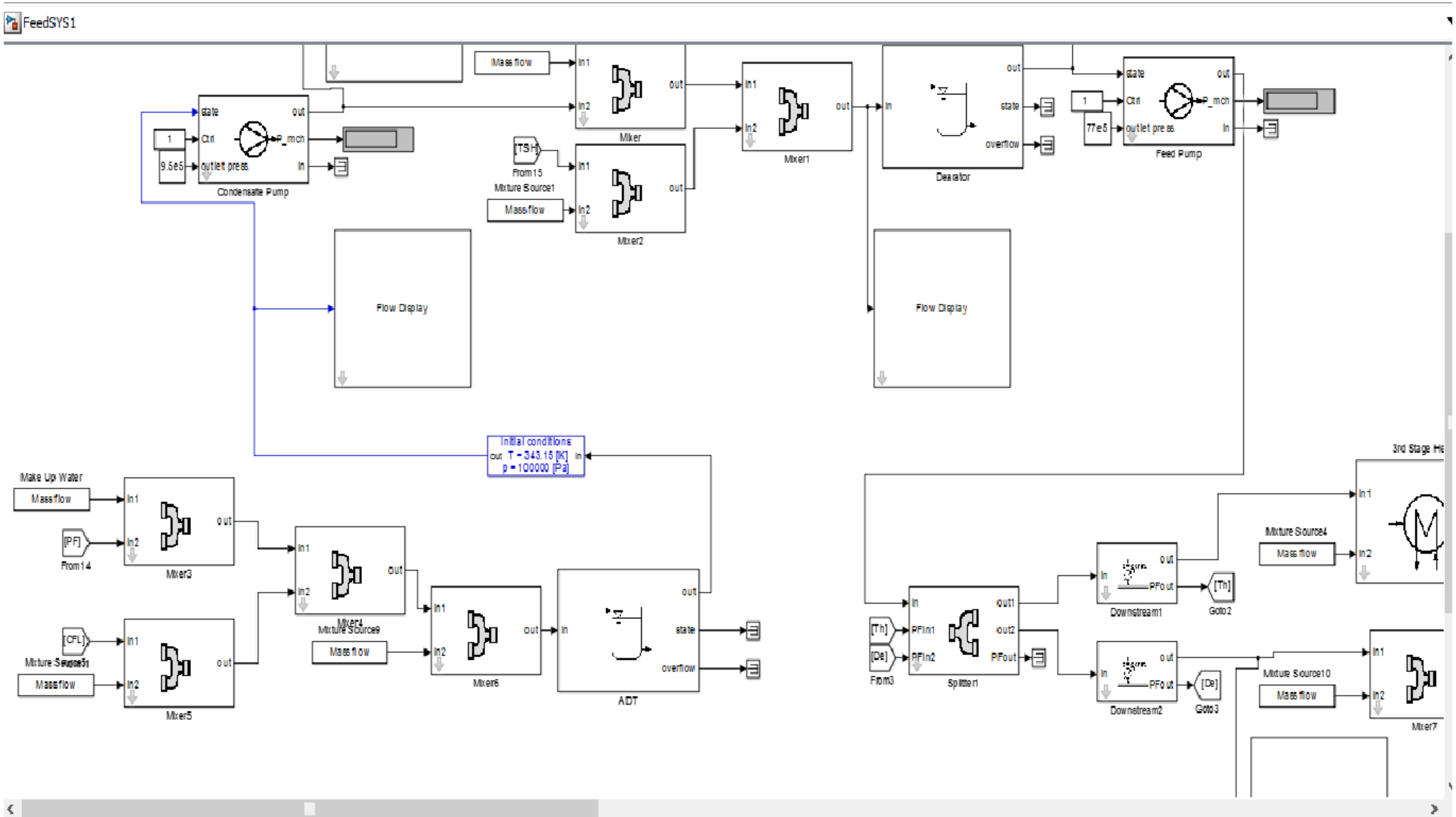


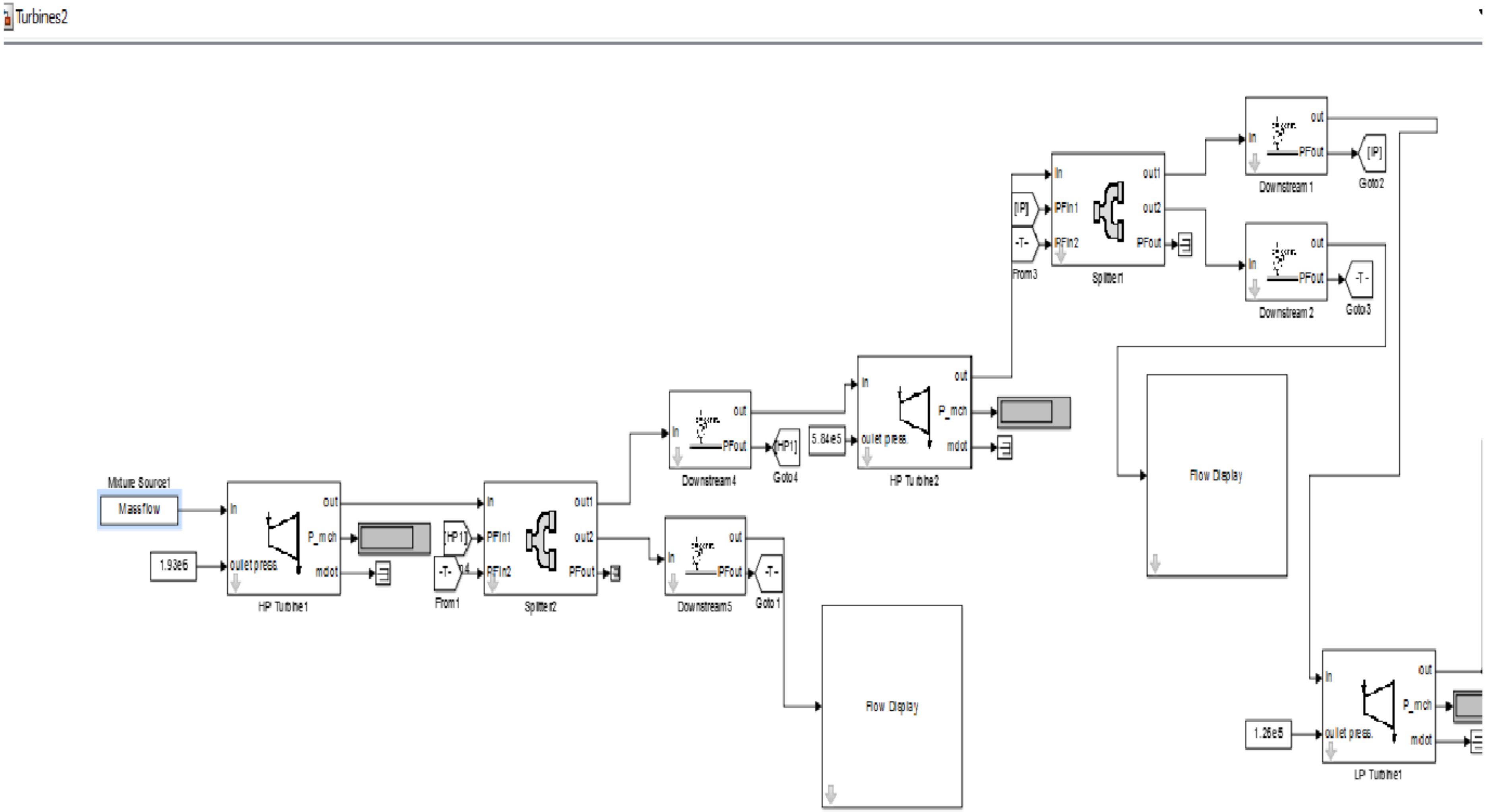
Ship Condition: 90% MCR Dual Burning
Main Turbine Horse Power: 23180KW 79RPM
Norminal Fuel Rate: - 332.4g/KWh (FOE)
Fuel Consumption : HFO 1119Kg/h; Gas 4608Kg/h
Turbo Generator Load: 1624KW
Evaporator Load: 36Ton/Day
Sea Water Temperature: 25°C
Air Temperature: 35°C
HFO High Heating Value:42391Kj/kg ; Gas 54722kj/kg
Air Condition Plant (Cooling) In Use
Main Condenser : Scoop Cooling

Appendix 4- Model Subsystem Descriptions

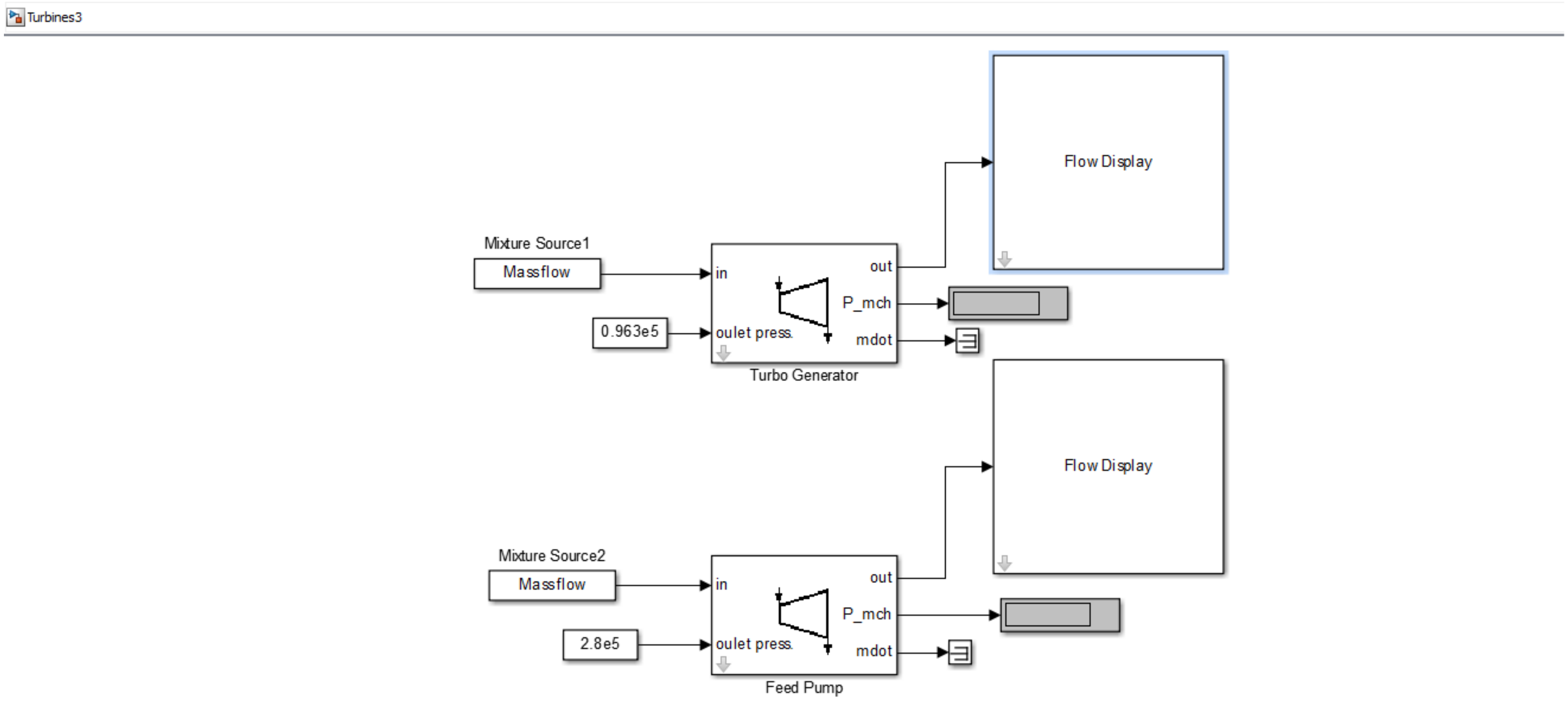


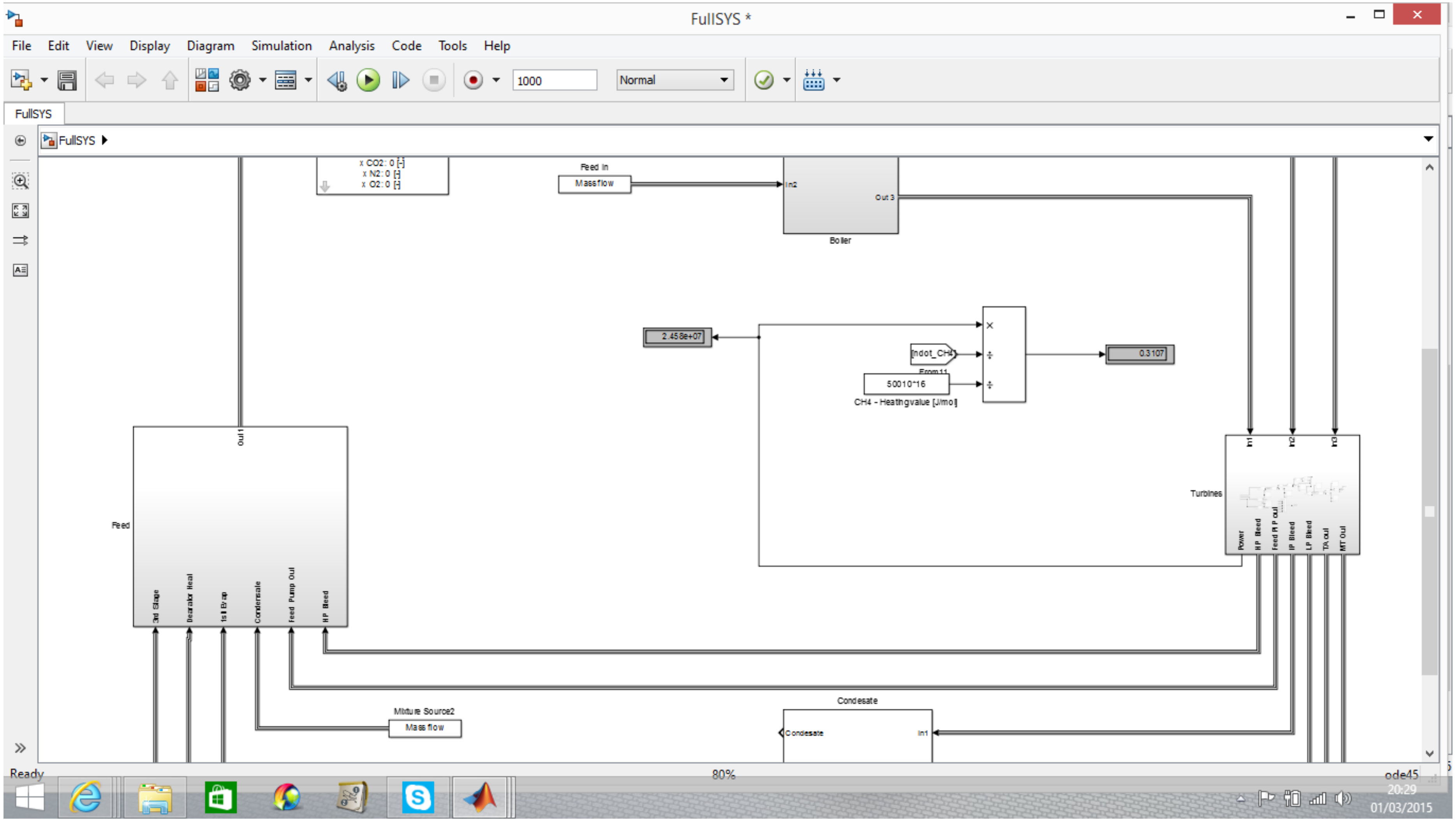

Condenser
File Edit View Display Diagram Simulation Analysis Code Tools Help
500
Normal
Condenser well
Flow Display
Main Condenser
Mixer
Water
Condensate Pump
Mixture Source3
Mass flow
Evaporator
1st stage heater
Mixture Source4
Mixer1
Ready
100%
ode45
20:16
22/02/2015


FeedSYS1
Mass flow
In1
In2
out
Mixer
Mixer1
Mixer2
state
Ctrl
outlet press
P_mch
In
1
9.5e5
Condensate Pump
[TSH]
From15
Mixture Source1
Deaerator
overflow
77e5
Feed Pump
Flow Display
Initial conditions
T = 343.15 [K]
p = 100000 [Pa]
Make Up Water
[PF]
From14
Mixer3
Mixer4
Mixture Source9
Mixer6
[CFL]
Mixer5
ADT
3rd Stage He
Mixture Source4
Downstream1
PFout
[Th]
Goto2
[De]
From3
PFin1
PFin2
out1
out2
Splitter1
Downstream2
Goto3
Mixture Source10
Mixer7

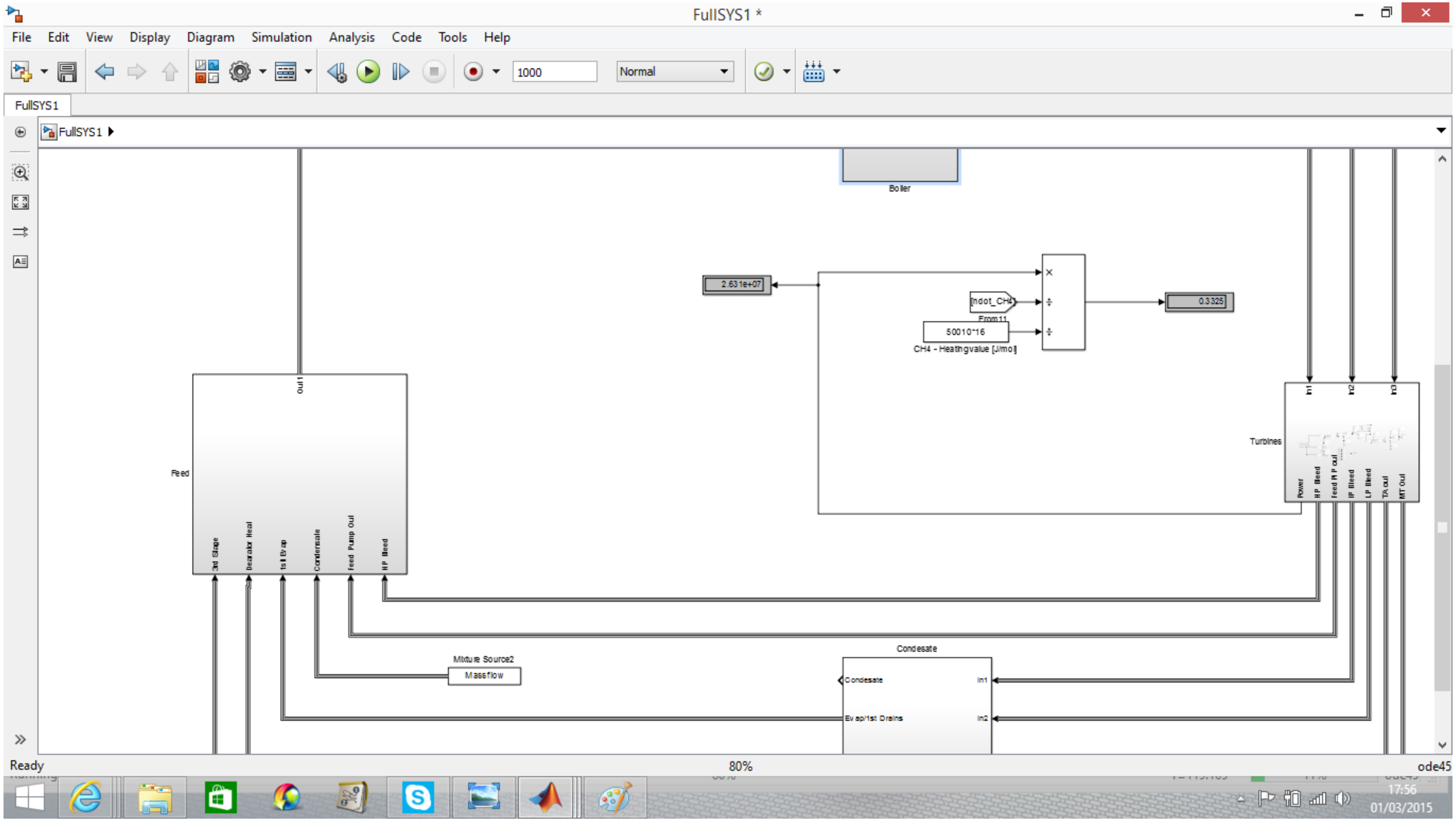


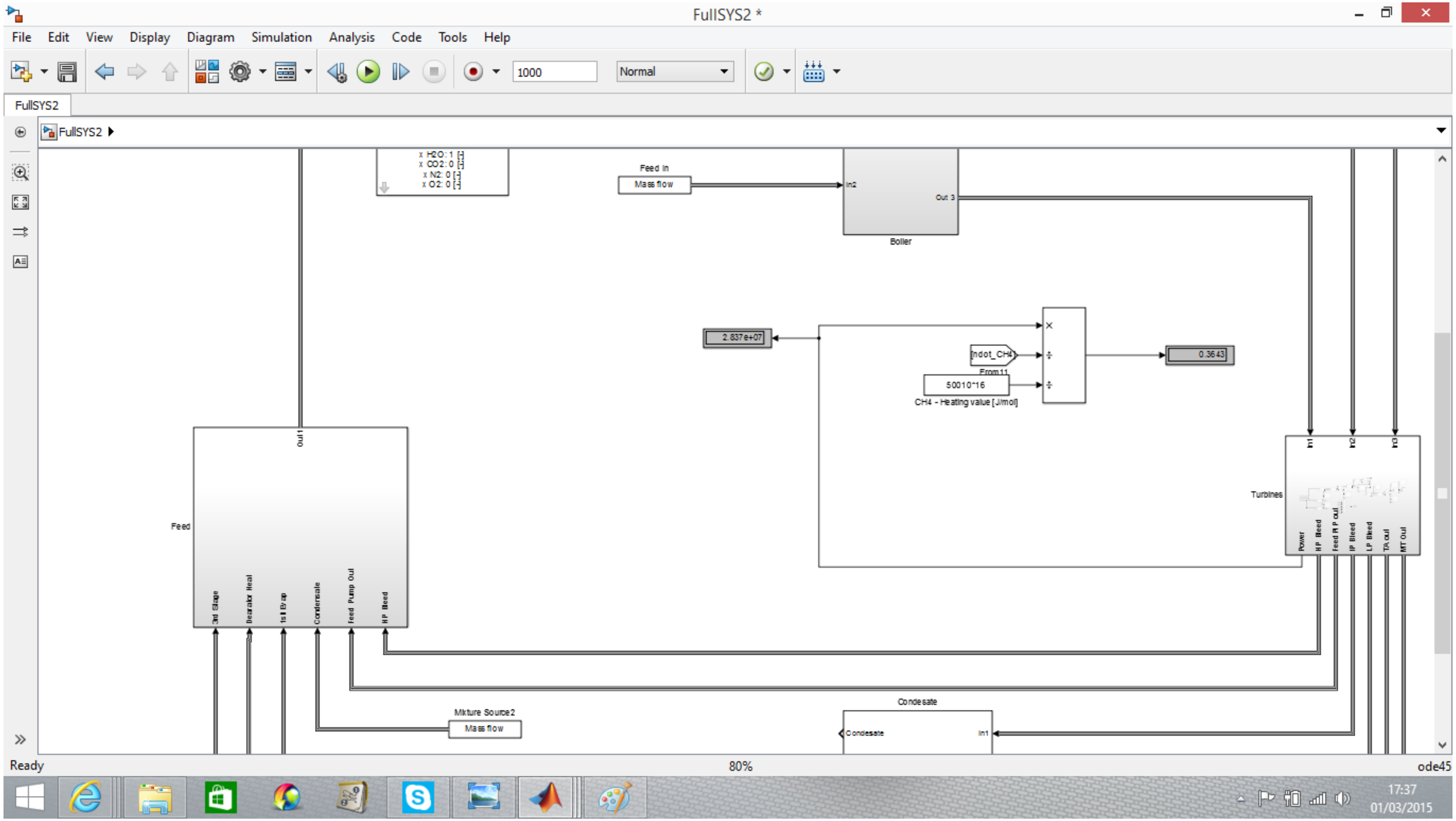
Turbines2
Mixture Source1
Massflow
1.93e5
HP Turbine1
Splitter2
From1
Downstream4
Downstream5
Goto4
Goto1
5.84e5
HP Turbine2
Splitter1
From3
Downstream1
Downstream2
Goto2
Goto3
Flow Display
Flow Display
1.26e5
LP Turbine1

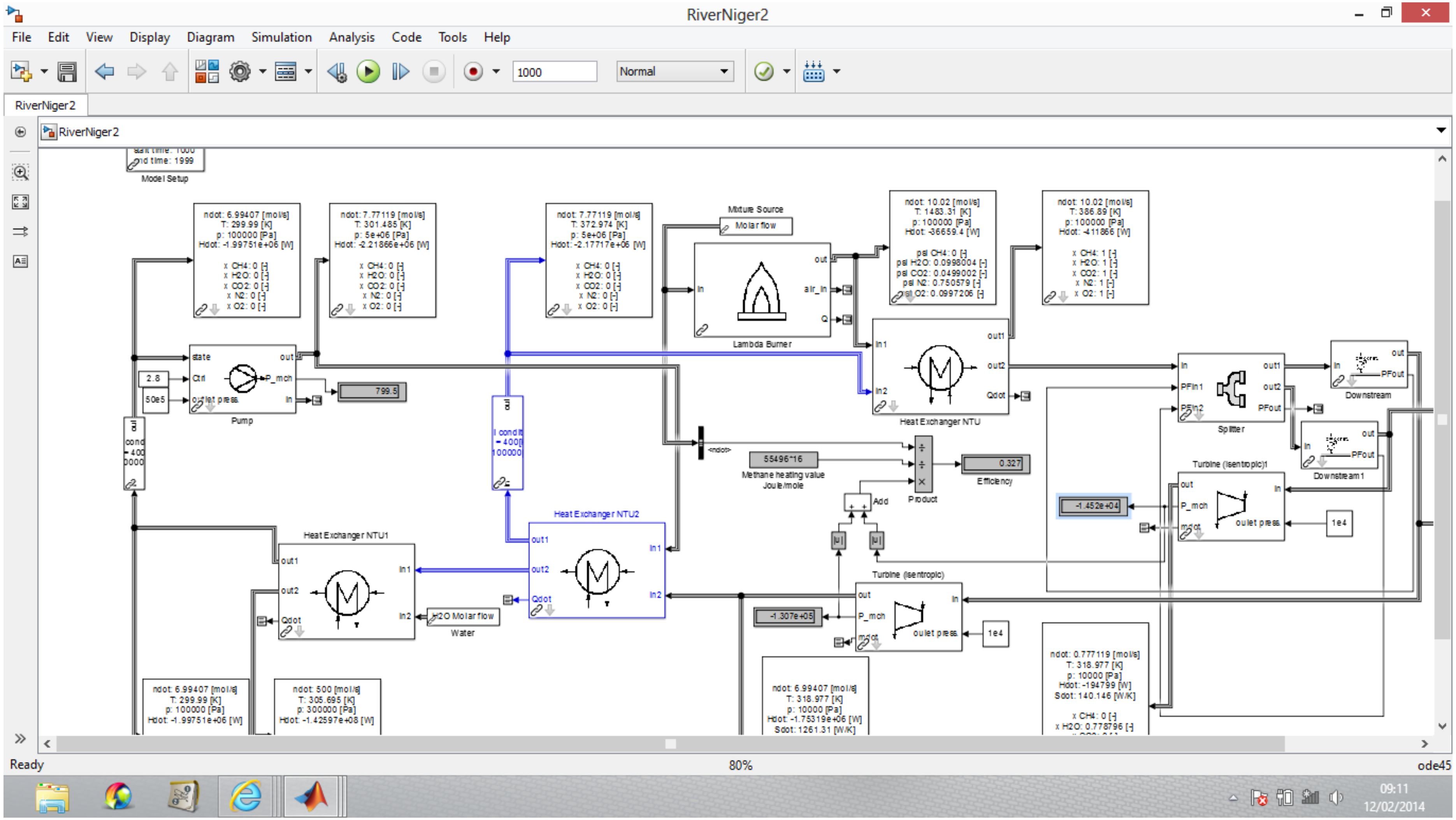

Turbines3
Flow Display
Mixture Source1
Massflow
in
out
P_mch
0.963e5
oulet press.
mdot
Turbo Generator
Flow Display
Mixture Source2
Massflow
in
out
P_mch
2.8e5
oulet press.
mdot
Feed Pump



FullSYS *
File Edit View Display Diagram Simulation Analysis Code Tools Help
1000
Normal
FullSYS
x CO2: 0 [-]
x N2: 0 [-]
x O2: 0 [-]
Feed In
Massflow
In2
Out 3
Boiler
2.458e+07
ndot_CH4
From11
50010^16
CH4 - Heatingvalue [J/mol]
0.3107
Out1
Feed
3rd Stage
Deaerator Heat
1st Evap
Condensate
Feed Pump Out
HP Bleed
Turbines
In1
In2
In3
Power
HP Bleed
Feed R P out
IP Bleed
LP Bleed
TA out
MT Out
Mixture Source2
Mass flow
Condensate
Condensate
In1
Ready
80%
ode45
20:29
01/03/2015


FullSYS1 *
File Edit View Display Diagram Simulation Analysis Code Tools Help
1000
Normal
FullSYS1
Boiler
2.631e+07
From11
CH4 - Heatingvalue [J/mol]
0.3325
Out1
Feed
3rd Stage
Deaerator Heat
1st Evap
Condensate
Feed Pump Out
HP Bleed
In1
In2
In3
Turbines
Power
LP Bleed
TA out
MT Out
Mixture Source2
Massflow
Condesate
Evap/1st Drains
Ready
80%
ode45
17:56
01/03/2015


FullSYS2 *
File Edit View Display Diagram Simulation Analysis Code Tools Help
1000
Normal
FullSYS2
Feed In
Mass flow
In2
Out 3
Boiler
2.837e+07
[ndot_CH4]
From11
50010*16
CH4 - Heating value [J/mol]
0.3643
Out 1
Feed
3rd Stage
Deareator Heat
1st Evap
Condensate
Feed Pump Out
HP Bleed
In1
In2
In3
Turbines
Power
HP Bleed
Feed R P out
IP Bleed
LP Bleed
TA out
MT Out
Mixture Source2
Mass flow
Condesate
Condesate
In1
Ready
80%
ode45
17:37
01/03/2015


RiverNiger2
File Edit View Display Diagram Simulation Analysis Code Tools Help
1000
Normal
RiverNiger2
Model Setup
ndot: 6.99407 [mol/s]
T: 299.99 [K]
p: 100000 [Pa]
Hdot: -1.99751e+06 [W]
ndot: 7.77119 [mol/s]
T: 301.485 [K]
p: 5e+06 [Pa]
Hdot: -2.21866e+06 [W]
ndot: 7.77119 [mol/s]
T: 372.974 [K]
p: 5e+06 [Pa]
Hdot: -2.17717e+06 [W]
Mixture Source
Molar flow
Lambda Burner
ndot: 10.02 [mol/s]
T: 1483.31 [K]
p: 100000 [Pa]
Hdot: -36659.4 [W]
ndot: 10.02 [mol/s]
T: 386.89 [K]
p: 100000 [Pa]
Hdot: -411866 [W]
Pump
799.5
2.8
50e5
Heat Exchanger NTU
Splitter
Downstream
Downstream1
Turbine (isentropic)1
Methane heating value Joule/mole
55496*16
Efficiency
0.327
Product
Add
-1.452e+04
1e4
Heat Exchanger NTU2
Heat Exchanger NTU1
H2O Molar flow
Water
Turbine (isentropic)
-1.307e+05
1e4
ndot: 6.99407 [mol/s]
T: 299.99 [K]
p: 100000 [Pa]
Hdot: -1.99751e+06 [W]
ndot: 500 [mol/s]
T: 305.695 [K]
p: 300000 [Pa]
Hdot: -1.42597e+08 [W]
ndot: 6.99407 [mol/s]
T: 318.977 [K]
p: 10000 [Pa]
Hdot: -1.75319e+06 [W]
Sdot: 1261.31 [W/K]
ndot: 0.777119 [mol/s]
T: 318.977 [K]
p: 10000 [Pa]
Hdot: -194799 [W]
Sdot: 140.146 [W/K]
Ready
80%
ode45
09:11
12/02/2014

Appendix 5- Explanation of the Mathematical Solution to Calculate profit of LNGC Propulsion System

In general, LNG carrier propulsion systems may consume a part of the loaded LNG, see *fig. 2*, so we can write

$$LNG_{Load} = LNG_{Del} + LNG_{Burnt}$$

Using above expressions, the simplified charterer's profit equation (2) then becomes

$$PROFIT^{A} - PROFIT^{B} > 0 \quad \text{if}$$

$$LNG^{A}_{Del} \cdot CIF_{LNG} - LNG^{B}_{Del} \cdot CIF_{LNG} - \left[(LNG^{A}_{Del} + LNG^{A}_{Burnt}) \cdot FOB_{LNG} - (LNG^{B}_{Del} + LNG^{B}_{Burnt}) \cdot FOB_{LNG} \right]$$
$$- \left[HFO^{A}_{Burnt} \cdot FOB_{HFO} - HFO^{B}_{Burnt} \cdot FOB_{HFO} \right] > 0$$

$$\Leftrightarrow (LNG^{A}_{Del} - LNG^{B}_{Del}) \cdot \frac{CIF_{LNG}}{FOB_{LNG}} - (LNG^{A}_{Del} - LNG^{B}_{Del}) - (LNG^{A}_{Burnt} - LNG^{B}_{Burnt})$$
$$- (HFO^{A}_{Burnt} - HFO^{B}_{Burnt}) \cdot \frac{FOB_{HFO}}{FOB_{LNG}} > 0$$

$$\Leftrightarrow \frac{FOB_{HFO}}{FOB_{LNG}} \cdot (HFO^{A}_{Burnt} - HFO^{B}_{Burnt}) < (LNG^{A}_{Del} - LNG^{B}_{Del}) \cdot \frac{CIF_{LNG}}{FOB_{LNG}}$$
$$+ (LNG^{B}_{Del} - LNG^{A}_{Del}) + (LNG^{B}_{Burnt} - LNG^{A}_{Burnt})$$

$$\Leftrightarrow \left(\frac{FOB_{HFO}}{FOB_{LNG}} \right) < \frac{LNG^{A}_{Del} - LNG^{B}_{Del}}{HFO^{A}_{Burnt} - HFO^{B}_{Burnt}} \cdot \left(\frac{CIF_{LNG}}{FOB_{LNG}} \right) + \frac{LNG^{B}_{Del} - LNG^{A}_{Del}}{HFO^{A}_{Burnt} - HFO^{B}_{Burnt}} + \frac{LNG^{B}_{Burnt} - LNG^{A}_{Burnt}}{HFO^{A}_{Burnt} - HFO^{B}_{Burnt}}$$

For a given class of LNG carrier design (cargo capacity) and transport distance the amount of consumed fuels and delivered cargos for two different LNG carrier propulsion technologies A and B (or two different fuel operation modes for a given propulsion system) is fixed and, hence, we can write

$$\Leftrightarrow \left(\frac{FOB_{HFO}}{FOB_{LNG}} \right) < C_1 \cdot \left(\frac{CIF_{LNG}}{FOB_{LNG}} \right) - C_1 + C_2$$

"Charterer Profit Criterion"

The result shall briefly be described:

C_1 and C_2 are constants the value of which is determined by purely technical aspects (amount of consumed and delivered LNG, amount of HFO burnt). The term on the left hand side represents the fuel price ratio of purchased LNG (FOB price) and HFO. The remaining term on the right hand side denotes the ratio of LNG selling price (CIF) to LNG purchasing price (FOB).

According to equation (5') the limiting case (i.e. $PROFIT^{A} = PROFIT^{B}$) represents a straight line of the form

$$Y = c_1 \cdot X - c_1 + c_2$$

It must be emphasized that the mathematical approach performed and the resulting equation ("Charterer Profit Criterion") are of a very general form and can be used for profit comparison of all kind of LNG carrier propulsion systems. The same formula can also be applied to compare the profitability of two different fuel operation modes (e.g. pure gas operation versus NBOG + HFO add up operation) for a given propulsion system.

A summary of the mathematical approach described above and of the resulting solution is given in *fig. 3*.

$$\text{Charterer } PROFIT = LNG_{Del} \cdot CIF_{LNG} - \left[LNG_{Load} \cdot FOB_{LNG} + FOE + CRE + PPF \right]$$

A... LNG carrier with propulsion system A
B... LNG carrier with propulsion system B

$\downarrow$

"Pure" Mathematics

$$PROFIT^{A} > PROFIT^{B} \quad \text{if}$$

$$\left(\frac{FOB_{HFO}}{FOB_{LNG}} \right) < \frac{LNG^{A}_{Del} - LNG^{B}_{Del}}{HFO^{A}_{Burnt} - HFO^{B}_{Burnt}} \cdot \left(\frac{CIF_{LNG}}{FOB_{LNG}} \right) + \frac{LNG^{B}_{Del} - LNG^{A}_{Del}}{HFO^{A}_{Burnt} - HFO^{B}_{Burnt}} + \frac{LNG^{B}_{Burnt} - LNG^{A}_{Burnt}}{HFO^{A}_{Burnt} - HFO^{B}_{Burnt}}$$

"Charterer Profit Criterion"
System A vs. System B

$$\left(\frac{FOB_{HFO}}{FOB_{LNG}} \right) < C_1 \cdot \left(\frac{CIF_{LNG}}{FOB_{LNG}} \right) - C_1 + C_2 \quad \Leftrightarrow$$

For given transport distance and ship design

Figure 3: Mathematical Solution for Profit Comparison from the Charterer's View