

CRANFIELD UNIVERSITY

ABDULAZIZ ALZAYEDI

Techno-Economic Environmental and Risk Assessment for Large
Container Ship Gas Turbine Combined Cycle Propulsion Systems

PhD

Academic Year: 2022 - 2023

Supervisor: Professor Pericles Pilidis
Associate Supervisor: Dr.Suresh Sampath

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ABSTRACT

In recent years, the International Maritime Organization's (IMO) stringent regulations on air pollutants, which are associated with increased fuel costs, have encouraged researchers to develop fuels and technologies that are cleaner and more efficient than conventional propulsion systems. This study defines and describes a techno-economic environmental and risk assessment (TERA) method for assessing substitute fuels and technologies that could be utilised in the maritime sector to replace two-stroke diesel engines fuelled by heavy fuel oil (HFO). This study aimed to develop a TERA method for marine technologies and to improve Cranfield University's ship resistance simulation code, "Poseidon". The study examined conventional propulsion systems, such as two-diesel engines fuelled by marine diesel oil and gas and steam combined cycle fuelled by liquefied natural gas and marine diesel fuel. The characteristic cryogenic properties of liquefied natural gas were employed to improve the efficiency of the combined cycle gas turbine cycles. The study selection criteria were performance, emissions, weight, and investment costs, including installation, operation, and maintenance costs for advanced combined gas and steam turbine cycles and two-stroke diesel engine propulsion systems for large container ships. A risk assessment was conducted to evaluate the impacts of capital cost, fuel cost, hull fouling resistance, container shipment price, discount rate, and emission taxation on the economic analysis. The results indicated that enhanced LNG combined cycles were the most efficient. Their enhanced combined cycle efficiency was 11% higher than two-stroke diesel engine efficiency and they reduced nitrogen oxide and carbon dioxide emissions by 76.3% and 44.7%, respectively. Regarding the weight of the propulsion systems, the combined gas and steam turbine propulsion system was approximately 24.7% lighter than the diesel engine propulsion system. For the routes that were considered and compared to a two-stroke diesel engine fuelled by MDO, the simple, intercooler/reheat, and enhanced gas and steam combined cycles that were fuelled by LNG increased the net present value by 78.3%, 78.5%, and 76.4%, respectively, and the payback period was reduced by 38.8%, 38.9%, and 35%, respectively. Additionally, the IRR showed a low-risk investment with significant

potential benefits of CCGT cycles fuelled with LNG. The discount rate, container price, capital cost, emissions tax, and fuel cost scenarios showed the highest impact on economic results compared with the other scenarios for all technologies. The TERA was performed for different routes to evaluate the benefits and disadvantages of installing combined cycles instead of two-stroke diesel engines.

Keywords:

advanced combined gas and steam turbine cycle; Two-stroke diesel engine; TERA ; large container ship; propulsion systems; liquefied natural gas; marine diesel oil; nitrogen oxide; carbon dioxide; Net present value; payback period; Internal rate of return; Taxation.

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LIST OF ABBREVIATIONS

CC	Combustion Chamber
CCGT	Combined Gas Turbine and Steam System
CO ₂	Carbon Dioxide
D.P	Design Point
DWT	Deadweight (tons)
EGT	Exhaust Gas Turbine Temperature
ELNG	Enhanced Liquefied Natural Gas Cycle
GT	Gas Turbine
HFO	Heavy Fuel Oil
HPC	High- Pressure Compressor
HPT	High Pressure Turbine
HRSG	Heat Recovery Steam Generator
I/R	Intercooler–Reheat Cycle
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPC	Low-Pressure Compressor
LPT	Low Pressure Turbine
MARPOL	Marine Pollution
MDO	Marine Diesel Oil
NO _x	Nitrogen Oxides
NPV	Net Present Value
O.D	Off-Design Point
PP	Payback Period
PT	Power Turbine
SFC	Specific Fuel Consumption
SO _x	Sulphur Oxides
ST	Steam Turbine
T _{ap}	Approach point temperature
T _{pin}	Pinch point temperature
TERA	Techno-economic environmental and risk assessment
TET	Turbine Entry Temperature
TEU	Twenty-Foot Equivalent Unit

1 INTRODUCTION

The international economy relies on the transport of goods. 90% of this transport is maritime, with ships traveling along seaways serving as the circulatory system underpinning global trade [1,2]. Throughout the last 20 years, the impact of ship-related pollution, which impacts both human and environmental health, has become a prominent global issue [3,4]. According to [5], harmful emissions from the maritime sector cause approximately 60,000 deaths per year. Reducing pollution, especially airborne pollution in the form of emissions, has become the focus on increasing international action, as evidenced by the International Maritime Organisation's (IMO) past adoption of regulations to reduce sulphur oxide (SO_x) and nitrogen oxide (NO_x) emissions, and its present consideration of carbon dioxide (CO₂) emissions [6]. Two-stroke diesel engines, mainly used by large vessels, are the predominant form of propulsion for ocean-going transport [7]. They are highly efficient and can run on heavy fuel oil (HFO), a relatively inexpensive fuel. However, it contains high levels of sulphur, the emission of which can be harmful to both humans and the environment [8]. It also emits high levels of CO₂. Replacing HFO with low-carbon fuels, such as liquefied natural gas and marine diesel fuel, is one potential path to reducing ship emissions [9]. Uncertainties over the price of fuel have propelled the search for more environmentally friendly and economically sound technological solutions. In comparison to diesel engine alternatives, a simple gas turbine has two drawbacks: fuel cost and lower efficiency [10]. Higher fuel costs are incurred as gas turbines cannot utilise HFO. A gas turbine with a steam turbine (CCGT) gives a higher cycle efficiency than a two-stroke diesel engine [11]. Combined gas and steam turbines (CCGT) have been used since 1970 for terrestrial power plants, producing low levels of emissions while providing high efficiency. Since its inception, the possibility of using CCGT technology for ship propulsion systems has been researched. However, conditions have changed due to the increasing focus on environmental concerns, and the possible performance gains achievable from CCGT.

A potential ban of HFO by the IMO would cause disruption due to the current reliance on the benefits it provides. Mitigating the challenges of gas turbine efficiency may be crucial to a fuel shift in global maritime trade. One option may be the use of CCGT, which this research aims to investigate. A question that needs answering is what the optimum alternative propulsion system for traditional prime mover diesel engines in the marine commercial sector might be. Alongside that, what action needs to be taken to overcome technical, environmental, and economic impediments to the efficiency of potential alternatives?

1.1 Aim

The aim of this project is to estimate the performance of integrated ship systems using the simple, reheat and intercooler/reheat combined gas and steam turbine in contrast to the two-stroke diesel engine utilising liquefied natural gas and marine diesel oil fuels for large container ship propulsion systems through a numerical model compact in techno-economic environmental and risk assessment to meet international maritime organisation standards.

1.2 Objectives

1. Review current shipping pollution and legislation for diesel engine propulsion systems with competitor combined gas and steam turbines and develop a method to evaluate propulsion systems in a large container ship using a TERA approach.
2. Model the main components of propulsion systems for large container ships including advanced combined gas and steam turbine cycles and two-stroke diesel engines with different fuels through numerical models (Turbomatch and MATLAB).
3. Further develop Poseidon for the prediction of the advanced combined gas and steam turbine cycles and two-stroke diesel engine propulsion performance in large container ships with different routes.
4. Comprehensively assess the environmental and economic impacts of CCGT propulsion systems for large container ships compared with conventional diesel propulsion systems in terms of emissions, capital costs, operational costs, and size and weight of the machinery.

5. Present a comprehensive risk evaluation to assess the potential impacts of various factors, such as capital costs, fuel costs, hull fouling resistance, container shipment price, discount rate, and emission taxation on the economic analysis.

1.3 Knowledge gap and Contribution to knowledge

A techno-economic environmental and risk assessment (TERA) to determine the integrated large container ship propulsion system's efficiency, power, emissions, investment, capital, maintenance, and fuel costs of (simple, reheat and intercooler/reheat) CCGT fuelled by liquefied natural gas and marine diesel oil in contrast to the two-stroke diesel engine fuelled by the same fuel with journeys distance (5000 to 11000 nautical mile), and following the IMO plan that bans HFO. Also the use of enhanced LNG cycles with cryogenic qualities to improve CCGT efficiency. As well sensitivity analysis and risk evaluation were performed to examine the effects of the fuel cost, capital cost, hull fouling resistance, container shipment price, discount rate on the economic analysis. Along with the risk assessment of emissions tax on the economic analysis.

The contribution to knowledge:

- Implementing a techno-economic environmental and risk assessment (TERA) to assess simple cycle CCGT, reheat CCGT and intercooler/reheat CCGT as prime movers for large container ship, instead of the diesel engine two-stroke with different fuel such as liquefied natural gas and marine diesel fuel.
- Upgrading marine performance and simulation prediction tool (Poseidon software) to evaluate the performance of different marine propulsion systems such as simple cycle, reheat, intercooler/reheat CCGT and two-stroke diesel engines with journeys distance (5000 to 11000 nautical mile).

1.4 Methodological approaches

Based on the above research objectives, the following six stages will be performed (as shown in Figure 1-1):

1- The first stage was divided into three models (see Figure 1-1). These models were inspired by the Rolls-Royce RB211-6762 gas turbine. Three cycles were examined (simple, reheat, and intercool-er/reheat) through a numerical model (Turbomatch). The cycles were analysed using different pressure ratios, turbine entry temperatures, and ambient temperatures. The evaluation of these cycles considered the output power, efficiency, air mass flow, fuel flow, exhaust mass flow, exhaust temperature, and compressor inlet pressure of each gas turbine cycle with different fuels (MDO and LNG) to integrate these cycles with a combined gas and steam turbine in the next stage. LNG and MDO fuels were examined only from the properties of the heat calorific value through Turbomatch.

2- The second stage was divided into four parts – (A), (B), (C), and (D) (see Figure 1-1):

Part (A) modelled the steam turbine cycle with a single heat recovery steam generator based on the thermodynamic Rankine cycle with MATLAB software. It was then integrated with a gas turbine (simple, reheat and intercooler/reheat) from stage 1, considering output power, efficiency, and fuel consumption. A steam model with a single HRSG assumption of approach point, pinch point, and superheated pressure value was based on previous studies outcomes, which have demonstrated that certain steam cycle parameter values must be maintained within specific ranges to achieve maximum efficiency.

Part (B) modelled the ELNG CCGT cycle with MATLAB software. The model followed the heat balance thermodynamics in the heat exchanger between the cryogenic properties unique to LNG and inlet compressor air to increase the efficiency of CCGT. An energy balance was carried out; the cooled fluid was the gas turbine inlet air, and the heated fluid was the fuel flow. The best CCGT propulsion systems were used in this study after a comprehensive consideration of performance from parts A and B.

Part (C) modelled a two-stroke diesel engine based on the thermodynamic diesel cycle in the cylinder with MATLAB software. This model was inspired by the MAN B&W K98ME7.1-TII marine two-stroke diesel engine. This model assessed the output power, fuel flow, and efficiency of a diesel engine.

Part (D): Poseidon simulator software was used to simulate the aerodynamic and hydrodynamic resistance of the ship. The integration of CCGT and two-stroke diesel engine models with Poseidon simulator software were manually transferred using Excel files. Two-stroke diesel engines fuelled with MDO and (simple, reheat, intercooler/reheat, and ELNG) CCGT fuelled by LNG and MDO were examined as prime movers in large container ships with different routes. The first route was from the port of Shanghai, China to Los Angeles Port, USA. The second route was from Shanghai, China to Hamburg, Germany. Furthermore, the climate of the routes was divided into three seasons (winter, summer, and midseason). Additionally, the climate and weather of the routes were determined using a midpoint city weather between the two ports. For the first route, Midway Island was the midpoint city between Shanghai and Los Angeles. The second route between Shanghai and Hamburg was divided into four midpoint cities: Vietnam, Sri Lanka, Crete Island (Greek), and Ushant Island (France).

3- The third stage evaluated the technical outcome of the prime movers' performance in large container ships after being analysed with Poseidon software. The baseline of the evaluation was the two-stroke diesel engine. At the end of this stage, the optimum container ship prime mover performance was obtained.

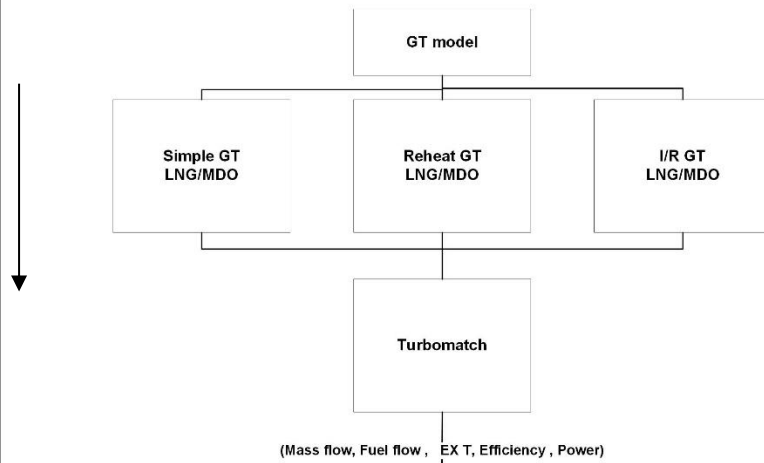
4- The fourth stage involved an environmental evaluation. It assessed the exhaust emissions of all prime movers in large container ships, such as CO₂ and NO_x, based on the fuel consumption of the route and the type of fuel.

5- The fifth stage consisted of an economic evaluation of all prime movers in large container ships based on the investment, capital, maintenance, size, weight, and fuel cost of each prime mover following the concept of payback period, net present value, and internal rate of return. The size and weight model following the fluid mechanics equations of the mass flow rate, volume, and specific weight will determine the weight of each component. The size and weight were not considered during the technical evaluation. Additionally, risk assessment was presented to assess the impacts of the fuel cost, capital cost, hull fouling

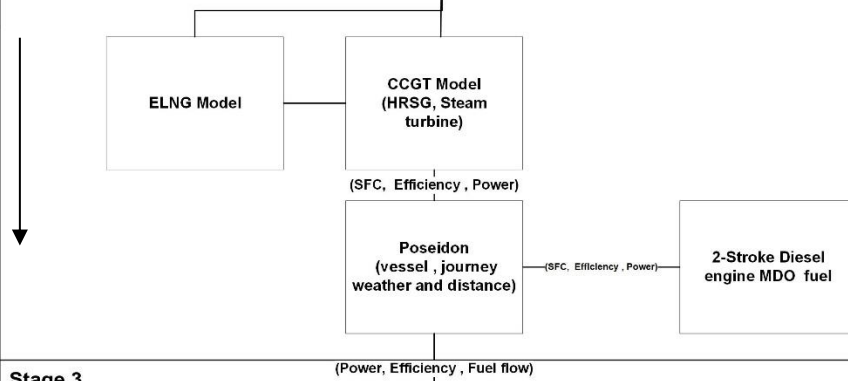
resistance, container shipment price, discount rate on the economic analysis, and the risk assessment of emissions tax on the economic analysis.

6- The sixth stage extracted TERA results for all propulsion systems of large container ships.

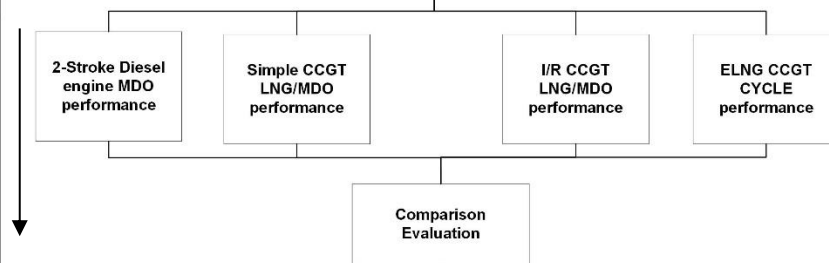
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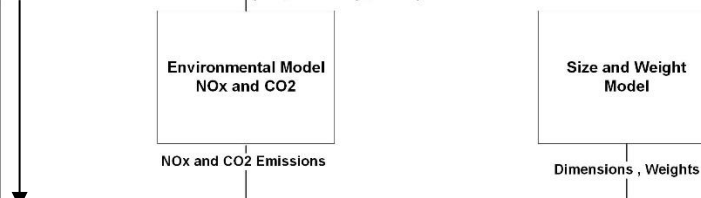
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Stage 3



Stage 4



Stage 5



Stage 6

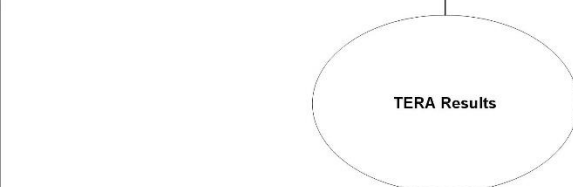


Figure 1-1 Project Methodology

1.5 List of publications

Table 1-1 shows the publication of this study:

Table 1-1 Thesis publication

Chapter	Paper	Objective	Title	Status
2	1	1,2,3	Alzayed AMT, Sampath S, Pilidis P. (2022) Techno-environmental evaluation of liquefied natural gas fuelled combined gas turbine with steam cycles for large container ship propulsion systems, Energies, Volume 15, Issue 5, February 2022, Article number 1764	Published
3	2	3,4	Alzayed AMT, Batra A, Sampath S, Pilidis P. (2022) Techno-environmental mission evaluation of combined cycle gas turbines for large container ship propulsion, Energies, Volume 15, Issue 12, June 2022, Article number 4426	Published
4	3	4,5	Alzayed AMT, Sampath S, Pilidis P. (2022) Techno-economic and risk evaluation of combined cycle propulsion systems in large container ships. Energies, Volume 15, Issue 14, July 2022, Article number 5178	Published
5	4	5	Alzayed AMT., Sampath S., Pilidis P. TERA of Combined Cycles for Large Container Ship Propulsion. 2022.	Submitted to the Journal of Marine

1.6 Thesis structure

The thesis is presented in the form of four, self-contained papers, supplemented by an overall discussion chapter, conclusion chapter, and chapter on potential future work. A brief description of the content of each section is given below.

Chapter 2 (Paper 1) – Techno-Environmental Evaluation of a Liquefied Natural Gas-Fuelled Combined Gas Turbine with Steam Cycles for Large Container Ship Propulsion Systems

Overview: The first paper (chapter two) modelled and assessed the performance of advanced CCGT cycles, including simple, reheat, and intercooler/reheat cycles fuelled with LNG and MDO. Additionally, an enhanced liquified natural gas cycle utilising cryogenic properties unique to LNG was used to improve the efficiency of CCGT. These assessments were conducted using numerical models (Turbo-match and MATLAB). After verifying the simple gas turbine cycle simulation on the Turbomatch with the reference RB211-6762 GT specifications such as output power, efficiency, exhaust mass flow and exhaust temperature then will examine the impact of increasing overall pressure ratio, TET, and ambient temperature. A mathematical model was developed to evaluate the size and weight of the proposed engines. The outcomes of this study showed that the efficiency of ELNG cycles increased by 2% more than the other cycle, and I/R ELNG CCGT was the most efficient cycle compared to all CCGT cycles. The CCGT cycles fuelled with LNG were higher efficiency than the CCGT cycles fuelled with MDO. In terms of the size and weight of the engine, CCGT cycles, including all components, were lighter than the two-stroke diesel engine. This paper covers the first, second, and part of the fourth objective.

Chapter 3 (Paper 2) – Techno-Environmental Mission Evaluation of Combined Cycle Gas Turbines for Large Container Ship Propulsion

Overview: The second paper (chapter 3) developed a two-stroke diesel engine model and updated Poseidon simulator software to examine the performance of advanced CCGT and diesel engines as prime movers in a large container ship with two different routes. A single shaft with CCGT was used in this study to

reduce the weight of the machinery. Single-shaft gas turbines are acceptable only when they are coupled with a constant-speed controllable pitch propeller. The G.T. and controllable pitch propeller can run at a constant speed, and the control system carefully synchronises the fuel flow with the power requirement as the controllable pitch propeller is changed. Given that the application is a container ship expected to sail for very long periods at nearly constant power, this scheme is considered reasonable. Further-more, the fuel consumption of the gas turbine would remain unchanged due to the gas turbine operating at a constant RPM, while the speed of the controllable pitch propeller would be adjusted to de-crease the ship's velocity. An environmental model was developed through a mathematical model to assess the NO_x and CO₂ emissions from all propulsion systems of each route. The results showed that the advanced CCGT cycles had higher efficiency than the two-stroke diesel engine, and the I/R ELNG was the most efficient propulsion system for a large container ship. The advanced CCGT cycles reduced NO_x and CO₂ by approximately 45% and 77%, respectively, compared to the two-stroke diesel engine. This paper covers the third and part of the fourth objective.

Chapter 4 (Paper 3) –Techno-Economic and Risk Evaluation of Combined Cycle Propulsion Systems in Large Container Ships

Overview: The third paper (chapter four) developed an economic model following net present value, payback period, and internal rate of return techniques through a mathematical model. The economic assessment included the capital, installation, maintenance, and operating costs of proposed propulsion systems for large container ships. It also included a risk assessment evaluating the impacts of fuel costs, capital costs, and hull fouling resistance on the economic results. The results showed that the simple, I/R, and I/R ELNG CCGT cycles had the highest NPV value. Regarding PP, the results showed that the simple, I/R, and I/R ELNG CCGT cycles reduced the period approximately 38.8%, 38.9%, and 35%, respectively, compared to a two-stroke diesel engine with the same route. Furthermore, the fuel cost and capital cost assessment results showed the

greatest impact on the economic results of all pro-pulsion systems. This paper covers the fourth and part of the fifth objective.

Chapter 5 (Paper 4) – TERA of Combined Cycles for Large Container Ship Propulsion

Overview: The fourth paper (chapter five) evaluated the risk assessment of emission taxes, container costs, and discount rates on the economic results. The results showed that the two-stroke diesel engine, simple, and I/R CCGT fuelled with MDO had the highest reduction in economic value compared to the other technologies. Furthermore, the discount rate and CO₂ tax risk assessment showed a significant impact on the economic profit. This paper covers the fifth objective.

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2 Techno-Environmental Evaluation of a Liquefied Natural Gas-Fuelled Combined Gas Turbine with Steam Cycles for Large Container Ship Propulsion Systems

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2.1 Abstract

Restrictions on emissions are being imposed by regional and international shipping organisations, which raise the question of which marine fuel and technology can most effectively replace heavy fuel oil and diesel engines. The aim of this study is to find appropriate advanced combined gas and steam turbine cycles for marine propulsion systems in a large container ship with respect to the evolving maritime environmental regulations. The selection criteria are the thermodynamic performance, emissions, size, and weight of advanced combined gas and steam turbine cycles in a large container ship. Two baselines are used: a two-stroke diesel engine using marine diesel oil and a combined gas and steam turbine system using liquefied natural gas and marine diesel oil. Then, liquefied natural gas cycles are examined based on fuel replacement and enhanced to assess the benefits of liquefied natural gas over marine diesel oil. The results show that the enhanced liquefied natural gas combined gas and steam turbine cycles are the most efficient, at up to 1.6% higher than the other cycles. Regarding the size and weight, the combined gas and steam turbine propulsion system is approximately 24.7% lighter than the original diesel engine propulsion system.

Keywords: advanced combined gas and steam turbine cycle; techno-environmental; combined gas and steam turbine cycle; large container; ship; propulsion systems; liquefied natural gas; marine diesel oil; nitrogen oxide; carbon dioxide

2.2 Introduction

Diesel engines have dominated merchant ship propulsion for several decades. Approximately 96% of vessels that weigh over 100 gross tonnes and are used in civilian applications are powered by diesel engines [1]. Two-stroke diesel engines power large oil tankers, container ships, and ore carriers. Since the 1970s, land-based power plants have used combined-cycle gas and steam turbine systems. The use of such systems has been considered for ship propulsion systems. Only a few vessels have utilised CCGT for propulsion systems, such as Royal Caribbean's Radiance, Celebrity, Millennium and Infinity Cruises, and two Russian Ro-Ro ships. [2]. The authors believe that the fuel costs of this type of propulsion system is the main cause of its rarity. However, this is changing owing to environmental issues. The efficiency of CCGT can reach up to 60%, which is higher than that of two-stroke diesel engines [3]. The CCGT efficiency can be improved by enhancing the gas turbine cycles (top cycle) or the steam turbine cycles (bottom cycle). To enhance G.T. cycle efficiency, complex components such as a reheater, intercooler, or both can be integrated into the simple cycle. To increase the efficiency of the steam turbine cycles, a heat recovery steam generator with double or triple pressure should be used, and the steam turbine cycle should be reheated [4]. The key reasons for the prevalence of the two-stroke diesel engine are its high efficiency and ability to burn on low-cost heavy fuel oil. However, the drawbacks of two-stroke diesel engines are related to the high levels of emissions contributed, such as nitrogen oxide, sulphur oxide, and particulate matter, which are currently the subject of continuously stricter regulations [5]. Some of these emissions result from the fuel that is used, whereas others depend on the engine cycle that is employed. Initially, the focus was on sulphur oxide and nitrogen oxide. More recently, environmental concerns have encompassed CO₂ emissions, as stated by the International Maritime Organisation [6]. The IMO put forward measures for evaluating and controlling the energy efficiency design index values of new ships [7]. The CO₂ emissions can be reduced by using a more efficient propulsion system or cleaner fuel (e.g., natural gas) [2]. In addition to the abovementioned environmental aspects and economic considerations related to fuel cost uncertainties, the researchers were

encouraged to find a more efficient engine for marine propulsion systems. Among these solutions are those based on the concept of combined cycles (CCGT systems). Techno-environmental evaluations are essential studies that measure the technical performance and emission impacts of a technology. For various reasons and applications, CCGTs have been studied as propulsion systems for vessels, but few ships have been built with CCGT propulsion. The previous studies of CCGTs as propulsion systems for vessels are summarised in this section:

- Jefferson [8] studied the performance of a simple CCGT propulsion system under steady-state operation and transient periods, including acceleration, deceleration, and the impact of inlet air conditions. The heat recovery steam generator adopted in this study was a single-pressure generator. Therefore, the CCGT performance was affected by atmospheric conditions such as temperature, pressure, and relative humidity;
- Wiggins [3] studied the cycle efficiency, specific fuel consumption, and boil-off gas of a simple CCGT fuelled by natural gas, in addition to a two-stroke diesel engine fuelled by heavy fuel oil for propulsion systems in liquefied natural gas ships. Additionally, they studied the emissions (SO_x, NO_x, and CO₂) and fuel consumption reductions in the CCGT. The results of this study demonstrated that CCGT propulsion is an attractive alternative for LNG ships. LNG permits a lower CO₂ footprint (by approximately 20%) because of its higher hydrogen content. Another fundamental advantage of natural gas fuel is that it delivers (in land applications) very low (25 ppm) amounts of NO_x with appropriately designed combustors;
- Benvenuto [9] studied a simple CCGT fuelled by marine gas oil as an alternative to a two-stroke diesel engine fuelled by heavy fuel oil for the propulsion of a 9000 twenty-foot equivalent unit container ship. They investigated the performance of the powerplant and the efficiency of the design and high-load off-design conditions in both steady-state and dynamic situations, and determined the engine weight, dimensions, layout,

capacity, and maintenance costs. The results revealed lower amounts of pollutant emissions from the CCGT plant than the two-stroke diesel engines. Furthermore, in terms of weight and dimensions, the two-stroke diesel engine had disadvantages compared with the CCGT with equivalent power. In terms of noise and vibration, the two-stroke diesel engine was much higher than the CCGT. The CCGT plant had a slight advantage over the two-stroke diesel engine in terms of engine efficiency. Additionally, the CCGT plant required significantly lower maintenance than a typical marine diesel engine. However, the costs of installation and operation still favoured the diesel engine;

- Benvenuto [10] also studied the performance of a CCGT with a marine gas turbine with a variety of steam turbine plants layouts, including single-pressure and dual-pressure HRSG layouts. The study results showed that the dual-pressure steam plant layout (with two boilers) had complex and high weights, dimensions, and costs, but had the best efficiency. The dual-pressure steam plant layout (with a single boiler) was less efficient. In terms of the complexity, weights, dimensions, and cost, the dual-pressure steam plant layout with one boiler was comparable to the dual-pressure steam plant layout with two boilers;
- Emmanuel-Douglas [11] analysed the performance of an optimal CCGT for cruise ships for 2000 h of operation and with various operating modes in terms of the vessel demands from power, electricity, and heat. The combined-cycle system consisted of a combined gas turbine electric and steam plant, CCGT turbines, a combined diesel–electric and gas turbine plant, a combined power and heat generation plant, and a diesel–electric plant with waste heat recovery. The results showed that the diesel engines show the best results compared with other propulsion systems in the cruise ship in terms of the economic aspects. Additionally, the flexibility of the gas turbine configuration enhanced the performance and made it appropriate for different applications;

- Altosole [2] studied a CCGT with single-pressure HRSG, CCGT with dual-pressure HRSG with a single boiler and CCGT with dual-pressure HRSG with two boilers in contrast to a conventional two-stroke diesel engine as a prime mover in a 9000 TEU unit large containership. He studied the two-stroke diesel engine with waste heat recovery as a prime mover in an oil tanker vessel and investigated the performance, emissions, and economic aspects along with the weight and dimensions of all propulsion systems. The results showed that the efficiency levels of the dual-pressure steam plant with two boilers was 1.3% and 2.3% better when compared with the dual-pressure (single boiler) and single-pressure steam plant, respectively. Moreover, the CCGT plant was smaller, and its components weighed less than those of the two-stroke diesel engine. However, it was 20–40% more expensive. The CCGT exhibited an 8% reduction in specific fuel consumption over the two-stroke diesel engine.

To date, only a limited number of studies have performed techno-environmental evaluations of advanced CCGT systems for large container ships. Hence, this study contributes two aspects:

1. Based on the literature review, the following concepts for marine propulsion systems were studied:
 - The use of enhanced LNG cycles with cryogenic qualities to improve CCGT efficiency.
 - A comprehensive environmental assessment to measure the emissions of NO_x and CO₂ from the presented CCGT cycles and a two-stroke diesel engine.
2. For these particular cycles, other analytical aspects were brought together for the first time using existing algorithms:
 - A technical assessment was performed on the CCGT cycles, simple combined gas turbine–steam system, reheat combined gas steam turbine, and the intercooler–reheat combined gas steam

turbine with a single HRSG fuelled by MDO and LNG as propulsion systems in a large container ship;

- The possibility of positing the intercooler and reheat was assessed, which can significantly affect the engine output and efficiency;
- A method and model for the sizing and weighting of advanced CCGT cycles for the large container ship was proposed.

The remainder of this paper is as follows. The second section describes the methods employed in this study. The third section defines the assumptions, simulation, and validation of the method. The fourth section provides the results and discussion, and the conclusion is presented in the fifth section.

2.3 Materials and Methods

The methodology for this research is divided into four stages, as shown in Figure 2-1, Stage one represents the gas turbine models evaluated using an in-house gas turbine performance software (Turbomatch) [12], which was built to simulate the three types of gas turbine cycles with different overall pressure ratios, turbine entry temperature (TET) values, and ambient temperatures. These three gas turbine cycles are:

1. Simple cycle fuelled by LNG and MDO;
2. Complex cycles incorporating reheating and intercooling fuelled by LNG and MDO;
3. Enhanced LNG benefitting from LNG's cryogenic properties

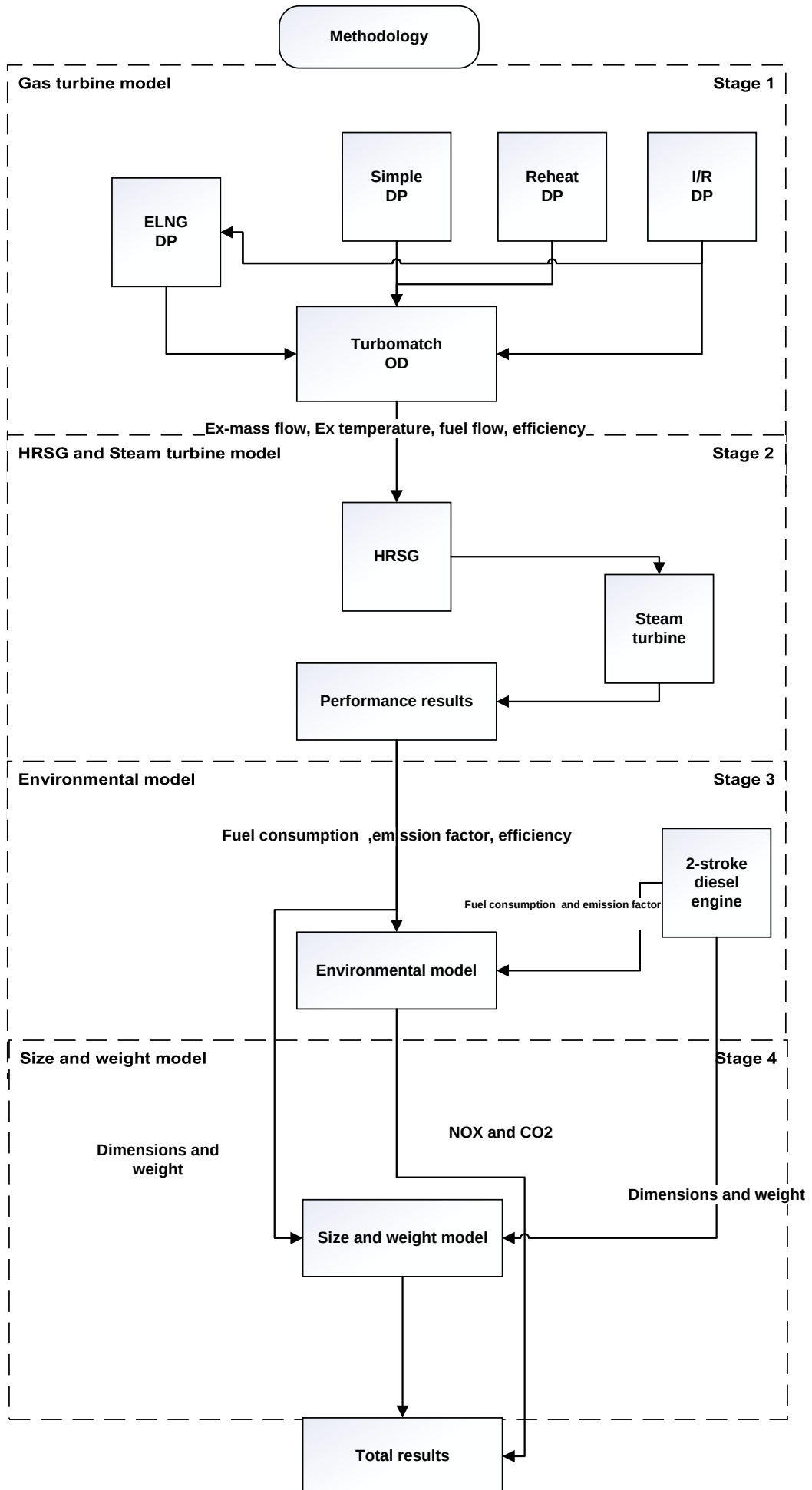


Figure 2-1 Flowchart of the methodology employed in this study. NO_x: Nitrogen oxide; CO₂: carbon dioxide; CCGT: combined-cycle gas turbine (with steam); I/R: intercooler–reheat cycle; HRSG: heat recovery steam generator; ELNG: enhanced liquefied natural gas.

The results of this model, which will be the exhaust mass flow, exhaust temperature, fuel flow, and efficiency of all cycles, will be the inputs for stage two. Stage two presents two models: the HRSG and steam turbine, which were constructed using the MATLAB software to simulate the CCGT performance with different inlet conditions from stage 1. Stage three presents the environmental model, which assesses the NO_x and CO₂ emissions from the fuel flows and emission factors of all CCGT and two-stroke diesel engines. The final stage evaluates the size and weight of all CCGT cycles and two-stroke diesel engines in a large container ship based on the dimensions and weight.

2.3.1 Combined-Cycle (CCGT) Model

The exhaust heat from the gas turbine increases the power and efficiency of the CCGT. Figure 2-2 shows the CCGT layout.

model with a single HRSG assumption was based on the optimal steam cycle parameters obtained from previous studies [2,10].

2.3.1.1 Gas Turbine Model

A performance model of the gas turbine was developed using the Cranfield in-house gas turbine performance software (Turbomatch) [12]. The software could model the design-point and off-design aspects of gas turbine cycles for any engine configuration. This study explores simple, reheat, and intercooler–reheat marine gas turbines that have a CCGT. The marine gas turbine used here was a two-shaft marine gas turbine with a power turbine. The simulation reference point for the G.T., inspired by the RB211 [13], was a gas turbine used extensively in offshore applications. The analysis was based on the published data for existing commercial gas turbines. Derived cycles were selected for simple, reheat, and intercooler–reheat (I/R) cycles, which allowed us to select the optimal locations for the reheater and intercooler to be implemented along with the simple cycle [14]. Simple, reheater, and I/R systems had the same D.P. in TET and output power to ensure a fair examination of these cycles for CCGT; the ELNG cycle was higher than TET = +50 K owing to its good characteristics. Because of the salinity of marine environments, the adopted TET values were much lower than those of state-of-the-art gas turbines used in land applications. Thus, the overall efficiencies obtained were typically 5% lower than the values of 0.60 or 0.60+ verified in modern cycles. Nonetheless, these efficiencies were very competitive.

D.P. matching calculation of the gas turbine the model inspired by the RB211-6762 GT is used to calibrate the engine D.P. parameters and predict the off-design performance. The target performance parameters for the D.P. simulation are the thermal efficiency, exhaust gas temperature (EGT), and exhaust mass flow that will influence the CCGT.

- Simple, reheat, I/R, and ELNG cycles for D.P. and Off-Design Performance Prediction

After verification, the model with the actual engine will modify the model to obtain the output power needed at D.P. The D.P. will increase the pressure ratio from

20 to 60. The D.P. for the reheat cycle will be obtained by choosing the best location for reheating to achieve the optimal efficiency with an exhaust temperature of 600 °C by changing the overall pressure ratio. The position of the reheater will influence the reheating between the high-pressure turbine (HPT) and low-pressure turbine (LPT) in position 1, as well as between the LPT and power turbine (P.T.) in position 2. The D.P. for the I/R will be obtained by selecting the best locations for the intercooler and reheater to achieve the optimal efficiency with an exhaust temperature of 600 °C by changing the overall pressure ratio. After choosing the best cycles for a gas turbine at the D.P., the off-design performance of CCGT will be subsequently predicted for a variety of different scenarios, such as when the TET changes from 1500 to 1800 K, or for the effect of ambient temperature, which ranges from -20 to 45 °C with different fuels (This study considered LNG and MDO fuel). The calculations used for changing ambient temperatures are off-design calculations carried out with Turbomatch, the Cranfield performance evaluation code. Turbomatch can perform design point, off-design, transient, and degraded G.T. calculations. For more realistic results, the exhaust temperature from the gas turbine will be as follows:

1. If $EGT < 873\text{ K}$, steam cycle $T = EGT - \text{pinch point}$.
2. If $EGT > 873\text{ K}$, steam cycle $T = 873 - \text{pinch point}$ (i.e., constant).

2.3.1.2 Heat Recovery Steam Generator Model

A single-pressure HRSG is adopted here as a standard type for the combined-cycle gas turbine power plant. A single-pressure HRSG with economiser, evaporator, and superheater sections is utilised for the generation of the superheated process steam. The temperature profile of the HRSG and heat balance is shown in Figure 2-3.

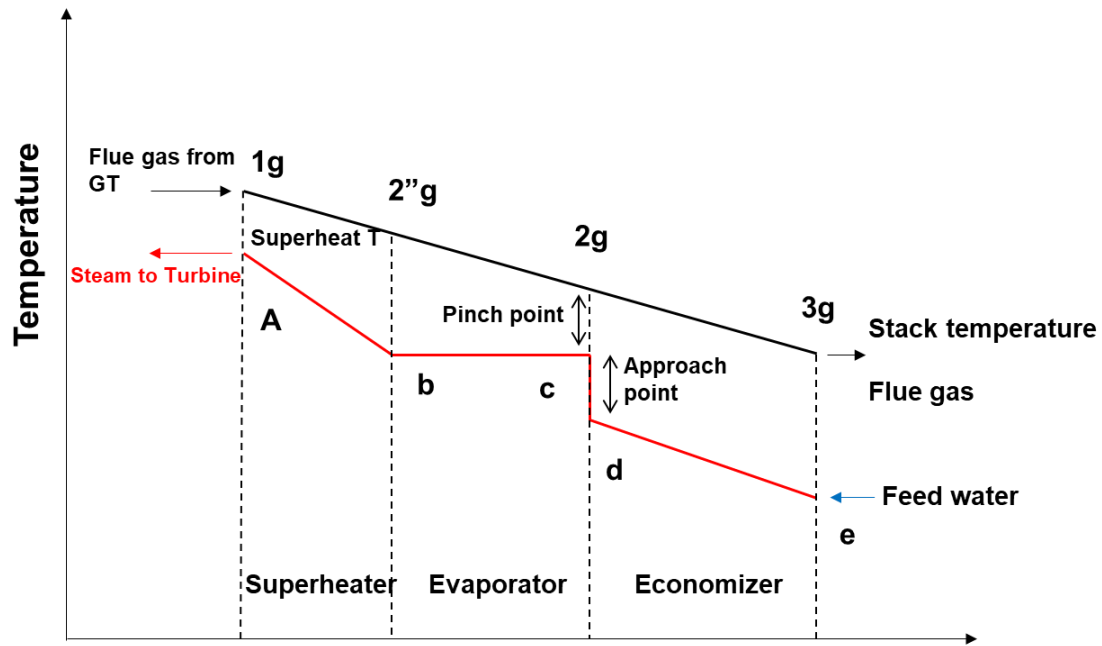


Figure 2-3 Temperature diagram of the heat recovery steam generator (HRSG); A: outlet steam mass flow temperature from HRSG to steam turbine; b and c: temperature of the steam inlet and outlet the evaporator; d: outlet fluid mass flow temperature from economizer.

The thermal investigation of the HRSG depends on the approach point (T_{ap}) and pinch point (T_{pin}), which contribute to the effectiveness of the heat exchange. The approach point (T_{ap}) is the difference between the water temperature entering the evaporator and the saturation temperature. The pinch point (T_{pin}) is the temperature difference between the hot and cold fluids. The first step in the process is to determine the temperature profile. The temperatures of the working fluid and exhaust gases at the inlet and outlet for each section can be calculated using the energy balance. The equation used to create the temperature profile is the heat balance equation:

$$Q_{1-3} = Q_{A-e} \quad (2-1)$$

where Q_{1-3} is the heat along with the exhaust gases from the gas turbine and Q_{A-e} is that along with the steam from the steam turbine.

$$T_b = T_c \quad (2-2)$$

where T_c is the saturation steam temperature at superheater pressure. The temperature of the gas leaving the superheated is:

$$T_{2g} = T_{pin} + T_c \quad (2-3)$$

The temperature of the water inlet the evaporator is:

$$T_d = T_c - T_{ap} \quad (2-4)$$

To apply the energy balance between the gas and steam to find the steam mass flow m_s :

$$Q_{1-2} = C_p \times m_g \times (T_{1g} - T_{2g}) = Q_{A-c} = m_s (h_A - h_c) \quad (2-5)$$

where m_g is the exhaust mass flow from the gas turbine, T_{1g} is the exhaust temperature from gas turbine, h_A is the enthalpy from temperature at A stagnation, and h_c is the enthalpy from temperature at c stagnation.

The temperature of the hot exhaust gases exiting the HRSG can be found by considering the energy balance between states 1 and 3:

$$m_s (h_a - h_e) = C_p * m_g * (T_{1g} - T_{3g}) \quad (2-6)$$

where h_e is the enthalpy from the temperature at e stagnation with the pump pressure.

2.3.1.3 Steam Turbine Model

The steam at high temperature and high pressure obtained from the HRSG expands to the condenser pressure in the steam turbine. The power generated by the steam turbine is:

$$w_s = m_s (h_A - h_7) \quad (2-7)$$

where h_7 is the enthalpy from the temperature of the steam at the exhaust steam turbine.

2.3.1.3.1 Condenser Model

The heat rejected from the condenser is:

$$Q_{\text{cond}} = m_s(h_7 - h_8) \quad (2-8)$$

where h_8 is the enthalpy of the fluid at the condenser pressure.

2.3.1.3.2 Pump Model

The pump extracts the condensate, which is raised to the economiser pressure.

The corresponding process is given by:

$$w_p = m_s(h_8 - h_e) \quad (2-9)$$

Therefore, the total power for the steam turbine plant is:

$$w_T = w_s - w_p \quad (2-10)$$

The overall thermal efficiency for the CCGT is:

$$\eta = \frac{w_T + w_{GT}}{Q_{\text{in GT}}} \quad (2-11)$$

where w_T is the total power from the steam turbine, w_{GT} is the power from the gas turbine, and $Q_{\text{in GT}}$ is the heat input in the gas turbine.

2.3.2 Enhanced Liquified Natural Gas Cycle

In the long term, CCGT cycles benefitting from the cryogenic properties unique to LNG may be implemented. LNG is assumed to be stored as a saturated liquid at atmospheric pressure. In the investigation described here, two enhancements are included. The first relates to the gasification of the fuel. The energy required to gasify the LNG is provided in a heat exchanger where the gas turbine inlet air is cooled. This permits the gas turbine to operate with a lower inlet temperature. An energy balance process is carried out where the cooled fluid is the gas turbine inlet air and the heated fluid is the fuel flow. The fuel flow changes phase and emerges at a temperature 15 K lower than the air inlet temperature. The natural gas used is assumed to be pure methane. The gas turbine inlet air is assumed to experience a pressure loss of 3%. Figure 2-4 shows the ELNG cycle layout.

Figure 2-5 show the heat balance in the heat exchanger between the LNG and inlet air.

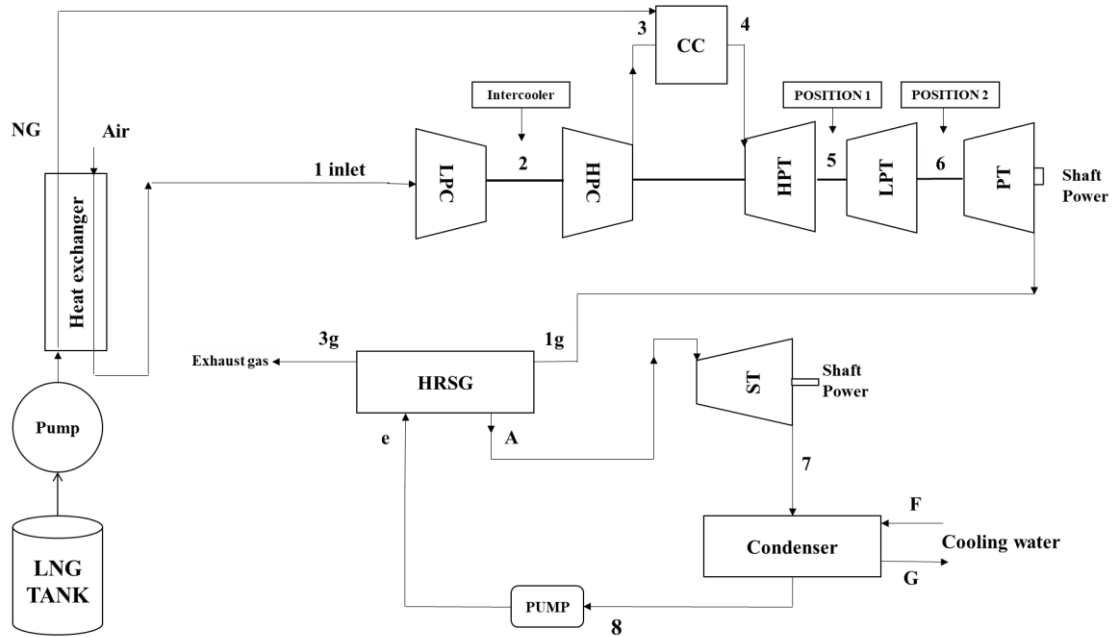


Figure 2-4 ELNG cycle layout. LNG: liquefied natural gas; HPC: high-pressure compressor; LPC: low-pressure compressor; CC: combustion chamber; S.T.: steam turbine; 1: outlet air mass flow temperature from heat exchanger to low-pressure compressor; NG: the outlet natural gas mass flow from heat exchanger to combustion chamber.

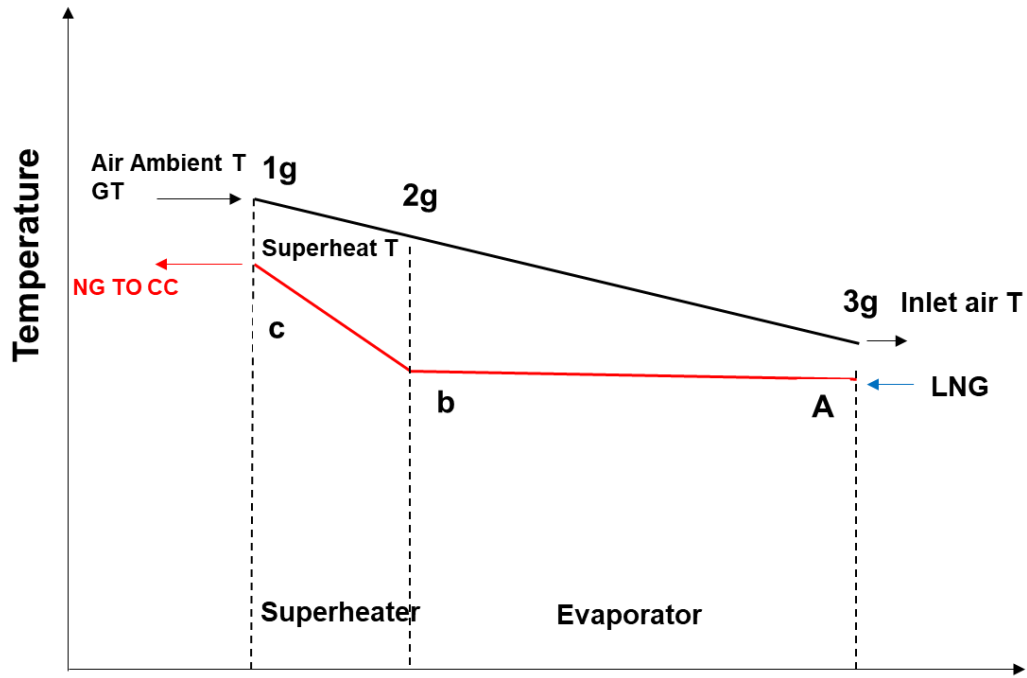


Figure 2-5 Heat balance in the heat exchanger between LNG and inlet air. 1g: inlet air mass flow temperature to heat exchanger; 2g: outlet air mass flow temperature from superheater stagnation to evaporator; 3g: outlet air mass flow temperature from heat exchanger to gas turbine; A: inlet LNG mass flow temperature to heat exchanger; b: outlet LNG mass flow temperature evaporator stagnation to superheater; c: outlet NG mass flow temperature from heat exchanger to combustion chamber gas turbine.

The other feature of LNG is that it permits the use of dry low-NO_x combustors [15], which can deliver very low NO_x emissions, as demonstrated in land-based gas turbines fuelled by natural gases. In this context, the ELNG cycles are considered with a TET that is 50 K higher than the other cycles.

2.3.3 Estimated Size and Weight of the CCGT

The total weight related to the CCGT can be determined using the following equation [16,17]:

$$W_{\text{total}} = W_{\text{GT}} + W_{\text{ST}} + W_{\text{HRSG}} + W_{\text{Cond}} + W_{\text{other}} \quad (2-12)$$

where W_{GT} is the gas turbine weight, W_{ST} is the steam turbine weight, W_{HRSG} is the HRSG weight, and W_{Cond} is the condenser weight.

Since the gas and steam turbines are rotating machines, similar approaches are used to calculate their weights. The same is applied for the HRSG and condenser, as they are heat exchangers. The heat exchanger's surface area is the main factor of its weight [8]. The W_{other} is used to estimate the auxiliary equipment weights, such as those for pumps, fan, pipes, and water in the steam turbine cycle, and to monitor and control device weights in the CCGT. A constant percentage (K) range of 3–7% of the total weight estimated will be included to determine the auxiliary weight.

2.3.3.1 Gas and steam turbine weight

General Electric developed a scaling technique to estimate the weight and size of gas and steam turbines based on information from an existing machine [18]. The power P and weight W_{GT} of the selected machine can be found in the manufacturer's design. The gas-turbine-specific coefficient for such a machine is:

$$w = k \times P^{\frac{3}{2}} \quad (2-13)$$

The gas-turbine-specific coefficient (k) used for scaling the gas turbine must be calculated.

Consequently, the gas and steam turbine weights calculated as functions of power are:

$$W_{GT} = k_{GT} \times P_{\text{gas}}^{\frac{3}{2}} + W_{GT \text{ stander}} \quad (2-14)$$

$$W_{ST} = k_{ST} \times P_{ST}^{\frac{3}{2}} + W_{ST \text{ stander}} \quad (2-15)$$

where $W_{GT \text{ stander}}$ is the weight of the gas turbine from the manufacturer's specifications and $W_{ST \text{ stander}}$ is that of the steam turbine from the manufacturer's specifications.

2.3.3.2 HRSG and condenser weight

Similarly, for turbine weight estimations, similar investigation methods are used here to calculate the weight of both the condenser and the HRSG. The heat transfer area for the considered HRSG (A_{HRSG}) can be decomposed into the

areas of its components, namely the economiser ($A_{\text{Economizier}}$), evaporator ($A_{\text{Evaporator}}$), and superheater ($A_{\text{Superheater}}$).

$$A_{\text{HRSG}} = A_{\text{Economizier}} + A_{\text{Evaporator}} + A_{\text{Superheater}} \quad (2-16)$$

$$Q_{\text{EC}} = U_{\text{EC}} A_{\text{EC}} \frac{(T_{2g} - T_d) - (T_{3g} - T_e)}{\ln\left(\frac{T_{2g} - T_d}{T_{3g} - T_e}\right)} \quad (2-17)$$

$$Q_{\text{EV}} = U_{\text{EV}} A_{\text{EV}} \frac{(T_{2g''} - T_b) - (T_{2g} - T_d)}{\ln\left(\frac{T_{2g''} - T_b}{T_{2g} - T_d}\right)} \quad (2-18)$$

$$Q_{\text{SH}} = U_{\text{SH}} A_{\text{SH}} \frac{(T_{1g} - T_A) - (T_{2g''} - T_b)}{\ln\left(\frac{T_{1g} - T_A}{T_{2g''} - T_b}\right)} \quad (2-19)$$

where U is the overall heat transfer coefficient for the heat exchanger and A is its surface area; T_{1g} , T_{2g} , $T_{2g''}$, and T_{3g} are the temperatures in the gas side of the heat exchanger; T_A , T_b , T_d , T_e are the temperatures in the fluid side of the heat exchanger. See Figure 3 for a graphical explanation of the subscript notation used in the temperature calculation.

In Equations (18)–(20), all temperatures of the HRSG are known from the model presented earlier, while the economiser (U_{EC}), evaporated (U_{EV}), and superheater (U_{SH}) heat transfer coefficients have typical values in the ranges of 30–50, 25–65, and 50–90 W/(m²K), respectively [19]. Following the same method, the heat transfer area for the condenser (A_{COND}) can be calculated as:

$$Q_{\text{COND}} = U_{\text{COND}} A_{\text{COND}} \frac{(T_7 - T_G) - (T_8 - T_F)}{\ln\left(\frac{T_7 - T_G}{T_8 - T_F}\right)} \quad (2-20)$$

where T_7 , T_8 , T_G , and T_F are the temperatures in the condenser, as shown in Figure 2. Again, all temperatures of the condenser are known from the model presented earlier, and the heat transfer coefficient (U_{COND}) values are in the typical range of 2000–4000 W/(m²K) [20]. Importantly, the heat transfer

coefficient values (U_{EC} , U_{EV} , U_{SH} , and U_{COND}) will be assumed constant. The following expressions will be used for the HRSG and condenser weight:

$$W_{HRSG} = K_{HRSG} * A_{HRSG} + P_{HRSG} \quad (2-21)$$

$$W_{COND} = K_{COND} * A_{COND} + P_{COND} \quad (2-22)$$

2.3.4 Environmental Model

This model will assess the emissions from all CCGT cycles fuelled by the LNG and MDO and from a two-stroke diesel engine fuelled by MDO. The assessment will be based on the emission factors and fuel consumption of the propulsion system. This study will examine NOx and CO₂ emissions.

2.3.4.1 Nitrogen Oxides NOx

NOx is produced as a by-product of combustion in engines where nitrogen and oxygen react in the air. Their production depends on the temperature and pressure of the combustion [21].

2.3.4.2 Carbon dioxide CO₂

When energy is produced by consuming oxygen, CO₂ is produced [22]. However, excess CO₂ traps heat in the atmosphere, making the earth warmer [23]. The average global temperature increase for this century is estimated to be between 0.5 and 4.0 °C [24].

Two different procedures can be used to estimate emissions: fuel consumption and engine power [25]. The emissions are estimated from fuel consumption here, which can be expressed as:

$$E = \sum (FC_{j,m,p} * EF_{i,j,m}) \quad (2-23)$$

where E represents the emissions (kg/hr), $F.C.$ is the fuel consumption (tonnes/hr), $E.F.$ is the emission factor (kg/tonne), i is the pollutant, j is the engine

type (slow-speed diesel engine, gas turbine, and steam turbine), and m is the fuel type (bunker fuel oil, MDO/marine gas oil, and gasoline).

2.4 Results

2.4.1 Assumptions, Simulation, and Validation

The influence of the parameters, namely the cycle compression ratio, TET, ambient temperature, and fuel type (LNG and MDO), on the performance of CCGT cycles is discussed in this section. The effects on the power output and efficiency were evaluated using the Turbomatch and MATLAB software. The simulation results for G.T. obtained via the D.P. simple cycle matching for RB211-6762 are presented in Table 2-1.

Table 2-1 Turbomatch output design point (D.P.) parameters of the simple-cycle gas turbine.

Parameter	Simulated Value	RB211-6762 GT	Deviation %
Thermal Efficiency (%)	38.1	38.8	-0.494
Exhaust Gas Temperature (°C)	492.83	492	0.586
Exhaust Mass Flow (kg/s)	96.066	96	0.046

However, the inlet steam temperature depends on the material development. Regarding parts design for superheaters, piping, and valves exposed to high steam temperatures, there is a steam temperature limit based on the material strength, structural design, and cost. Currently, the highest inlet steam temperature range is between 566 °C and 620 °C [4]. It has been assumed that the maximum temperature may reach 600°C. The assumptions for the three G.T. cycles, HRSG, and steam turbine are presented in Tables 2-2 and 2-3, respectively.

Table 2-2 Assumed parameters of the G.T. cycles.

Parameter	Value
Ambient Conditions	15° C = 288 K, 1 atm = 101 kPa
Compressor Isentropic Efficiency (%)	87
Intercooler Efficiency (%)	99
LPC = HPC Pressure Ratio for Simple-Cycle	LPC = 4.6368, HPC = 4.6368
Combustor Efficiency (%)	99
Turbine Isentropic Efficiency (%)	88.0
Power Turbine Isentropic Efficiency (%)	88.0
Mass Flow (kg/s)	106
Combustor Pressure Loss (%)	5.0
Bleed Air for Turbine Cooling (% of Core Mass Flow)	10.0
Intake/Nozzle Pressure Loss (%)	0.0
TET: turbine entry temperature (K) Variable	1600
Exhaust Pressure Loss(%)	2
Intercooler Pressure Loss (%)	2
Humidity (%)	60

Table 2-3 Steam model with single HRSG assumption.

Parameter.	Value
Steam Turbine Isentropic Efficiency (%)	88
Output power (MW)	Up to 20
Approach point (C)	7.5
Pinch point (C)	20
Steam turbine efficiency	88.0
Superheated pressure (bar)	60
Condenser pressure (bar)	0.06
Pump pressure (bar)	3
Steam turbine Isentropic Efficiency (%)	88

2.4.2 Design point (D.P) and Off-Design Point (O.D) Results for All CCGT Cycles

2.4.2.1 D.P. of CCGT Cycles

- Combined cycle (CCGT) with a simple-cycle gas turbine

Single-shaft gas turbines are acceptable only when they are coupled with a constant-speed controllable pitch propeller. The G.T. and controllable pitch propeller can run at a constant speed, and the control system carefully synchronises the fuel flow with the power requirement as the controllable pitch propeller is changed. Given that the application is a container ship expected to sail for very long periods at nearly constant power, this scheme is considered reasonable. Furthermore, if a separate and independent power turbine was chosen, the fuel consumption details (this is a key objective of the paper) presented here would not change.

The optimum pressure ratio for a gas turbine in a combined cycle application is significantly lower than that required to achieve peak thermal efficiency using a simple-cycle gas turbine. The air leaves the compressor at a higher temperature when an increased pressure ratio occurs. Therefore, achieving the desired turbine entry temperature requires less fuel [26]. Therefore, the compressor and output power work will increase by increasing the pressure ratio then decreasing the exhaust gas temperature. This will result in lower steam production from HRSG, thereby lowering the outputs of the steam cycle. Figure 2-6 shows the variations in the compression ratio from 21.5 to 60 and the effects on the overall thermal efficiency for the simple-cycle CCGT at the D.P. with different fuels ($TET = 1600$). The overall thermal efficiency decreases for the CCGT because an increase in the compressor ratio reduces the exhaust temperature of G.T., which decreases the HRSG efficiency. The efficiency of the HRSG increases with an increasing exhaust G.T. temperature. Furthermore, there is a slight difference between LNG and MDO fuels in their overall thermal efficiency.

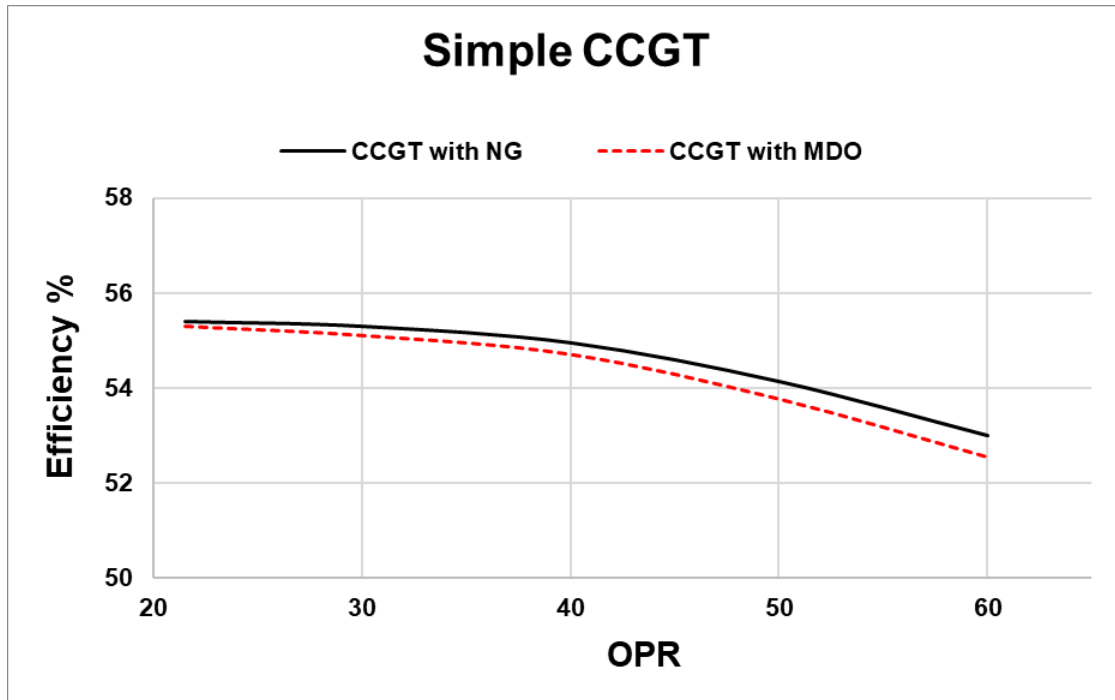


Figure 2-6 Effects of the compression ratio on the overall thermal efficiency. MDO: marine diesel oil; OPR: overall pressure ratio.

- Combined cycle (CCGT) with a reheat cycle gas turbine.

For the reheat cycle, the best location must be selected for the reheater between the HPT and LPT or the LPT and P.T. in the G.T. at the D.P., with an overall pressure ratio (OPR) that allows the optimal overall efficiency and an exhaust temperature that influences the CCGT. Figure 2-7 shows the effects of the OPR of the low-pressure compressor (LPC) on the reheat cycle gas turbine. The efficiency increases for OPR when the reheat location is between the HPT and LPT and decreases when the reheat location is between the LPT and P.T. Since this study aimed to find the optimal location for the reheater with overall efficiency at the D.P., it has been selected the reheat location between the HPT and LPT with a different OPR to obtain the optimal efficiency for the exhaust temperature that increases the efficiency of the CCGT.

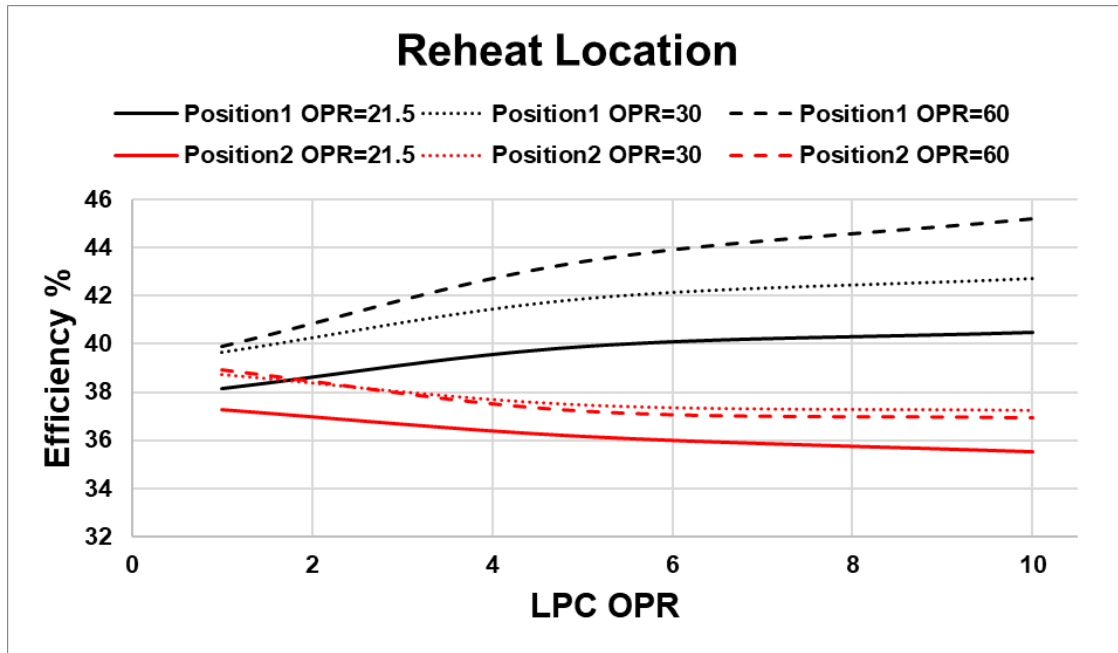


Figure 2-7 Effects of the compression ratio with different LPC in the reheat cycle.

Figure 2-8 and 2-9 shows the variations in the compression ratio from 21.5 to 90 and the effects on the overall thermal efficiency of the reheat CCGT at the D.P. The overall thermal efficiency decreases as the LPC compression ratio's effect on the CCGT increases. This is because an increase in the LPC compression ratio reduces the exhaust temperature of the G.T., which decreases the HRSG efficiency. The range of life materials is from LPC 8 to LPC 10 (as the highest inlet steam temperature currently applied is between 566 °C and 620 °C [8] of the steam turbine, with the EGT from the G.T. recording being below 600 °C.) The difference in efficiency from 40 to 90 OPR is less than one per cent; from an economic perspective, a small compression ratio is better. Thus, an OPR of 40 was selected in this study.

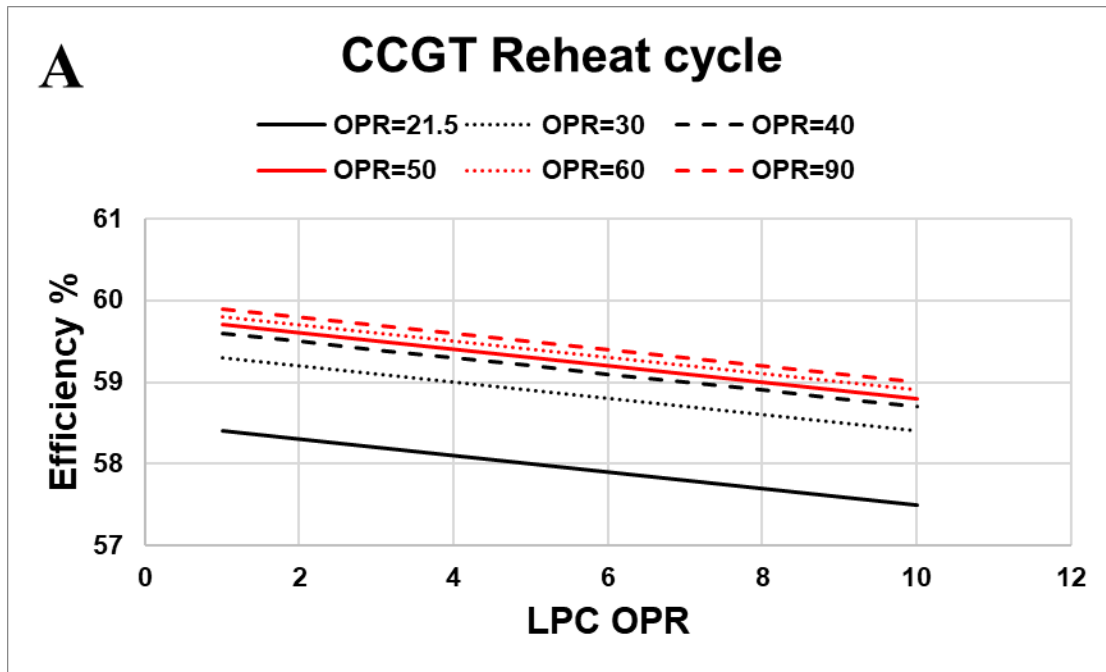


Figure 2-8 Effects of the compression ratio with changing LPCs in the reheat CCGT cycle.

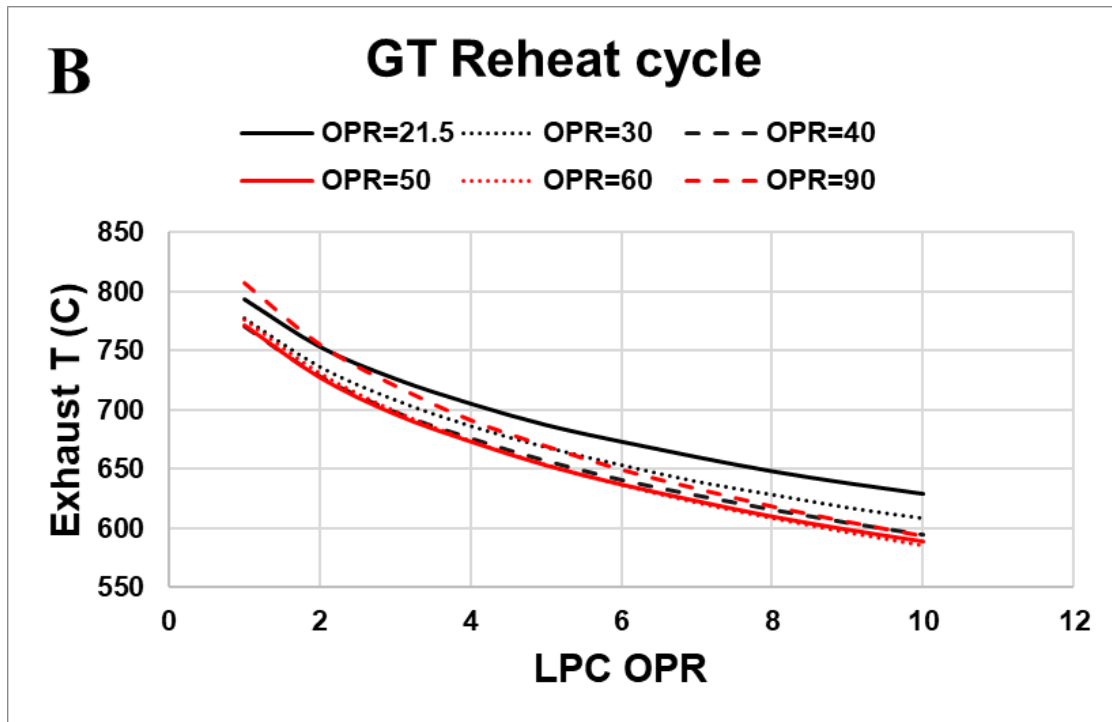


Figure 2-9 Effects of the compression ratio with changing LPCs in the reheat GT cycle.

- Combined cycle (CCGT) with an I/R gas turbine

For the I/R turbine, it has been selected the best location for the intercooler as being between the G.T. at D.P. with OPR to obtain the optimal overall efficiency and exhaust temperature, which influence the CCGT. Figures 2-10 and 2-11 shows the effects of the LPC OPR on the I/R CCGT cycle. The overall thermal efficiency decreases as the LPC compression pressure increase. This is because an increase in the LPC compression ratio reduces the exhaust temperature of the G.T., which decreases the HRSG efficiency. The material life range is from LPC 3.5 to LPC 10, where the EGT from the G.T. can be tolerated by the steam turbine. The difference in efficiency from 60 to 90 OPR is less than one per cent at the LPC 4 compression ratio; from an economic perspective, a small compression ratio is better. Thus, an OPR of 60 was selected in this study.

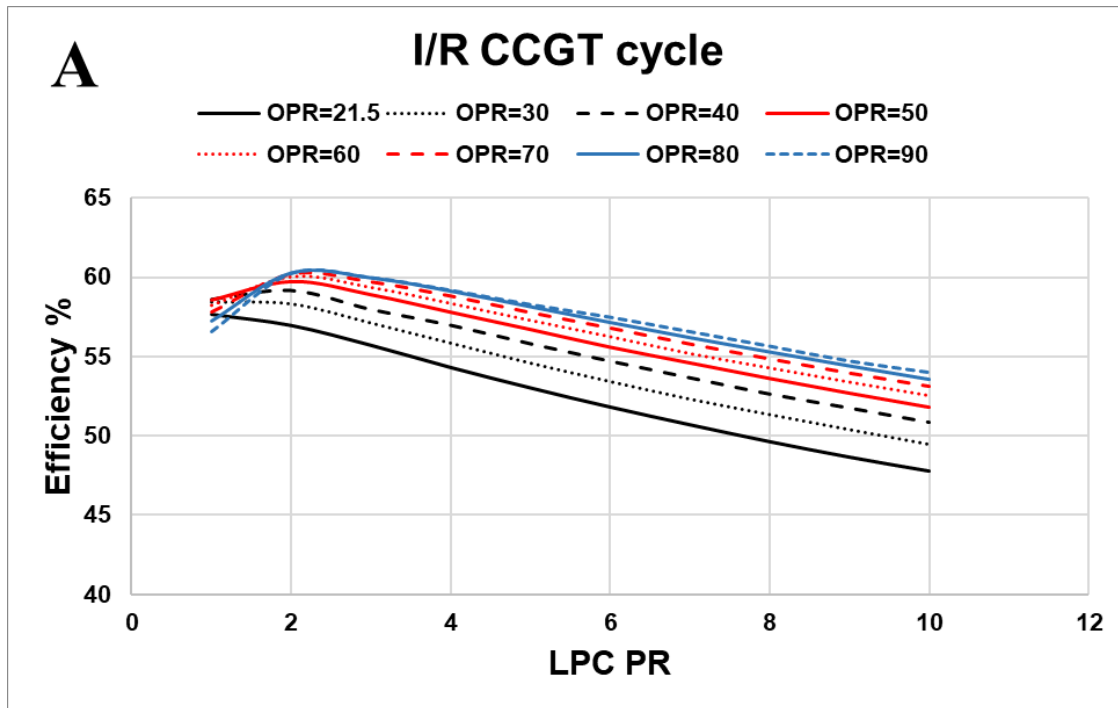


Figure 2-10 Effects of the compression ratio with changing LPC in the I/R CCGT cycle.

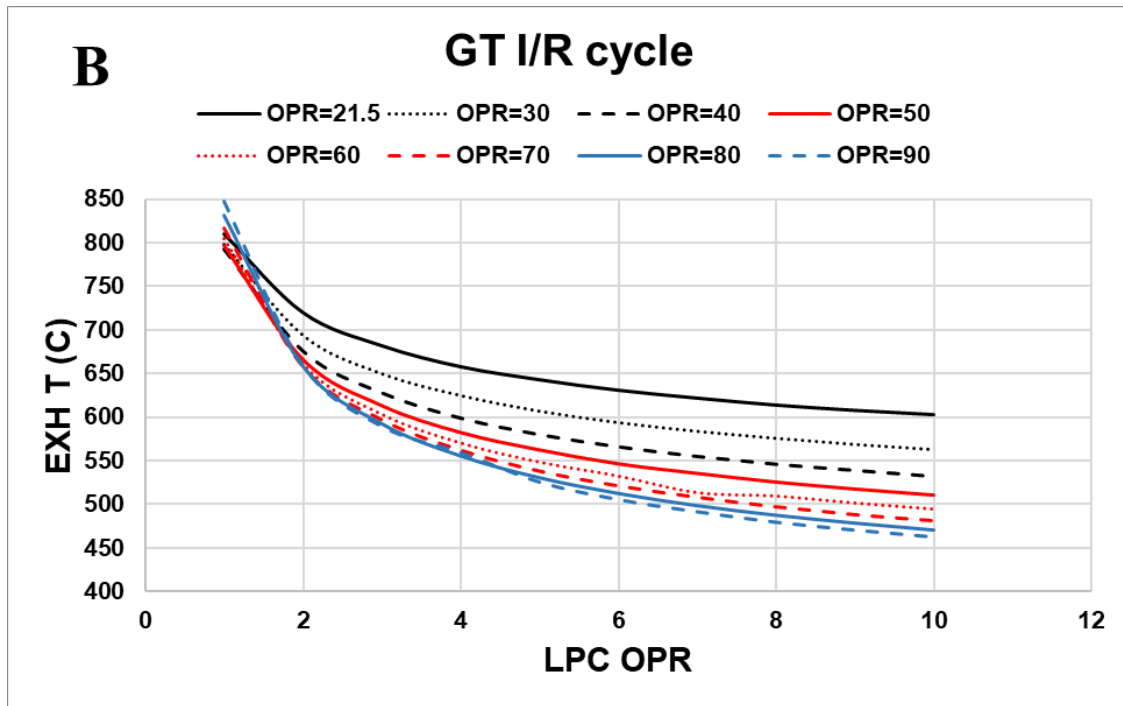


Figure 2-11 Effects of the compression ratio with changing LPC in the I/R GT cycle.

For the D.P. of simple, reheat, and I/R systems, the reheat and I/R cycles compete for efficiency. Thus, we selected those two cycles and examined them at the O.D.

2.4.2.2 Off Design point of CCGT Cycles

- **Effect of Turbine Entry Temperature on CCGT**

Figure 2-12 shows the effects of TET values ranging from 1500 to 1800 K for the CCGT at O.D. in terms of efficiency with different fuels. With increasing TET values, the CCGT efficiency increases and then decreases. The efficiency of the CCGT with TET decreased due to the constant EGT when it was above 873 K. The difference between TET = 1600 K and TET = 1800 K is less than 2% in terms of efficiency in the reheat CCGT; thus, TET = 1600 K was selected for the environmental aspect. I/R CCGT cycle was more efficient than the reheat cycle.

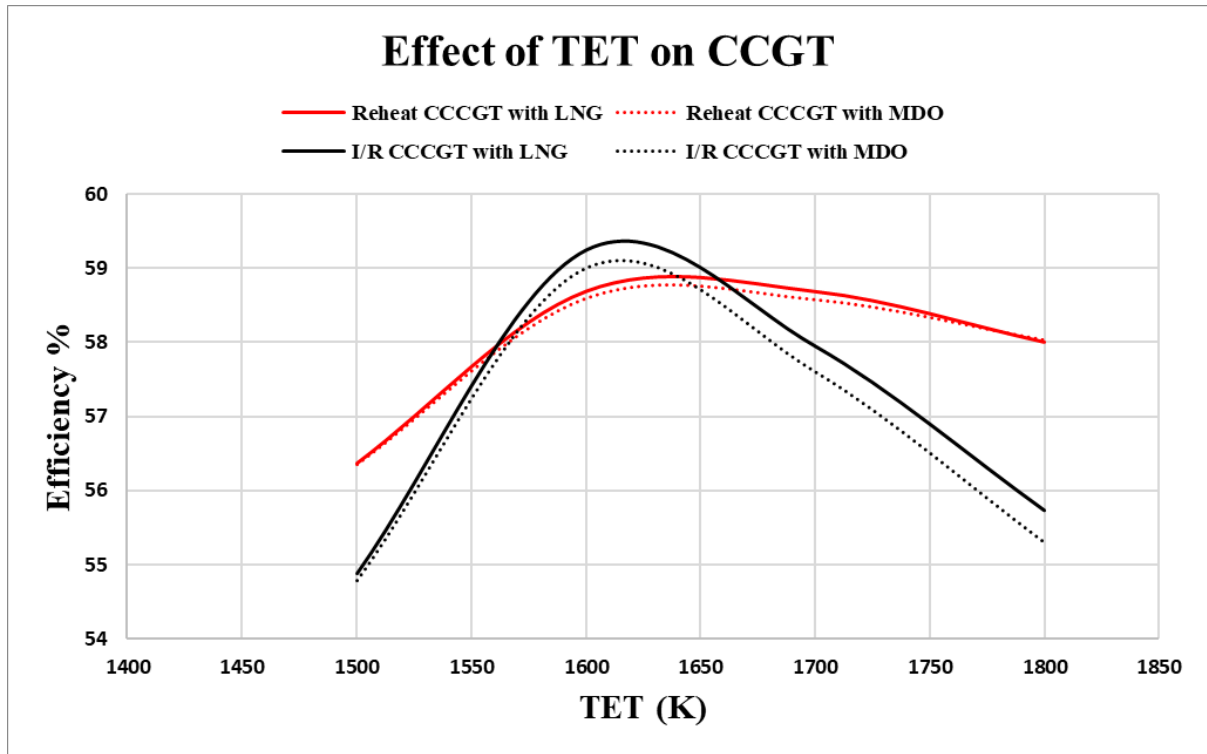


Figure 2-12 Effect of the TET on the overall thermal efficiency.

- **Effect of ambient temperature on CCGT**

The air density changes with the change in ambient temperature. An increased ambient temperature decreases the density of the inlet air, thereby reducing the mass flow through the turbine, which decreases the power output. Furthermore, for a given TET, it reduces the temperature ratio and the pressure ratio of the gas turbine cycle, thereby ultimately reducing the specific power and efficiency. Table 2-4 shows the effect of the ELNG CCGT cycle on the fuel-to-air ratio and the ambient temperature. This table results from an iterative calculation, where TET is constant and FAR and compressor inlet temperatures are varied until they match.

Table 2-4 Effects of the ELNG cycle on the fuel-to-air ratio and the inlet air temperature.

Inlet air temperature	Reduction in the inlet air temperature	FAR
288	269.5	0.03211
298	279.5	0.03223
308	289.5	0.03245
318	299.5	0.03284

Figure 2-13 shows the effects of ambient temperature values from -20 to 45 °C on the efficiency of the reheat, I/R, and ELNG CCGT systems at the O.D. With increasing ambient temperature, the efficiency of the CCGT decreases; ELNG cycles show higher efficiency than the other cycles.

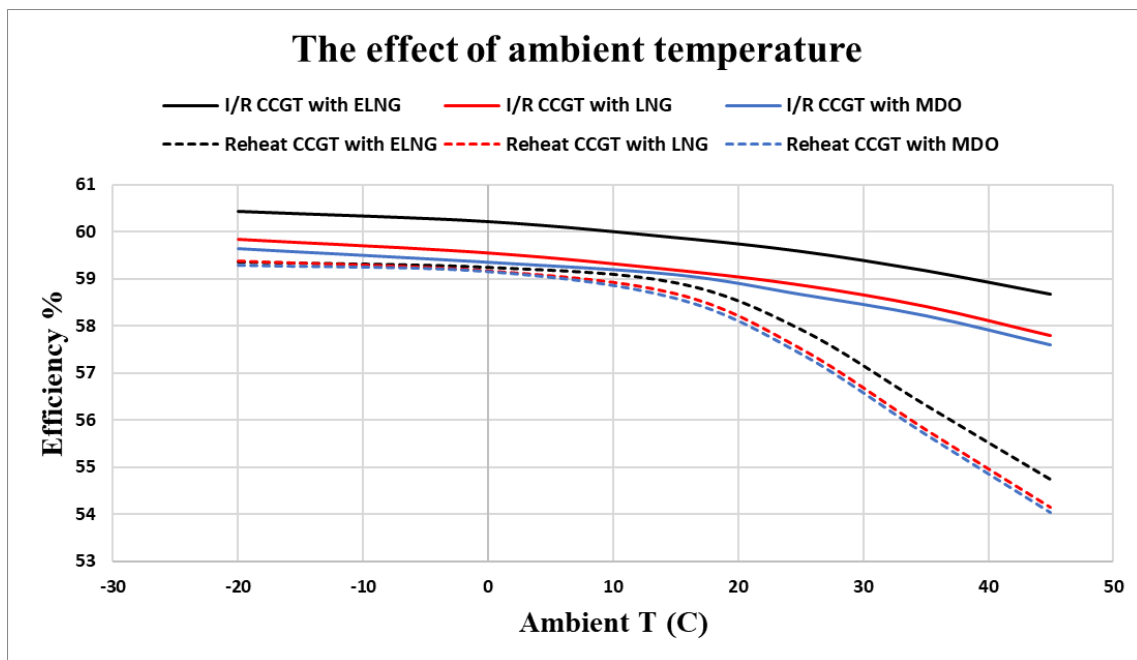


Figure 2-13 Effects of the ambient temperature on the overall thermal efficiency.

2.4.3 Environmental Results

As discussed earlier, for this study, only NO_x and CO₂ emissions were considered. It was assumed that the CCGT burns LNG and MDO, and the two-stroke diesel engine burns MDO. It was also assumed that NO_x and CO₂ were used for CCGT and two-stroke diesel engine emission factors in g/kWh regarding the engine or fuel type found in [27–33], as shown in Table 2-5.

Table 2-5 Emissions factor for the CCGT and two-stroke diesel engines.

Emission Factors (g/kWh)	NO_x (g/kWh)	CO₂ (g/kWh)
Diesel engine with MDO	9	588
CCGT with MDO	5.7	524
CCGT with LNG	3.05	522
CCGT with ELNG	1.17	412

Figure 2-14 shows the effect of TET with NO_x emission on all CCGT cycles; increasing the TET increases the NO_x emission. Notably, the I/R and simple cycle perform better than the reheat cycle owing to the higher fuel flow in the reheat cycle.

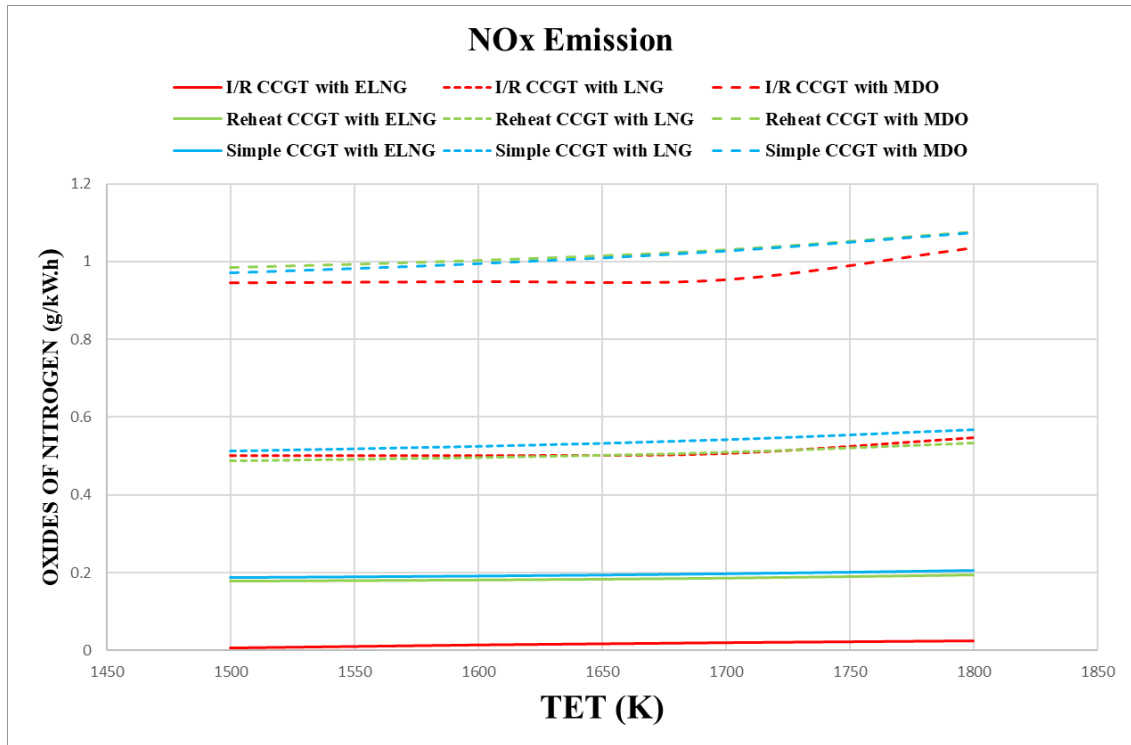


Figure 2-14 Effects of the TET on the NO_x.

Figure 2-15 shows the effect of the TET on the CO₂ emissions for all CCGT cycles; increasing the TET decreases the CO₂ emissions.

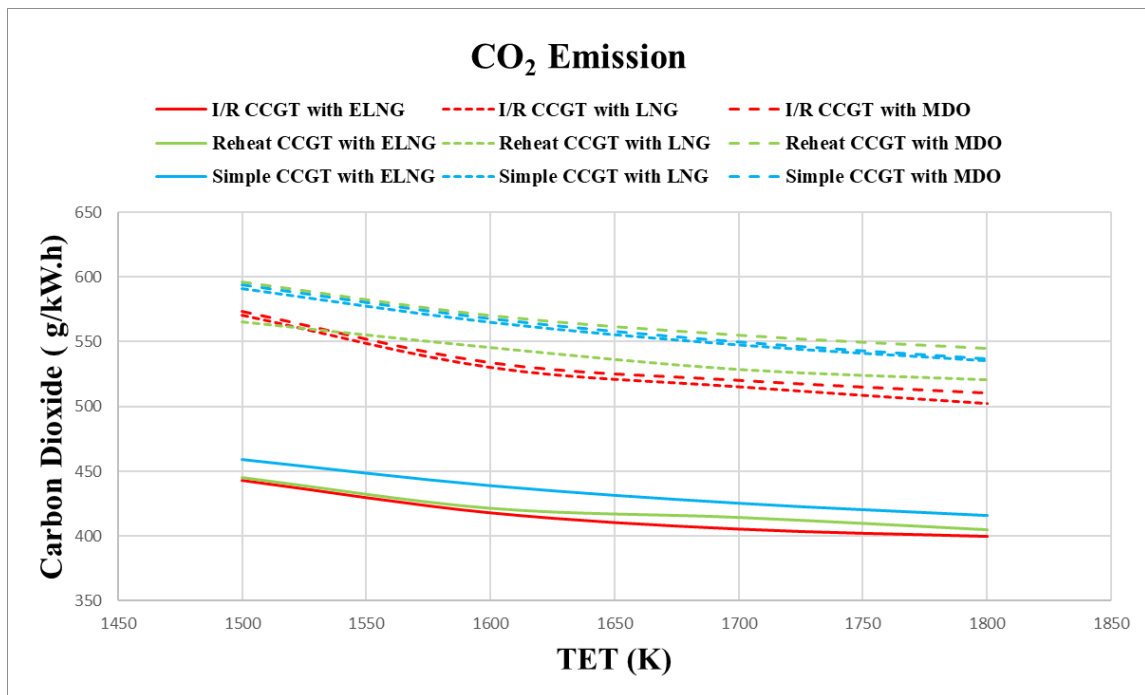


Figure 2-15 Effects of the TET on the CO₂ emissions.

The diesel engine emissions assessment from the reference [34] .Figures 2-16 and 2-17 show all of the CCGT cycles and diesel two-stroke engine emissions. The CCGT cycles are fewer than the two-stroke diesel engine cycles for both NOx and CO₂.

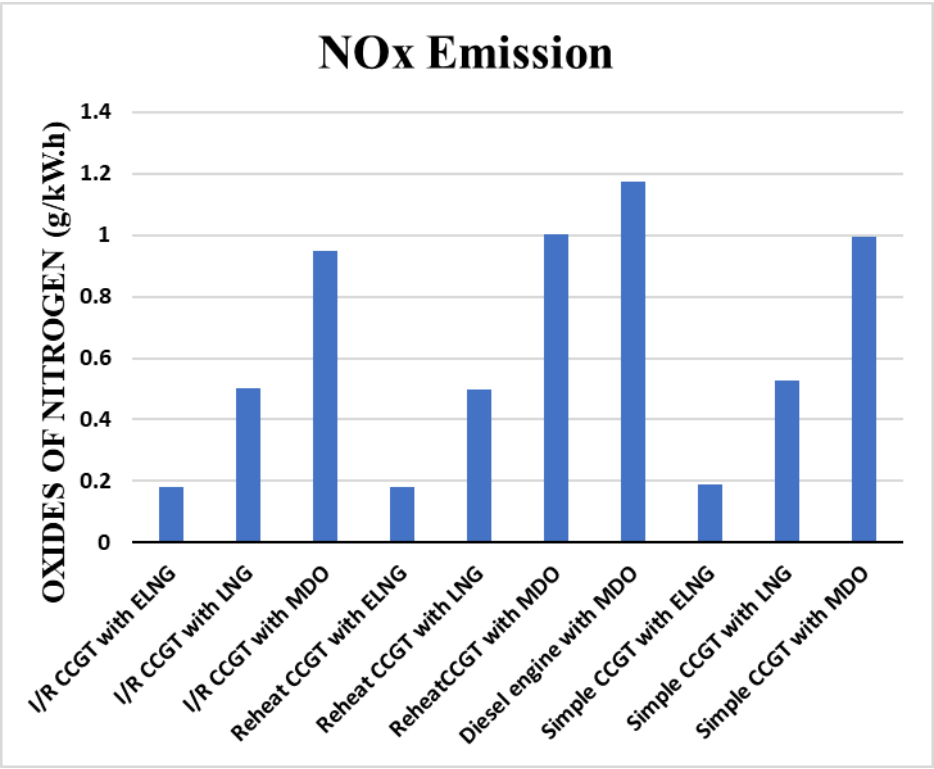


Figure 2-16 NOx emissions from all propulsion systems.

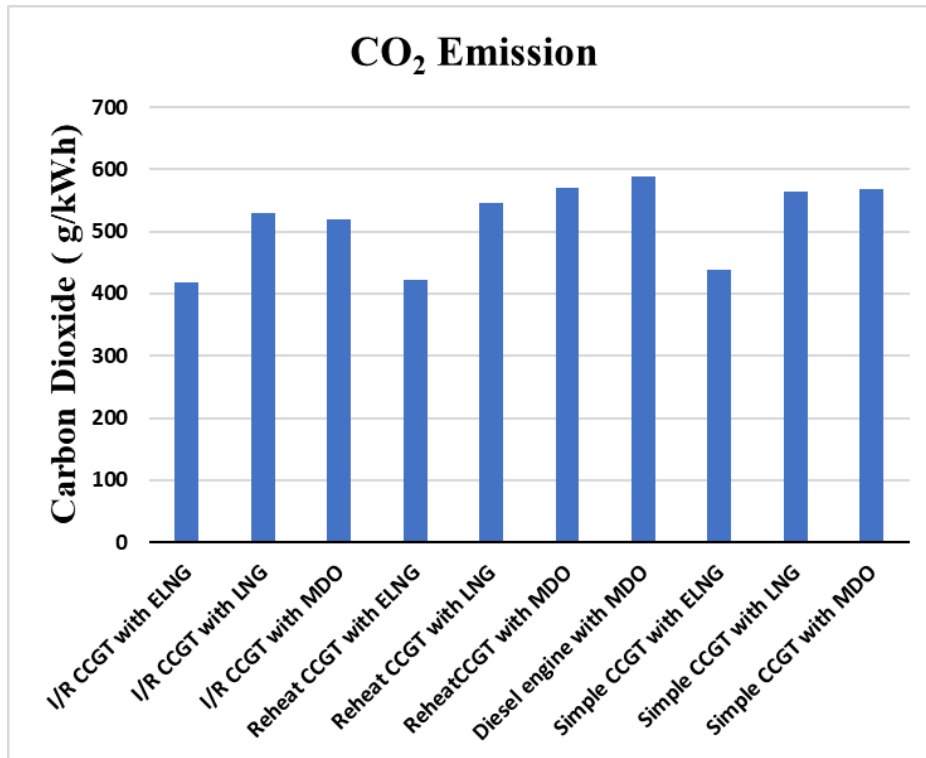


Figure 2-17 CO₂ emissions from all propulsion systems.

2.4.4 Engine Size and Weight

The data presented in Tables 2-6 and 2-7 show the power, weight, and k_{GT} values for a number of commercially available gas turbines and steam turbines. The data indicate that as the weight increases, the value for k_{GT} increases.

Table 2-6 Commercially available gas turbine weights.

Gas Turbine Model Number	Power (MW)	Weight (tonne)	k_{GT} $\frac{\text{tonne}}{W^{3/2}}$
MT7	4.6	0.45	0.04561
RB211-6762	30.387	22.680	0.13545
MT30	36	65	0.30092

Table 2-7 Commercially available steam turbine weights.

Steam Turbine Model Number	Power (MW)	Weight (tonne)	k_{GT} $\frac{\text{tonne}}{W^{3/2}}$
ELLIOT MYR (8-stage)	7.5	7.71	0.37488
ELLIOT MYR 2SQV6	11	11.5	0.3152
Siemens SST 300	20	26	0.9206

As mentioned before, the CCGT is an alternative propulsion system to a two-stroke diesel engine for a large container ship, which has higher efficiency and uses better quality fuel but has a more complex configuration. However, because of the abovementioned emission regulations, it is reasonable to presume that cleaner fuel for diesel engines will be implemented, and this condition could favour the choice of CCGT solution for large container ships, as they also consider fuel costs [7,35]. The main data considered for the propulsion of the CSCL GLOBE 19,000 twenty-foot equivalent unit container ship [34] are summarised in Table 2-8.

Table 2-8 Main data considered for the CSCL Globe 19,000 twenty-foot equivalent unit container ship.

Length Overall	399.67 m
Breadth	58.73 m
Depth	30.5 m
Draught	16 m
Engine Power	56 MW
Engine model	11k98ME7
Gross Tonnage	187541t
Net Tonnage	86434 t
Speed	23 knots

A nine-cylinder, two-stroke diesel engine with a slow speed (MAN B&W K98ME7.1-TII) and developing power of 56.070 Mw at 97 rpm is the prime mover in the CSCL Globe container ship, without reduction gear [36]. Table 2-9 clearly shows that the two-stroke diesel engine is much larger and heavier than the CCGT. A further comparison in terms of the weight of the overall propulsion system is presented.

Table 2-9 Data for the considered prime movers.

Engine Data	K98ME7.1-TII	Gas Turbine	Steam Turbine	HRSG
Length (m)	27.36	4.57	12	6.33
Height (m)	19.35	2.41	5	11.7
Breadth (m)	11.36	2.21	4	6.16
Weight (t)	2500	40.8	26	197.7
Power (mw)	56	45	20	

The overall propulsion plant weights are presented in Table 2-10. The reduction gear, HRSG, condenser, and pump weights were selected from a previous study [9]. The second combustor weight was calculated by comparing the first combustor density with the second one from the mass flow rate (assuming constant speed), as the density is proportional to the volume. The heat exchanger and intercooler weights were taken from the HRSG weight and mass flow and scaled with the mass flow in the heat exchanger and intercooler to obtain their weights. From Table 2-10, it is clear that the CCGT has a greater number of components (gas turbine, steam turbine, HRSG, condenser, and reduction gear). The CCGT propulsion system, with all components of the cycles, is approximately 1687 tonnes lighter than the original diesel engine propulsion system. Regarding the size of the CCGT and how it will fit in a container ship, [2,9] showed clearly that the CCGT is smaller than a two-stroke diesel engine in a large container ship.

The reduction in size in the engine room and reduced machinery weights for the CCGT solution allow an increased load capacity for the ship.

Table 2-10 Comparison of weights.

Component	Diesel Engine	Simple CCGT	Reheat CCGT	I/R CCGT	ELNG CCGT
Diesel engine (t)	2500	—	—	—	—
Gas turbine (t)	—	40.8	40.8	40.8	40.8
Steam turbine (t)	—	26	26	26	26
HRSG (t)	—	197.7	197.7	197.7	197.7
Condenser (t)	—	62.7	62.7	62.7	62.7
Pump (t)	—	13.8	13.8	13.8	13.8
Reduction gear (t)	—	278	278	278	278
Second combustor (t)	—	—	5.9	5.9	5.9
Intercooler (t)	—	—	—	67.38	67.38
Second Pump (t)	—	—	—	—	8.4
Heat exchanger (t)	—	—	—	—	111.67
Total weight (t)	2500	619	624.9	692.28	812.39

2.5 Conclusions

This study aimed to present CCGT systems as a good alternative to two-stroke diesel engine propulsion systems in large container ships because of their performance, emissions, size, and weight. In terms of performance, in the reheat cycle, the efficiency increased with OPR when the reheat location was between HPT and LPT and decreased when the reheat location was between LPT and

P.T. In the reheat–intercooler cycle, the overall thermal efficiency decreased as the LPC compression pressure increased. This was because an increase in the LPC compression ratio reduced the exhaust temperature of the G.T., which decreased the HRSG efficiency. With an increasing TET, the CCGT efficiency increased and then decreased. Its efficiency decreased when the TET was constant because the EGT was above 873 K. The difference between TET = 1600 K and TET = 1800 K is less than 2% in terms of efficiency. With an increasing ambient temperature, the efficiency of CCGT decreased. The CCGT was more efficient in burning LNG than MDO. ELNG cycles showed better results in terms of efficiency. For the NO_x emission of all CCGT cycles, an increasing TET increased the NO_x emission. Furthermore, increasing the TET decreased the CO₂ emissions, which made the TET more efficient. Thus, the NO_x and CO₂ emissions in CCGT cycles were lower than those in the two-stroke diesel engine. The CCGT propulsion system, with all of the components of all cycles, was approximately 1687 tonnes lighter than the original diesel engine propulsion system in the large container ship. The best alternative propulsion systems for the large container ship propulsion system with comprehensive consideration of the thermal and environmental performance was the I/R ELNG CCGT system, while in terms of weight this was the simple CCGT system.

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3 Techno-Environmental Mission Evaluation of Combined Cycle Gas Turbines for Large Container Ship Propulsion

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3.1 Abstract

The stringent regulations set by the International Maritime Organization on pollutant emissions combined with the rise in fuel prices have stimulated research on cleaner fuels and new propulsion systems. This study describes a new method for evaluating alternative technologies and cleaner fuels that can be utilised in the marine sector to replace heavy fuel oil and diesel engines, and thus improve their performance while lowering carbon dioxide and nitrogen oxide emissions. The proposed techno-environmental technique allows consistent evaluation of simple intercooler/reheat gas and steam combined cycles fuelled by marine diesel fuel and liquefied natural gas, instead of a two-stroke diesel engine fuelled by marine diesel fuel, as a propulsion system of a large container ship. The implementation of the enhanced combined gas and steam cycles, and combined gas and steam cycles, fuelled by liquefied natural gas, increases the engine's efficiency by 11% as compared with that of two-stroke diesel engines that run on marine diesel oil, while decreasing carbon dioxide and nitrogen oxide emissions by 44.7% and 76.3%, respectively. In addition, the advantages of using a gas and steam combined cycle to burn LNG over the gas and steam combined cycle for burning marine diesel oil are demonstrated.

Keywords: techno-environmental evaluation; gas turbine and steam turbine combined cycle; large container ship; propulsion system; liquefied natural gas; marine diesel oil; nitrogen oxide; carbon dioxide

3.2 Introduction

The global economy strongly depends on international shipping and approximately 90% of international cargo is carried by sea [1]. Most cargo is transported worldwide on ships because it is the most effective and reliable method, which necessitates a reduction in the operating costs. One of the main factors considered in the international shipping industry is the fuel cost [2]; however, the situation has recently changed due to the strict regulations on pollutant emissions and the possibility of emission taxation imposed by the International Maritime Organization (IMO). On the 10th of October 2008, the IMO introduced new regulations to reduce emissions from ships; these regulations have been subsequently amended and extended [3]. Marine Pollution (MARPOL) Annex VI has established strict limits on nitrogen oxide and sulphur oxide emissions. Most merchant ships are powered by diesel engines due to their ability to run efficiently on low-cost heavy fuel oil [4]. However, diesel engines fuelled with heavy fuel oil produce relatively high emissions of particulate matter, carbon dioxide, nitrogen oxides, and sulphur oxides, which are subject to strict regulations [5]. Some of these emissions are caused by the engines or fuels that are used. There are two approaches for reducing these harmful emissions: using a cleaner fuel or implementing an engine with higher efficiency. Among these solutions, the combination of a gas and steam turbine, called a gas turbine combined cycle (CCGT), offers a cycle efficiency of up to 60%, which exceeds that of a low-speed diesel engine [6]. The thermal efficiency of the CCGT can be further enhanced by improving the simple gas cycle (upper cycle) or the simple steam cycle (lower cycle). Some components, such as an intercooler, reheater, or these together, can be integrated into a simple gas turbine cycle to enhance the upper cycle's thermal efficiency. To improve the steam turbine cycle's efficiency, a double or triple pressure heat recovery steam generator (HRSG) should be employed, and the lower cycle needs to be reheated [7]. The banned or unutilised low-cost heavy fuel oil helps eliminate a significant drawback in the CCGT. Therefore, this paper aims to implement CCGT cycles as a viable alternative to the conventional propulsion system through a techno-

environmental method and evaluate all propulsion systems of large container ships.

Thus far, only a limited number of studies have implemented the techno-environmental assessments of advanced CCGTs for large container vessel. Therefore, this paper contributes:

- A technical assessment of CCGT cycles, a simple gas steam turbine combined cycle, and an intercooler/reheat gas steam combined cycle with a single heat recovery steam generator fuelled by liquefied natural gas (LNG) and marine diesel oil (MDO) for a large container ship with different international missions. In addition, the paper implements enhanced liquified natural gas cycles with cryogenic properties to enhance CCGT efficiency and evaluates a two-stroke diesel engine fuelled by MDO for the same system.
- A comprehensive environmental evaluation with different international missions to assess the emissions of nitrogen oxide and carbon dioxide from the presented CCGT cycles fuelled by MDO and LNG and a two-stroke diesel engine fuelled by MDO as propulsion systems.

The rest of this paper is organised as follows. The second part defines the methodology utilised in this paper. The third part describes the obtained results and establishes their significance, and the fourth section summarises the conclusions

3.3 Materials and Methods

The main aim of this paper was to establish a comprehensive method for evaluating the techno-environmental benefits of installing a CCGT instead of a two-stroke diesel engine on a large container ship fuelled by LNG and MDO. The following assumptions were made in this study:

- The voyages of large container ships are expected to follow straight and direct routes unaffected by weather conditions, physical geographic entities.

- A large container ship is always assumed to maintain an operating speed of 23 knots.

To investigate an alternative solution for ship propulsion systems, a techno-environmental model framework has been developed. This framework (Figure 3-1) is modular and contains several core models that allow the detailed performance simulation of propulsion systems. The core models are further linked with the Poseidon ship simulator to assess the propulsion system of a large container ship from the technical and environmental viewpoints. The modules used in this study are described in detail in [2,8,9].

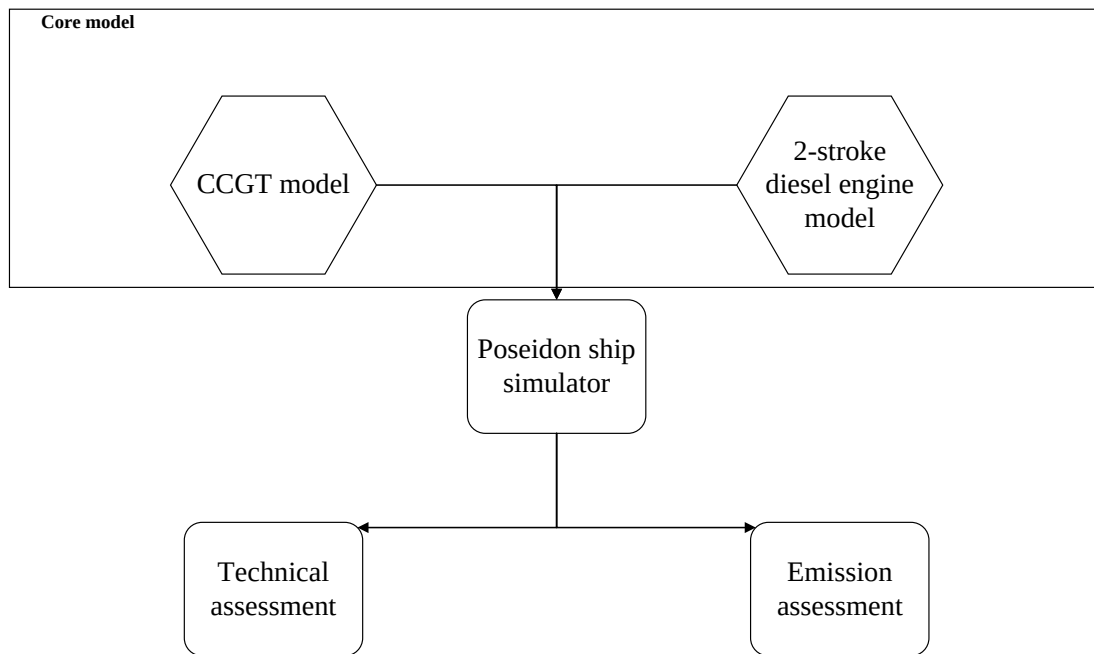


Figure 3-1 Flow diagram of the methodology used in this study. CCGT: gas and steam combined cycle.

3.3.1 Core Models

3.3.1.1 CCGT Model

CCGT performance was simulated using the in-house gas turbine performance evaluation software Turbomatch [10] and MATLAB. A CCGT model was established to assess the engine performance. A single HRSG steam turbine model was established on the optimum steam cycle properties defined in previous studies [11,12]. In the long period, the CCGT cycles benefit from the

unique cryogenic qualities of the liquified natural gas applied in this study. It is assumed that LNG is stored as a saturated liquid at atmospheric pressure. The results of this model are described in detail in [13]. The best CCGT propulsion systems were used in this study with comprehensive consideration of the performance and emissions level [13]. Table 3-1 lists various CCGT engines with fuels that are utilised in each cycle. The enhanced LNG cycle includes advanced NO_x abatement technology procured from land-based gas turbines. It also incorporates an air precooling heat exchanger benefitting from the cryogenic properties of the fuel. This enables increased efficiency. Figure 3-2 shows the heat balance in the air precooling heat exchanger between the LNG and the inlet air in the ELNG cycle.

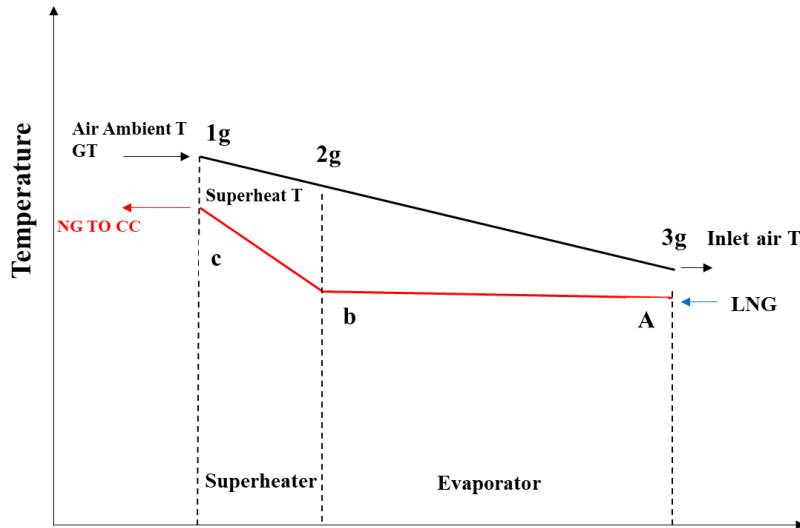


Figure 3-2 Heat balance in heat exchanger between the inlet air and LNG. 1g: inlet air mass flow temperature to heat exchanger; 2g: outlet air mass flow temperature from superheater stagnation to evaporator; 3g: outlet air mass flow temperature from heat exchanger to gas turbine; A: inlet LNG mass flow temperature to heat exchanger; b: outlet LNG mass flow temperature evaporator stagnation to superheater; c: outlet NG mass flow temperature from heat exchanger to combustion chamber gas turbine.

Table 3-1 CCGT engines with different fuels.

Engine	Fuel
Simple CCGT	LNG/MDO
Intercooler/reheater CCGT	LNG/MDO
ELNG intercooler/reheater CCGT	LNG

3.3.1.2 Two-Stroke Diesel Engine Model

A 2-stroke diesel engine model was constructed using the MATLAB software installed on a reference ship. Engine data were obtained from Hyundai–MAN B&W [14]. The most critical objective of this model was to design and investigate the performance (thermal efficiency) of a two-stroke diesel engine during different journeys fuelled by MDO, which was employed as the propulsion system of a large container ship. The diesel engine model was used as the baseline scenario and verified against the ship's fuel consumption.

3.3.2 Poseidon Ship Simulator

The Poseidon ship simulator is described in detail in [2,8,9]. It is divided into five subroutines that balance the power available from propulsion machinery and the power required by the aerodynamic and hydrodynamic resistance of the vessel. The total resistance calculation allows to estimate the required power from the propulsion system to maintain the established velocity of the vessel. The resistance model enables determination of the propulsive power of a ship using the method developed by Holtrop and Mennen [15]. The aerodynamic resistance (wind resistance of the upper body) of the ship was simulated by employing the approach developed in [16]. Note that the Poseidon ship simulator did not take into consideration the hydrodynamic resistance impacts of shallow water and cavitation of propeller. This case study simulated container ships in an open sea with different prime movers, such as the two-stroke diesel engine and various CCGT engines on different journeys (Figures 3-3 and 3-4) [17]. The first journey

was from the port of Shanghai, China, to Los Angeles, USA, with a distance of 5708 nautical miles (Nm). The second journey was from Shanghai, China, to Hamburg, Germany, with a distance of 10,778 Nm. The journey climate included three seasons (winter, summer, and midseason); the winter and summer seasons had 82.5 day, the midseason had 165 day, and the day in each season contained 24 hour. The climate weather for each journey was selected based on the midpoint city weather between the two ports predicted using publicly available data [18]. Midway Island is the midpoint between Los Angeles (USA) and Shanghai (China) on the first journey. The second journey between Shanghai (China) and Hamburg (Germany) included four midpoint cities: Vietnam, Sri Lanka, Crete Island (Greece), and Ushant Island (France) for a more accurate weather forecast.

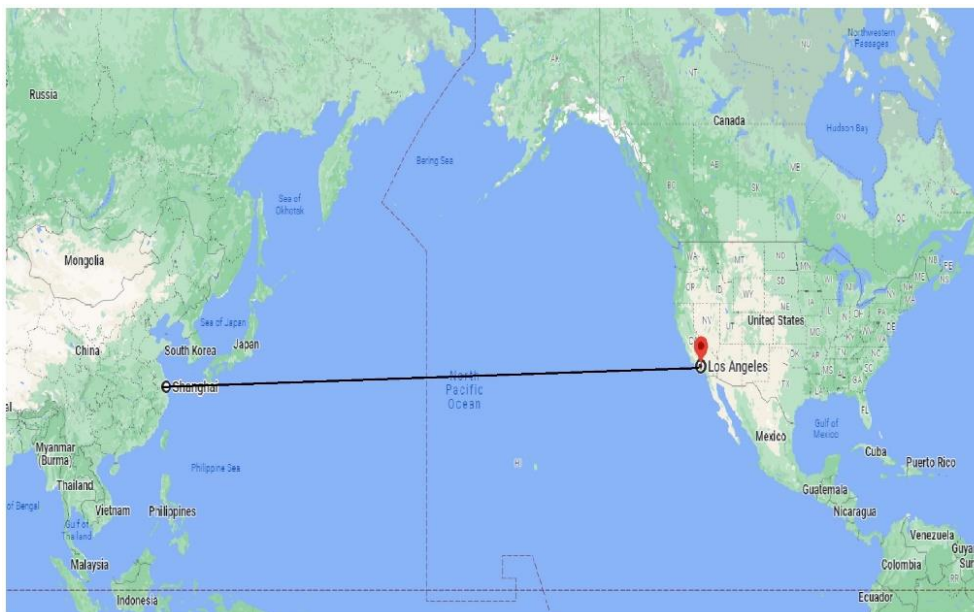


Figure 3-3 The first journey route Shanghai, China, to Los Angeles, USA.

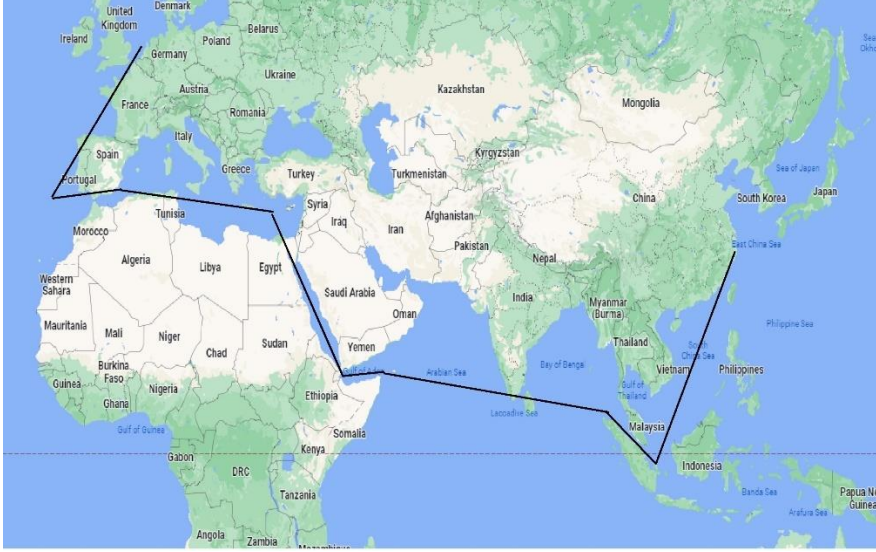


Figure 3-4 The second journey from Shanghai, China, to Hamburg, Germany.

3.3.3 Environmental Model

Two different factors can be used to assess emissions levels: engine power and fuel consumption [19]. In this study, emissions were determined from the fuel consumption as follows:

$$E = \sum (FC_{j,m} * EF_{I,j,m}) \quad (3-1)$$

where E is the total emission (kg/h), FC is the consumption fuel (tonnes/h), EF is the emissions factors (kg/tonnes), I is the emission types, j is the engine types (gas turbine, steam turbine, or 2-stroke diesel engine), and m is the types of fuel (LNG or MDO).

To calculate the NO_x emission scale factor, the following equation was used [20]:

$$EF_{i,k} = (IF_{i,k} \times 10^{-6}) \left(\frac{P \cdot V}{R \cdot T} \times \frac{MW_k}{P_p} \right) \quad (3-2)$$

where $EF_{i,k}$ is the emissions factor (g/kWh), i is the engine types, k is the emission types, $IF_{i,k}$ is the concentration of gaseous species (ppm), P is the pressure (N/m²), V is the engine exhaust flow rate (m³/h), R is the ideal constant gas (J/mol·K), T is the exhaust gas temperature (K), MW is the molecular weight (g/mol), and P_p is the engine power (kW).

To calculate the CO₂ emission per kilogram of fuel, the following equation was applied [21]:

$$\text{kg CO}_2 = \left(\frac{44}{12} \times C_m \right) \quad (3-3)$$

where C is the carbon content in the fuel, and m is the fuel type.

3.4 Results

3.4.1 Assumptions, Simulation, and Validation

In this study we assumed calm sea and air, and thus, the wind resistance only dealt with the drag caused by the speed. A large container ship (CSCL Globe Container Ship) with the main parameters based on published data (Table 3-2) was used in this study [22]. The baseline vessel was powered by a two-stroke diesel engine (MAN B&W K98ME7.1-TII marine two-stroke diesel engine) with a speed of 23 knots.

Table 3-2 Main ship parameters.

Gross tonnage (t)	187,541
Net tonnage (t)	86,434
Displacement	280,920.3
Overall length (m)	399.67
Breadth (m)	58.73
Depth (m)	30.5
Draught (m)	16
Speed (knots)	23
Cargo capacity (TEU)	19,000

The two-stroke diesel engine model was inspired by a MAN B&W K98ME7.1-TII marine two-stroke diesel engine. Its main parameters derived from published data are listed in Table 3-3 [14].

Table 3-3 Two-stroke diesel engine parameters.

Power (MW)	56.070
Specific fuel consumption (g/kwh)	174
Engine speed (rpm)	97
Compression ratio	21
Number of cylinders	9
Cylinder bore (mm)	500
Piston stroke (mm)	2660

Table 3-4 shows the deviations between the simulation data and the actual values of the marine two-stroke diesel engine.

Table 3-4 Simulation data and actual parameters of the two -stroke diesel engine model.

	Simulation	Actual	Deviation
Power (MW)	56.06	56.07	-0.007
Efficiency (%)	48.45	48.4	0.0353
Specific fuel consumption (g/kW·h)	174.07	174	0.0494

3.4.2 Route Analysis

The performance of the large container ships on different voyages between the selected ports was assessed over a period of one year (Table 3-5). Maximum ship utilisation was assumed. Therefore, the estimated time required to maintain,

unload, and load the ship was one day per ship's journey. The ship was assumed to operate 330 d per year [2]. The climate of the journey included three seasons (winter, summer, and midseason); the winter and summer seasons had 82.5 day; the midseason had 165 day. The numbers of journeys per year and per each season were estimated, assuming continuous operation of the large container ship on a given route, and are listed in Table 3-5.

Table 3-5 Numbers of journeys per year and per each season.

Journey	Trip Duration	Annual Trips	Annual Winter Trips	Annual Summer Trips	Annual Trips in the Midseason
Route 1: Shanghai to Los Angeles	13 d 05 h	20.56	5.14	5.14	10.28
Route 2 Shanghai to Hamburg	24 d 23 h	12.11	3.029	3.029	6.05

The ambient temperature during each season determined for routes 1 and 2 are shown in Figures 3-5 and 3-6, respectively.

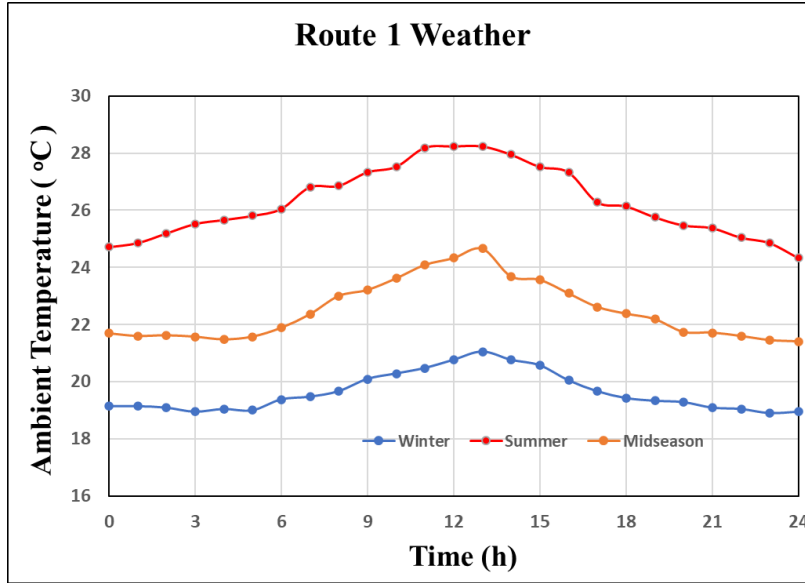


Figure 3-5 Ambient temperature of all seasons for the first journey route Shanghai, China, to Los Angeles, USA.

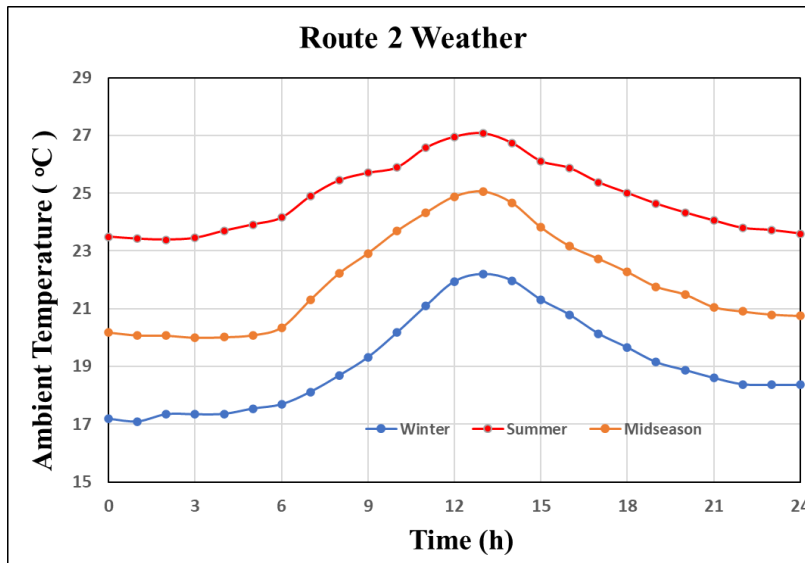


Figure 3-6 Ambient temperature of all seasons for the second journey from Shanghai, China, to Hamburg, Germany.

3.4.3 Technical Evaluation

Figures 3-7 and 3-8 display the thermal efficiencies of the propulsion systems of the large container ships plotted for all cycles against the journey times of routes 1 and 2 for all seasons. They show that the efficiency of the I/R ELNG CCGT cycle exceeds those of the CCGT cycles fuelled by LNG and MDO in all seasons

by approximately 1% and 2%, respectively, due to the lower inlet temperature, which increased the air density and thus the turbine output. The higher calorific value of natural gas as compared with that of diesel oil, reduces the amount of fuel needed to produce the same heat output; therefore, the fuel efficiency of natural gas is higher than that of MDO in all CCGT cycles. The efficiency of LNG in all CCGT cycles was approximately 1% higher than that of MDO fuel. The maximum efficiency of the CCGT cycles was approximately 11% higher than the two-stroke diesel engine, and the minimum efficiency value was approximately 4% higher than two-stroke diesel engine due to the low specific fuel consumption of CCGT. The winter season demonstrated the highest efficiency because the power output depended on the air mass flow. The hot air was less dense than cold air, which reduced the power output. In addition, warm air requires more energy to compress than cold air, which increases the work performed by the compressor and internal energy losses. The ambient conditions of routes 1 and 2 were different, and route 1 was more energy efficient than route 2.

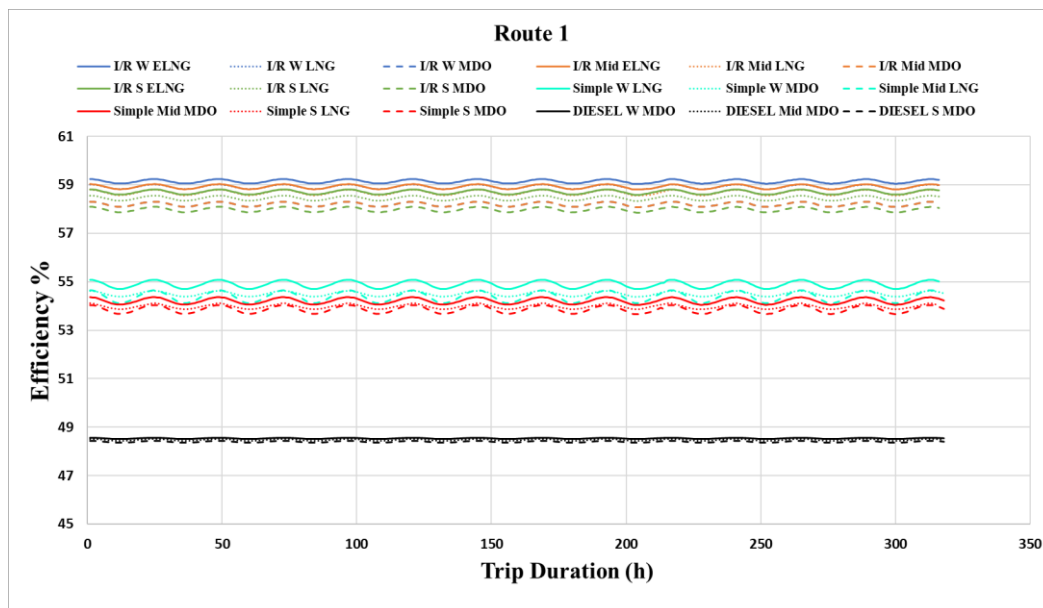


Figure 3-7 Performance of various propulsion systems of the large container ship travelling between Shanghai and Los Angeles. I/R: intercooler/reheater CCGT; S: simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer season; ELNG: enhanced liquified natural gas; MDO: marine diesel fuel; LNG: liquified natural gas.

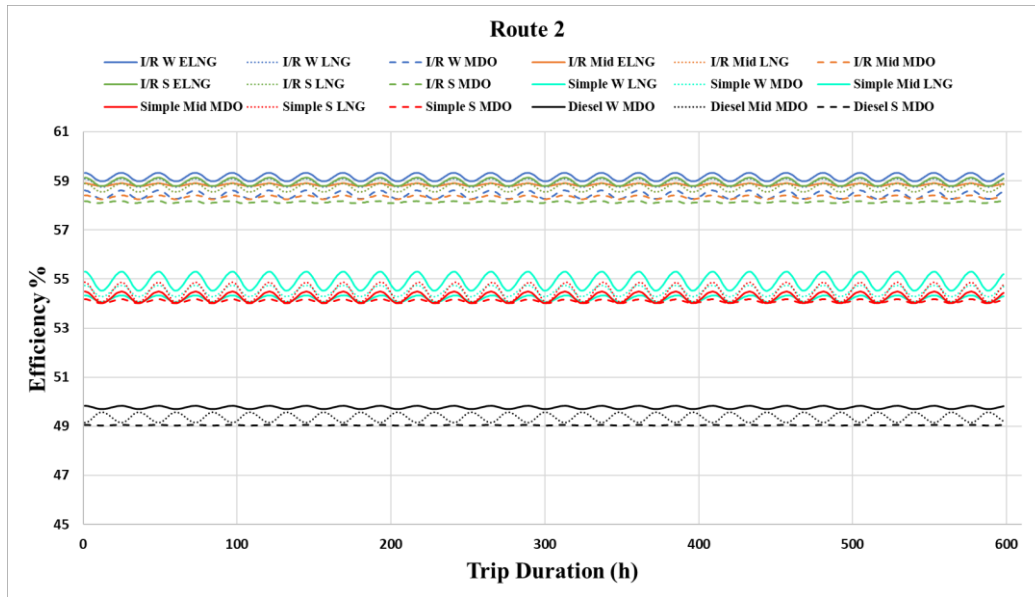


Figure 3-8 Performance of various propulsion systems of the large container ship travelling between Shanghai and Hamburg. I/R: intercooler/reheater CCGT; S: simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer season; ELNG: enhanced liquified natural gas; MDO: marine diesel fuel; LNG: liquified natural gas.

3.4.4 Environmental Results

As mentioned earlier, only CO₂ and NO_x emissions were considered in this study. The CCGT was assumed to burn MDO and LNG while the two-stroke diesel engine was fuelled by MDO. The NO_x emissions from the two-stroke diesel engine were predicted based on the publicly available MDO data and were in the range 5.7–14.8 g/kW·h [19,23–28]. The ELNG CCGT cycle allows the use of a dry low-NO_x combustor [29] that produces very low NO_x emissions, as demonstrated by the natural gas-fuelled land-based gas turbines [30]. The NO_x concentrations of the ELNG, LNG, and MDO fuels utilised in this study were taken from [30-32]. The molecular weights of LNG and MDO were determined from previously published data [31,33]. The CO₂ emissions depend on the fuel consumption and carbon concentration in the fuel. The CO₂ fuel content was obtained from [34]. Table 3-6 show the theoretical parameters of each fuel.

Table 3.6. Theoretical parameters of different propulsion systems and fuels.

Fuel	ELNG	LNG	MDO
NOx concentration in the gas turbine (ppm)	17.4	25	156
Molecular weight (g/mol)	16.04	16.04	198–202

Figures 3-9 - 3-12 show the environmental CO₂ and NO_x emissions generated during the ship's operation for one year on the three-season routes. It was found that CCGT emitted less NO_x and CO₂ than the two-stroke diesel engine because of the lower CCGT fuel consumption caused by its higher efficiency. The NO_x emissions from routes 1 and 2 produced during different seasons (winter, summer, and midseason) are displayed in Figures 3-9 and 3-10, respectively. They show the NO_x levels emitted per hour during a single trip in different seasons by the different propulsion systems of the large container ships. The results indicate that the CCGT NO_x emissions are significantly lower than those of the diesel engine because CCGT operated at lower and more homogeneous temperatures. Indeed, CCGT utilises a steady combustion process that allows better NO_x emission control as compared with that of a two-stroke diesel engine, where the peak temperatures generated during the discontinuous process trigger the formation of thermal NO_x species. As a result, the difference between the NO_x emissions of the I/R ELNG CCGT cycles and two-stroke diesel engine fuelled by MDO was approximately 76.3%. In addition, the NO_x emissions of the I/R and simple CCGT cycles fuelled by LNG were lower than the MDO-fuelled two-stroke diesel engine by 73.6% and 31.5%, respectively. The NO_x emissions of the I/R and simple CCGT cycles fuelled by MDO were lower than the MDO-fuelled two-stroke diesel engine by 68.4% and 10.5%, respectively. Moreover, the NO_x emissions of the I/R ELNG CCGT cycles were lower than those of the LNG-fuelled I/R and simple CCGT cycles by 3.3% and 57.6%, respectively. Finally, the NO_x emissions of the I/R ELNG CCGT cycles were lower than those of the MDO-fuelled I/R and simple CCGT cycles by 8.4% and 67.3%, respectively.

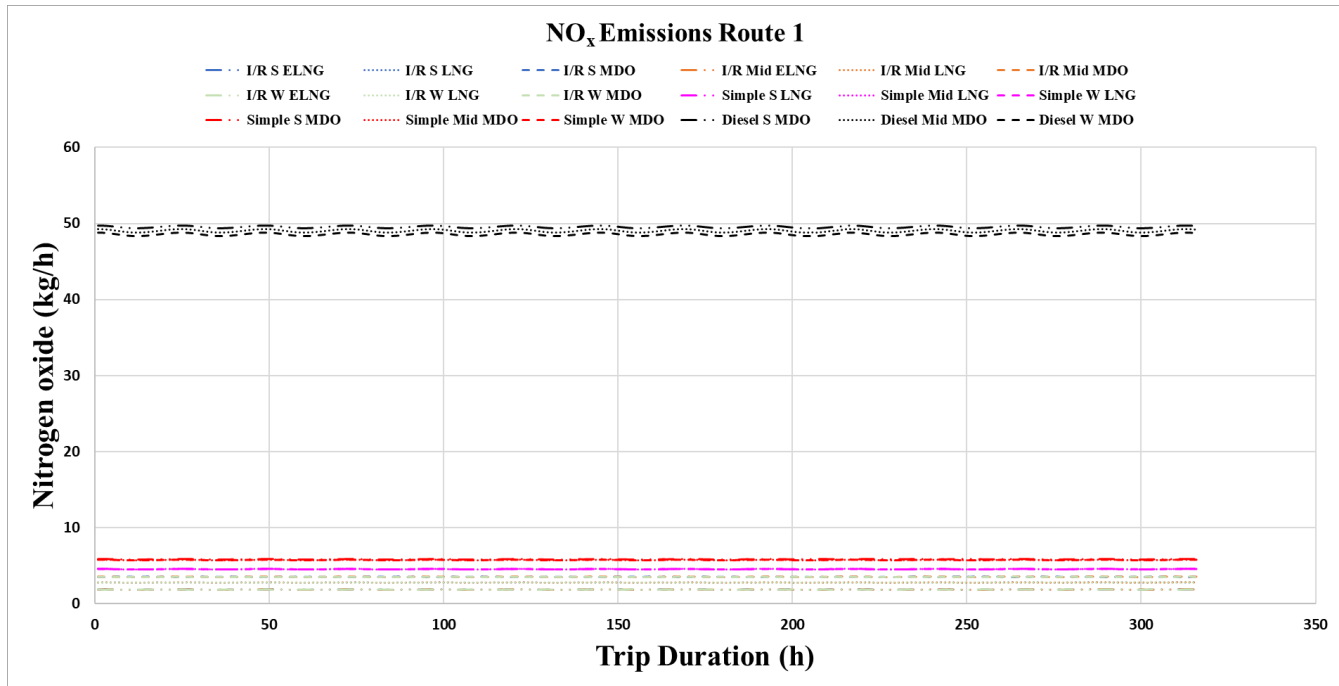


Figure 3-9 NO_x emissions of various propulsion systems of the large container ship travelling between Shanghai and Los Angeles. I/R: intercooler/reheater CCGT; R: reheater CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

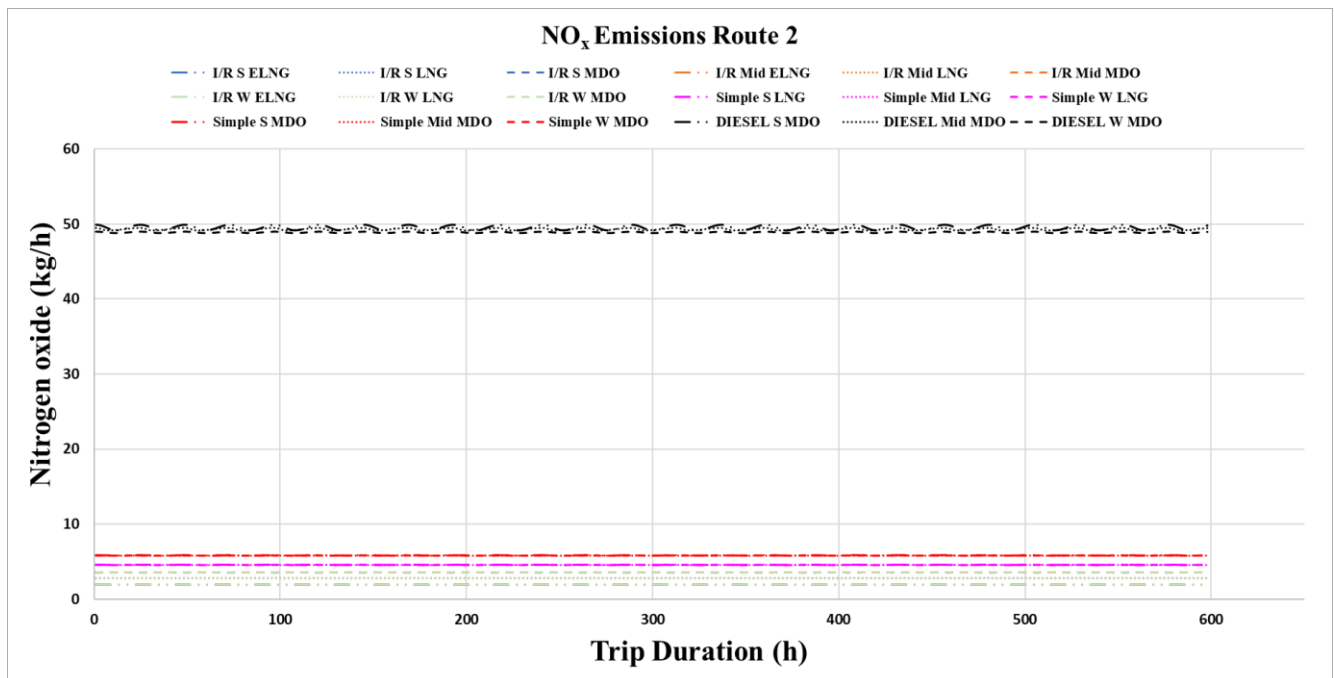


Figure 3-10 NO_x emissions of various propulsion systems of the large container ship travelling between Shanghai and Hamburg. I/R: intercooler/reheater CCGT; R: reheater

CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

Figures 3-11 and 3-12 display the amounts of CO₂ emitted per hour during a single trip with different seasons determined for various propulsion systems of the large container ships. Owing to the higher efficiency of CCGT, the difference between the CO₂ emissions of the I/R ELNG CCGT cycles and two-stroke diesel engine fuelled with MDO was approximately 44.7%. In addition, the CO₂ emissions of the I/R and simple CCGT cycles fuelled by LNG were lower than the MDO-fuelled two-stroke diesel engine by 43.7% and 35.41%, respectively. The CO₂ emissions of the I/R ELNG CCGT cycles were lower than the LNG-fuelled I/R and simple CCGT cycles by approximately 2%, and 14.5%, respectively. Furthermore, the CO₂ emissions of the MDO-fuelled I/R and simple CCGT cycles were lower than the two-stroke diesel engine by 25% and 12.5%, respectively. Finally, the CO₂ emissions of the I/R ELNG CCGT cycles were lower than the MDO-fuelled I/R and simple CCGT cycles by 26.3% and 36.9%, respectively.

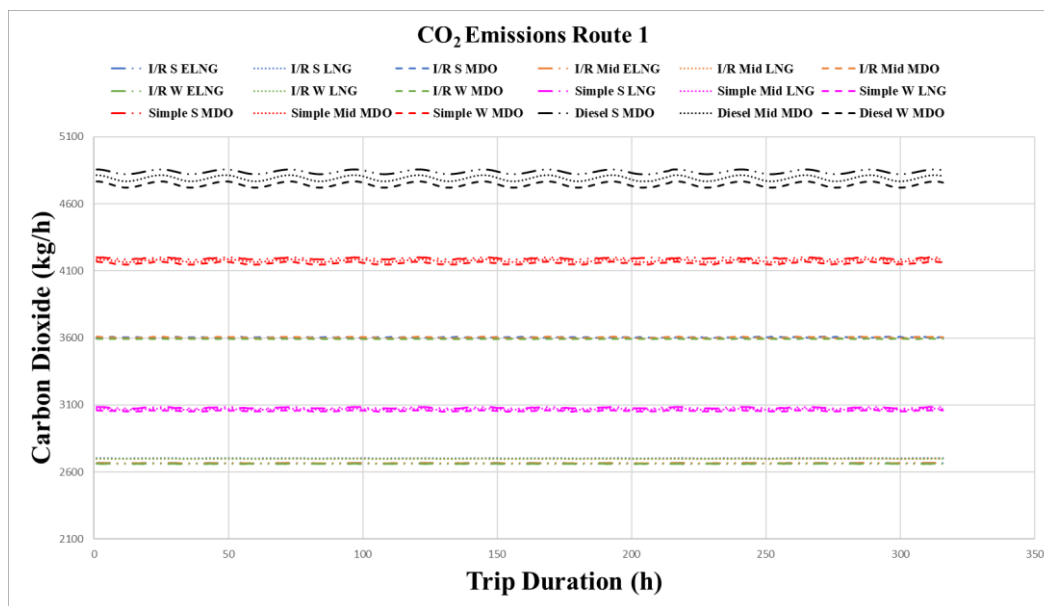


Figure 3-11 CO₂ emissions of various propulsion systems of the large container ship travelling between Shanghai and Los Angeles. I/R: intercooler/reheater CCGT; R: reheater CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

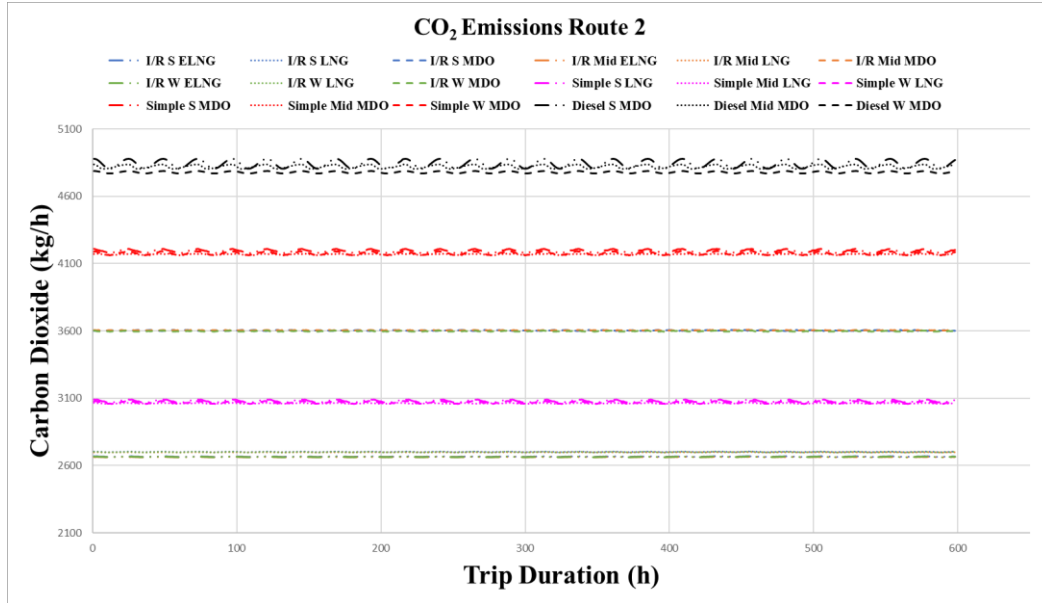


Figure 3-12 CO₂ emissions of various propulsion systems of the large container ship travelling between Shanghai and Hamburg. I/R: intercooler/reheater CCGT; R: reheater CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

3.5 Conclusions

A techno-environmental assessment methodology was utilised to evaluate the performance and CO₂ and NO_x emissions of CCGT cycles, which could potentially replace the two-stroke diesel engine as a propulsion system of large container ships. The simple and intercooler/reheater ELNG and CCGT systems were fuelled by LNG and MDO, while the two-stroke diesel engine propulsion systems were fuelled by MDO. The findings of this study are very promising from the techno-environmental perspective and the utilised methodology can be potentially used for engine selection. The obtained results can be summarised as follows:

- Two international routes were investigated. The ambient conditions of the specific environmental regions in which the ships were operating were used as the simulation environments. For these specific simulated routes, the overall performance, and emissions of the CCGT cycles were very promising.
- Fuelling CCGT cycles with MDO was undesirable.

- Although the simulated journeys were assumed to be direct routes, the stability of the ships was not considered. The obtained results indicated that the implementation of the ELNG-fuelled and LNG-fuelled CCGT cycles on large container ships could increase the fuel efficiency by 11% as compared with that of the MDO-fuelled two-stroke diesel engine, while the observed reductions in the CO₂ and NO_x emission levels amounted to 44.7% and 76.3%, respectively.

Finally, the evaluation procedure used in this work confirmed that the techno-environmental assessment employed in the marine sector was a highly effective tool for comparing and choosing between multiple technologies.

Author Contributions: A.M.T.A.: Conceptualisation, data curation, formal analysis, funding acquisition, investigation, methodology, project administration and resources. A.B.: software assistance. S.S.: supervision. P.P.: supervision. All authors have read and agreed to the published version of the manuscript.

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4 Techno–Economic and Risk Evaluation of Combined Cycle Propulsion Systems in Large Container Ships

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4.1 Abstract

Owing to the stringent regulations on pollutant emissions that are imposed by the International Maritime Organization and increasing fuel prices, there has been significant research on developing cleaner fuels and novel propulsion systems. This study presents a techno-economical and risk assessment method for evaluating alternative propulsion technologies and cleaner fuels as substitutes for heavy fuel oil and two-stroke diesel engines in marine transportation. This analysis was carried out for two different journeys. Accordingly, it has been evaluated the economic benefits of using an enhanced intercooler/reheat combined gas and steam cycle or simple and intercooler/reheat combined gas and steam cycles that were fueled by marine diesel oil or liquified natural gas instead of a two-stroke diesel engine that was fueled by MDO as the propulsion system in a large container ship, considering different shipping routes. The results highlighted the advantages of implementing the simple, intercooler/reheat, and enhanced combined gas and steam cycles as propulsion systems. A sensitivity analysis was performed to investigate the effects of the fuel cost, capital cost, and hull fouling resistance on the economic analysis. For the routes that were considered herein, compared to a two-stroke diesel engine that was fueled by MDO, the simple, intercool-er/reheat, and enhanced gas and steam combined cycles that were fueled by LNG increased the net present value by 78.3%, 78.5%, and 76.4%, respectively, and reduced the payback period by 38.8%, 38.9%, and 35%, respectively. Furthermore, the fuel and capital costs had a significant influence on the overall economic profit.

Keywords: techno-economic evaluation; combined gas and steam cycle; large container ship; propulsion system; liquefied natural gas; net present value; IMO; marine diesel oil; net present value; payback period; internal rate of return.

4.2 Introduction

International cargo transportation primarily occurs via shipping [1]. To improve the profitability and efficiency of cargo transportation, shipping costs must be reduced. Moreover, the sustainability of the transport business is related to profitability and demand, which are influenced by reduced operating costs [2]. Currently, fuel cost is the biggest contributor to the overall operating costs of the shipping industry [3]. However, owing to increasing concerns over greenhouse gas emissions, this trend is expected to change in the future. The International Maritime Organization (IMO) has enforced strict regulations on pollutant emissions and examined the viability of introducing an emissions tax [4]. On the 10 October 2008, the IMO introduced regulations for reducing emissions from ships, which have since been amended and extended [5]. The Marine Pollution (MARPOL) Annex VI sets strict limits on nitrogen oxides (NO_x), sulphur oxides, and carbon dioxide (CO₂) emissions. Diesel engines drive the majority of merchant ships [6] owing to their predominance and ability to efficiently burn inexpensive heavy fuel oil. However, diesel engines produce significant amounts of particulate matter, CO₂, NO_x, and sulphur oxides, which are considered harmful emissions and subjected to strict regulations [7,8]. Some emitted emissions from heavy fuel oil and others from the propulsion system that is utilized. There are two possible approaches for reducing emissions using high efficiency propulsion systems or cleaner fuels [9]. One such solution is employing a combined gas and steam cycle propulsion system. Combined gas and steam cycles have been evaluated as propulsion systems in vessels used for various purposes and applications. However, few ships have been built with combined cycle propulsion systems. The authors from a previous study have summarized the existing research on the use of combined cycle propulsion systems in large ships [10]. The authors have also performed a techno–environmental comparison between advanced gas and steam combined cycle (CCGT) systems and a two-stroke diesel engine in large container ships [11]. Techno-economic and risk analysis is a necessary method that consists of a framework of mathematical models to simulate the performance of a single or a set of technologies. The

framework allows increased visibility of risks while allowing the user to compare and rank competing schemes on a formal and consistent basis to enable the efficient allocation of resources. This method can be used for a variety of vessels type simulations with electrical or mechanical propulsion systems and for different voyage scenarios.

Few studies have attempted to identify the techno-economic aspects and assess the risks of employing advanced combined gas and steam cycles in large container ships. This study makes the following contributions:

- A comprehensive economic evaluation is performed using the net present value (NPV), payback period (PP), and the internal rate of return (IRR) to evaluate the capital, operating, and maintenance costs of combined gas and steam cycle propulsion systems that are fueled by marine diesel oil (MDO) or liquified natural gas (LNG) in a large container ship. A two-stroke diesel engine that is fueled by MDO is also evaluated for comparison.
- A sensitivity analysis and risk evaluation are conducted to examine the effects of the fuel cost, capital cost, and hull fouling resistance on the results of the economic evaluation.

The rest of this paper is organized as follows: Section 2 describes the methodology that was used in this study; the results are presented and discussed in Section 3; and finally, the main conclusions of this study are presented in Section 4.

4.3 Methodology

This study aims to establish a method to assess and evaluate the economic benefits of implementing a CCGT that is fueled by LNG or MDO instead of a two-stroke diesel engine that is fueled by MDO as the propulsion system in a large container ship. This study builds on the comprehensive technical and environmental analysis that was conducted in our previous study [10,11].

To establish a viable and profitable solution for ship propulsion systems, we establish an economic model framework (Stage 3). The methodology (see Figure 4-1) of developing this framework is modular and contains several core models

that enable performance simulations of ship propulsion systems. The methodology of this paper is divided into three-stage. Stage 1 represents the technical performance of all propulsion systems. Stage 2 represents the missions of the large container ship with different propulsion systems from technical and environmental aspects with two international journals. Stage 1 and 2 are then linked to Stage 3, which represents the economic assessment aspects of all the propulsion systems for a large container ship taking into account the ambient conditions and fuel consumption of each journey. Stage 1 is subsequently linked with the Poseidon ship simulator to assess various propulsion systems in a large container ship from a technical and environmental perspective (Stage 2). The modules that were used in this study have been defined in detail in the literature [12–14].

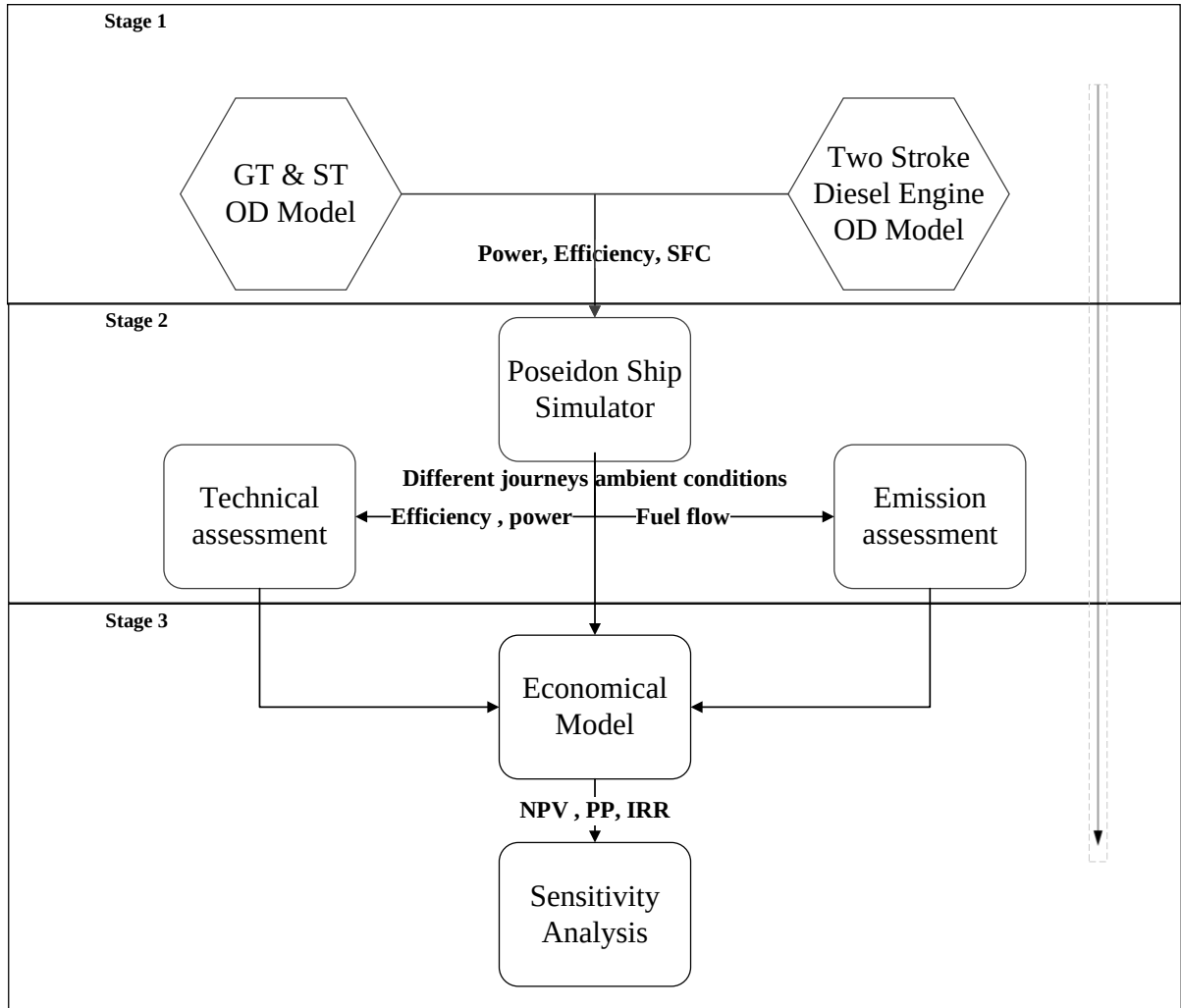


Figure 4-1 The framework of the methodology. GT: Gas turbine; ST: Steam turbine; OD: Off-design; NPV: Net present value; PP: Pay-back period; IRR: Internal rate of return.

4.3.1 Stage 1

4.3.1.1 Gas and Steam Turbine and Two-Stroke Diesel Engine Models

The gas turbine was simulated using Turbomatch—an in-house software that was developed by Cranfield University [15]. A model of a steam turbine with a single heat recovery system that was based on the optimum steam turbine cycle characteristics was designed using MATLAB in previous study [10]. The unique cryogenic properties of LNG were also implemented in the combined cycle. The results of this steam turbine model are described in detail in [10]. A total of three CCGT propulsion systems with the good thermal and environmental performance

[10] were considered in this study. Table 4-1 lists the CCGT engines and their corresponding fuels.

Table 4-1 CCGT engines and their corresponding fuels.

Engine	Fuel
Simple CCGT	LNG/MDO
Intercooler/reheater CCGT	LNG/MDO
ELNG intercooler/reheater CCGT	LNG

A two-stroke diesel engine model that was installed on a reference ship was constructed using MATLAB; this model has been described in previous study [11]. The model was designed to investigate the performance (thermal efficiency) of a two-stroke diesel engine that was fueled by MDO acting as the propulsion system in a large container ship, considering different voyages. The results of the models were obtained from [11].

4.3.2 Stage Two Models

The Poseidon ship simulator is described in detail in [12–14]. A simplified method was introduced to calculate the increase in ship resistance due to hull fouling or rough-ness. The hull fouling model, which is described in [14,16] simulates the impact of hull roughness degradation over the lifetime of the ship.

A technical assessment of the propulsion systems of large container ships was performed in the previous study by the author. The results of this model are described in detail in [11]. Environmental models of NO_x and CO₂ emissions from the CCGT and two-stroke diesel engine propulsion systems were also developed, as described in [11].

4.3.3 Stage Three Models

4.3.3.1 Economic Model

This study aims to evaluate the economic benefits of advanced CCGTs compared to a conventional propulsion system. Accordingly, the NPV, IRR, and PP are used

to evaluate the performance of various propulsion systems. The approach that was used herein is as follows:

- The capital cost includes the installation cost of the propulsion systems.
- The maintenance and operating costs consider the fuel cost of the voyage.
- A sensitivity analysis and risk evaluation were performed to examine the effects of the fuel cost, capital cost, and hull fouling resistance on the economic analysis.

An essential consideration in capital budgeting is the NPV, which is used to estimate future cash flows [17]; a high NPV attracts investment and promises good returns. There are two possible outcomes while selecting the NPV it is either positive and exceeds the project capital cost or runs at a deficit. In this case, the first outcome is desirable, whereas the second should be avoided [18]. Therefore, one of the primary considerations of establishing this project is to reduce investor risk by using NPV tools that indicate a good expected return on investment [19].

The NPV can be calculated as follows [20]:

$$NPV = \sum_{t=0}^n \frac{x_t}{(1+R)^t} \quad (4-1)$$

where t and n represent the time period, R is the average periodic investment or discount rate, and x_t is the future net cash flow.

The IRR is another important consideration in capital budgeting. The criterion for selecting the IRR is simple the project should be accepted if the IRR exceeds the discount rate. Conversely, the discount rate should be less than the IRR. The IRR is calculated as follows [18]:

$$\sum_{t=0}^n \frac{c_t}{(1+IRR)^t} = 0 \quad (4-2)$$

where t and n represent the time period, c_t is the future cash flow, and IRR is the internal rate of return.

Another important consideration in capital budgeting when the project is required to repay the initial investment is the PP , which is crucial for investors. However,

it should be noted that the PP is only a metric and should not be used to evaluate the financial competitiveness of a project. It only serves to advise investors on the ability of a project to repay its initial investment. The PP can be calculated as follows:

$$PP = \frac{I_o}{C_o} \quad (4-3)$$

where I_o is the initial investment and C_o is the net annual cash inflow.

4.4 Results and Discussion

4.4.1 Economic Analysis

Based on the scale and size of the technology and the information that is available in the literature, it has been estimated the capital and operating and maintenance (O&M) costs. The hull appraisal cost can be estimated in several ways, with prices of approximately 2.5–3 (€/kg) [21]. The available literature for CCGTs suggests a cost of 525–1200 (\$/kW), O&M costs of 0.0331 (\$/kWh) or 4% of the capital cost per year, and an installation cost that is equal to 30% of the capital cost [22–30]. The literature suggests costs of 20,000 (\$/MW), 80,000 (\$/MW), 150,000 (\$/MW), and USD1.5 million, for the intercooler, combustor, heat exchanger, and gearbox, respectively [26,31]. Considering the two-stroke diesel engine, the literature suggests a cost of 460 (\$/kW), O&M costs of 1.4–7.6 (\$/MWh) or 2.5% of the capital cost per year, and an installation cost that is equal to 30% of the capital cost [32,33]. The costs of the CCGT components and two-stroke diesel engine are shown in Table 4-2. The CCGT cost was assumed to be the average between 525–1200 (\$/kW). The reduction in the engine room size and the decreased engine weight with the CCGT would increase the cargo loading capacity of the ship. The weight reductions that were derived from using a CCGT propulsion system instead of a diesel engine propulsion system were described in detail in previous study [10].

Table 4-2 Costs of CCGT components and two-stroke diesel engine.

Component	Diesel Engine	Simple CCGT	I/R CCGT	I/R ELNG CCGT
Diesel engine (\$/kW)	460	—	—	—
CCGT (\$/kW)	—	862.5	862.5	862.5
Gear box (million \$)	—	1.5	1.5	1.5
Second combustor (\$/MW)	—	—	80,000	80,000
Intercooler (\$/MW)	—	—	20,000	20,000
Heat exchanger (\$/MW)	—	—	—	150,000
Total capital cost (million \$)	25.760	49.8	55.4	63.8
Installation cost	30%	30%	30%	30%
O&M costs	2.5%	4%	4%	4%
Ship cost (million \$)	176.9	176.9	176.9	176.9

To determine the fuel cost, a fuel price analysis was carried out using the economic module. The LNG prices in the European Union (EU) and Henry Hub markets [34] are shown in Figure 4-2. To simplify the model, the LNG price was assumed to be the average of the EU and Henry Hub market prices. As shown in Figure 4-3, the global price of MDO [34,35] in (\$/tonne) was considered in this study.

To estimate the cash flow and inflow of all the propulsion systems as part of an economic assessment. The inflow estimation is based on the total number of containers on a large container ship—the CSCL Globe Container Ship. It can carry 19,000 TEU of cargo per trip. The international shipping cost per container can vary significantly, based on several considerations. As a rough estimate, the shipping cost of a 20-foot container varies between USD1390.01 and USD6950.04 [36]. There were two routes that were considered herein: Route 1 was from Shanghai, China, to Los Angeles, USA, a distance of 5708 nautical miles; and Route 2 was from Shanghai, China, to Hamburg, Germany, a distance

of 10,778 nautical miles . In this study, we assumed average prices of USD4170 for Route 1 and USD6403.9 for Route 2; the difference in prices can be attributed to the difference in the length of each route. Route 2 is 50% longer than Route 1. The estimated income was calculated based on the number of trips per year over 30 years, as the life cycle of a ship is 25–30 years [37]. The cash outflows were estimated based on O&M and fuel costs.

A sensitivity analysis and risk evaluation were performed to examine the effect of the fuel cost, capital cost, and hull fouling resistance on the economic analysis. Accordingly, higher (+50%) and lower (–20%) capital and fuel costs were considered in the analysis. In addition, the hull roughness was assumed to be 4% higher.

The propulsion systems that were investigated herein are:

- An intercooler/reheater (I/R) ELNG CCGT with a single heat recovery steam generator (HRSG).
- A simple CCGT and an I/R CCGT with an HRSG that was fueled by LNG or MDO.
- A two-stroke diesel engine that was fueled by MDO.

A total of four scenarios were evaluated herein to obtain a comprehensive understanding of the economic profits and risks that are associated with each propulsion system considering different international routes. The first scenario acts as the baseline scenario, with no changes in the fuel cost, capital cost, and hull fouling resistance. The second scenario investigates the effect of changes in the fuel cost. The third scenario investigates the effect of changes in the capital cost. The fourth scenario investigates the effect of a change in the hull fouling resistance.

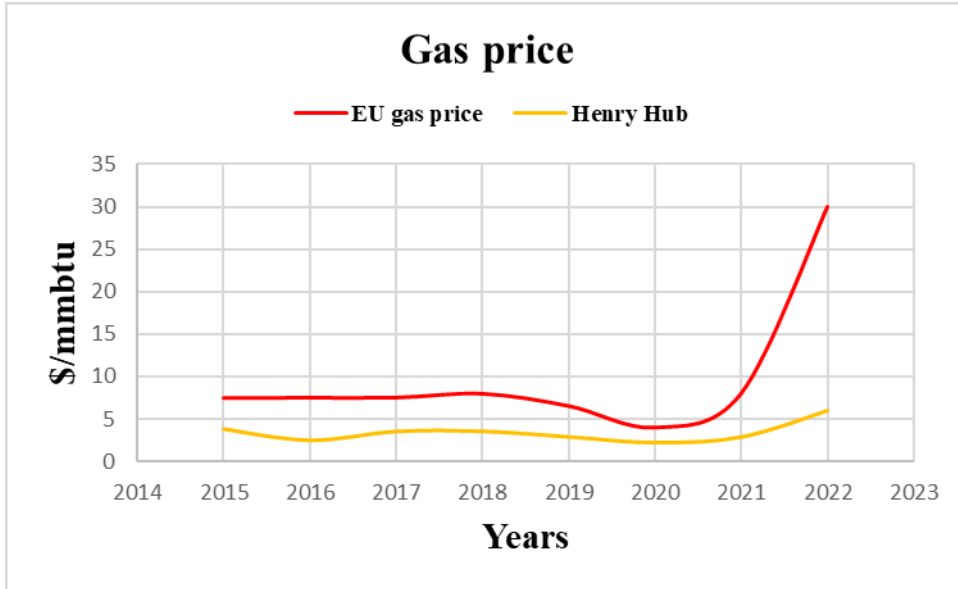


Figure 4-2 LNG prices in the European Union (EU) and Henry Hub markets.



Figure 4-3 Global MDO fuel prices.

To compare LNG and MDO in an equivalent manner, the price of LNG was expressed in \$/tonne by making certain assumptions. The prices of LNG and MDO that were used in this study are listed in Table 4-3.

Table 4-3 Average marine fuel prices.

Fuel	Price (\$/tonne)
LNG	500
MDO	887

4.4.2 The First Scenario

A discount rate of 10% [13] was assumed in this study. Tables 4-4 and 4-5 show the NPV, PP, and IRR of all the propulsion systems for Routes 1 and 2.

Table 4-4 Economic results for Route 1

	Simple LNG	Simple MDO	I/R ELNG	I/R LNG	I/R MDO	Two-Stroke Diesel
NPV	\$367,960,759.11	\$153,733,476.41	\$338,162,288.79	\$372,233,784.20	\$170,879,982.89	\$79,740,967.16
PP	4.62 years	6.57 years	4.91 years	4.61 years	6.39 years	7.56 years
IRR	22%	15%	20%	22%	15%	13%

Table 4-5 Economic results for Route 2

	Simple LNG	Simple MDO	I/R ELNG	I/R LNG	I/R MDO	Two-Stroke Diesel
NPV	\$104,994,834.90	\$-133,881,155.79	\$76,700,960.45	\$111,717,948.74	\$-112,301,091.44	\$-198,630,055.28
PP	7.27 years	15.18 years	7.80 years	7.19 years	13.72 years	24.55 years
IRR	13%	5%	12%	14%	6%	3%

In the first scenario, the CCGTs that were fueled by LNG had the highest NPV as they have fewer components and lower fuel costs. The NPV of the ELNG CCGT was lower than that of the other two CCGTs that were fueled by LNG owing to its higher component cost. Comparing all three CCGTs, the I/R CCGT that was fueled by LNG had the highest NPV, as it had the least fuel consumption. In general, the CCGTs that were fueled by MDO were superior to the two-stroke diesel engine that was fueled by MDO owing to lesser fuel consumption. The simple and I/R CCGTs and the two-stroke diesel engine that was fueled by MDO

were not acceptable for Route 2 owing to their high fuel consumption and cost. In general, the NPVs of Route 1 were better than those of Route 2 owing to the differences in the fuel consumption, distance, and ambient conditions between the two routes. The PP was used to estimate the period that was required to recover the investment cost. The I/R CCGT that was fueled by LNG had the shortest PP, whereas the two-stroke diesel engine that was fueled by MDO had the longest PP owing to its high fuel consumption cost. The two-stroke diesel engine had PP of 7.56 years and 24.55 years for Routes 1 and 2, respectively. The PPs of the I/R ELNG CCGT and simple and I/R CCGTs that were fueled by LNG for Route 1 were 4.91 years, 4.62 years, and 4.61 years, respectively, and those for Route 2 were 7.8 years, 7.27 years, and 7.19 years, respectively. These values represent approximately 16% of the total project life cycle for Route 1 and 26% of the total project life cycle for Route 2. The simple and I/R CCGTs that were fueled by MDO had PPs of 6.57 years and 6.39 years, respectively, for Route 1, and PPs of 15.18 years and 13.72 years, respectively, for Route 2. The IRR was used to assess the benefit that was derived from investments and obtain the accurate discount rate that was required for the cash flow of the project to reach a zero NPV. The results revealed that the I/R ELNG CCGT and simple and I/R CCGTs that were fueled by LNG had IRRs of 20%, 22%, and 22%, respectively, for Route 1. This indicates that these propulsion technologies are low-risk investments, with significant potential benefits. For Route 2, the I/R ELNG CCGT and simple and I/R CCGTs that were fueled by LNG had IRR of 12%, 13%, and 14%, respectively. The simple CCGT, I/R CCGT, and two-stroke diesel engine that were fueled by MDO had IRRs of 15%, 15%, and 13%, respectively, for Route 1, and IRRs of 5%, 6%, and 3%, respectively, for Route 2. Therefore, the simple and I/R CCGTs and two-stroke diesel engine that were fueled by MDO are high-risk investments for Route 2.

4.4.3 The Second Scenario

The second scenario analyzes the effect of variations in the fuel cost (50% increase and 20% decrease). Figures 4-4 – 4-6 illustrates the difference in NPV, PP, and IRR between the first and second scenarios for Routes 1 and 2.

Considering a 20% decrease in fuel cost, and a 50% increase in the fuel cost. The I/R ELNG CCGT, I/R CCGT and simple CCGT that were fueled by LNG exhibited better results compared to the other propulsion technologies. The MDO fuel with CCGT cycles were not good enough as LNG. The fuel price played a key role on the economical results.

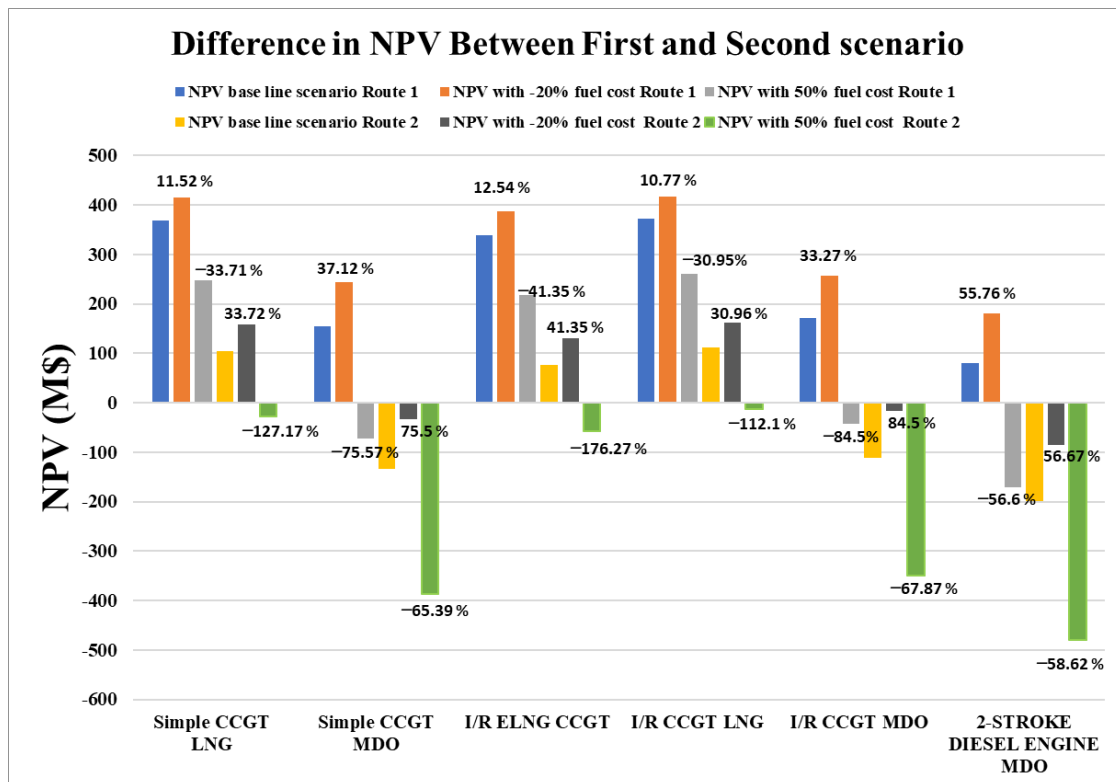


Figure 4-4 Difference in NPV between the first and second scenarios for Routes 1 and 2.

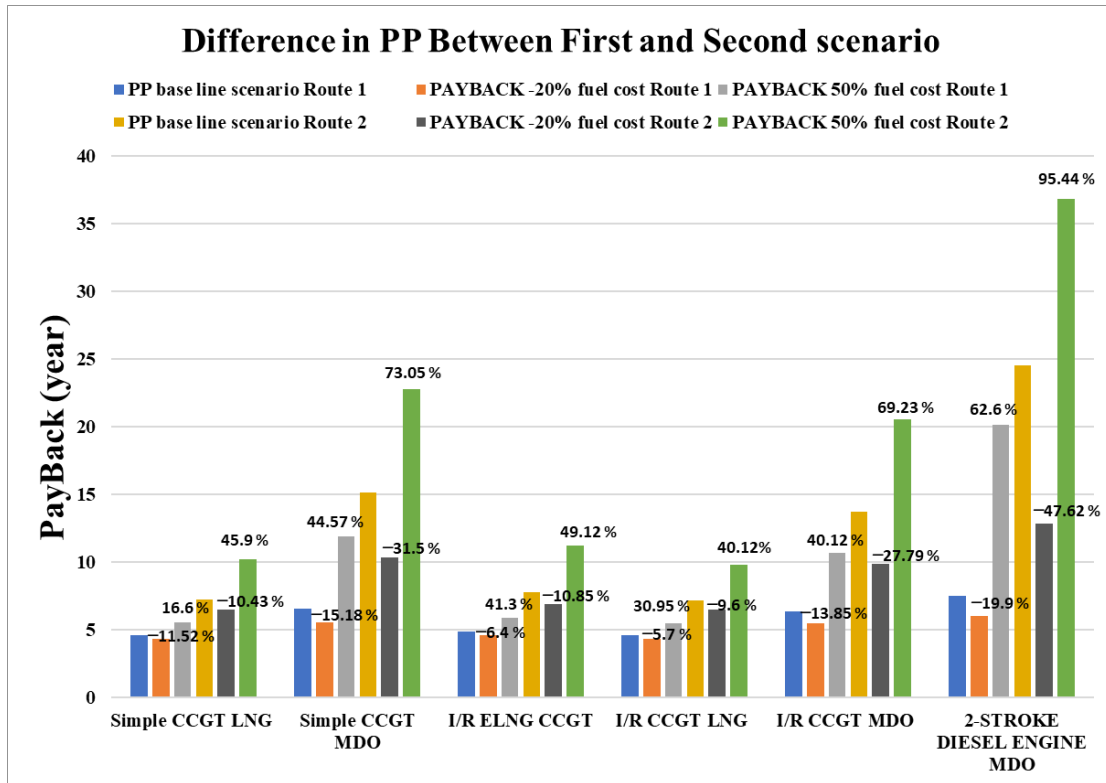


Figure 4-5 Difference in PP between the first and second scenarios for Routes 1 and 2.

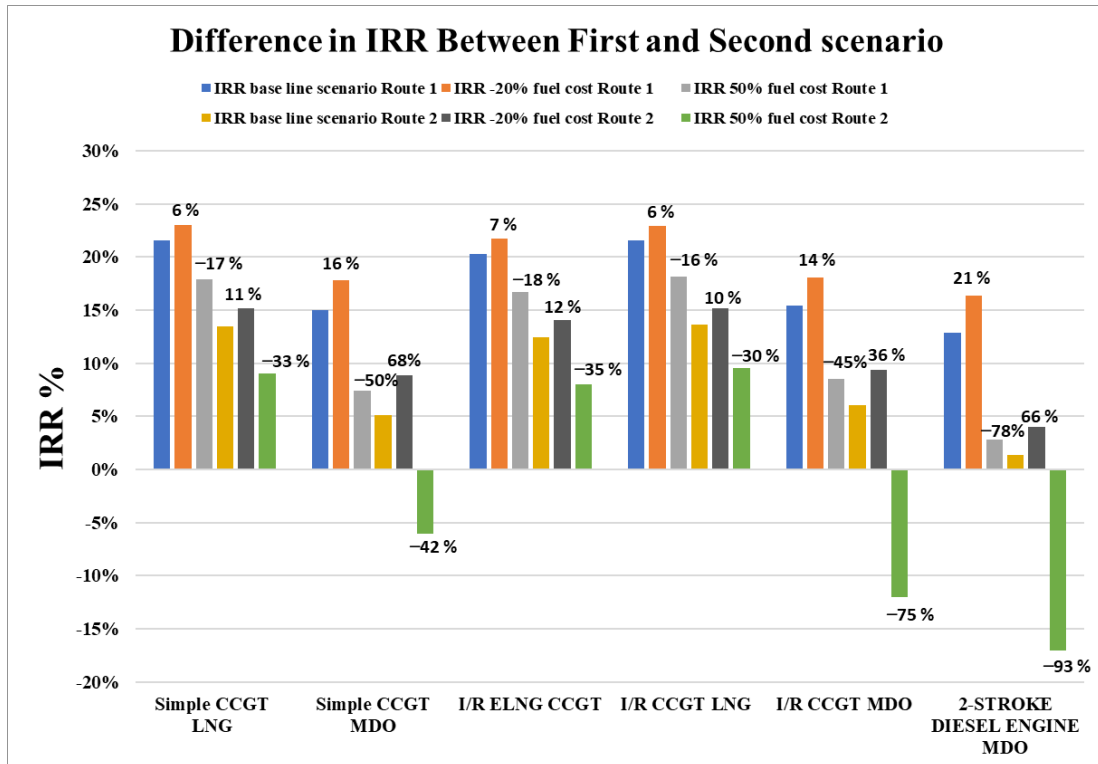


Figure 4-6 Difference in IRR between the first and second scenarios for Routes 1 and 2.

4.4.4 The Third Scenario

The third scenario analyzes the effect of variations in the capital cost (50% increase and 20% decrease). Figures 4-7 – 4-9 show the difference in NPV, PP, and IRR between the first and third scenarios for Routes 1 and 2 when considering a 20% decrease in the capital cost and a 50% increase in the capital cost. With increasing capital cost, the 2-stroke diesel engine and CCGT cycles fueled by MDO show a higher impact regarding the higher capital cost.

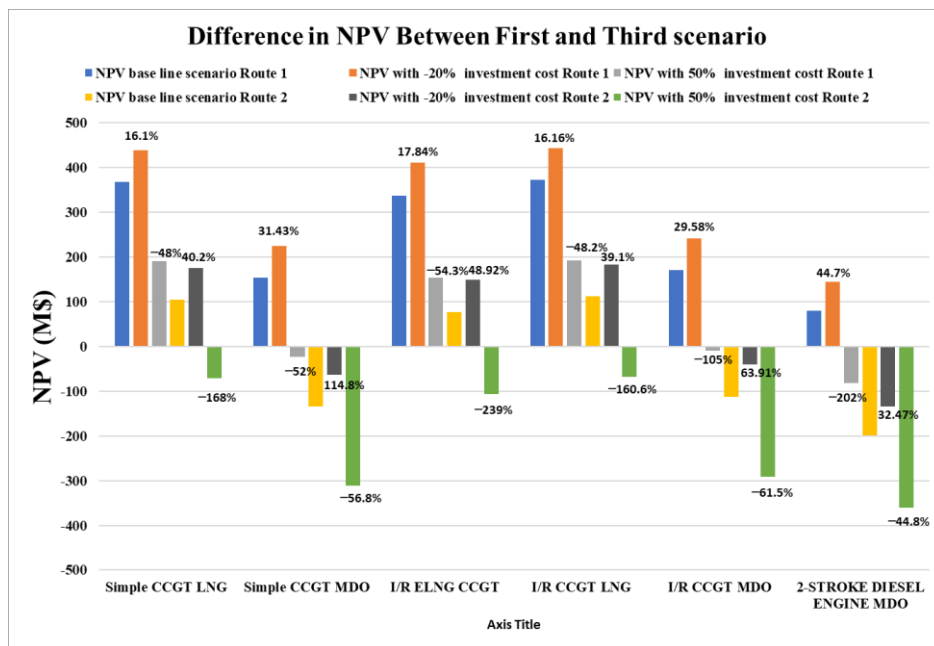


Figure 4-7 Difference in NPV between the first and third scenarios for Routes 1 and 2.

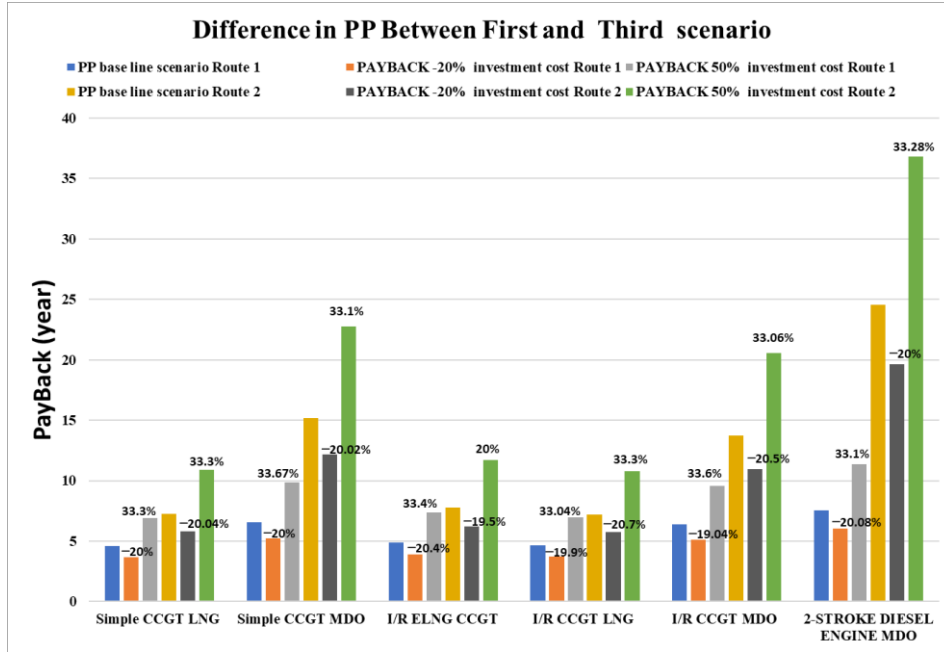


Figure 4-8 Difference in PP between the first and third scenarios for Routes 1 and 2.

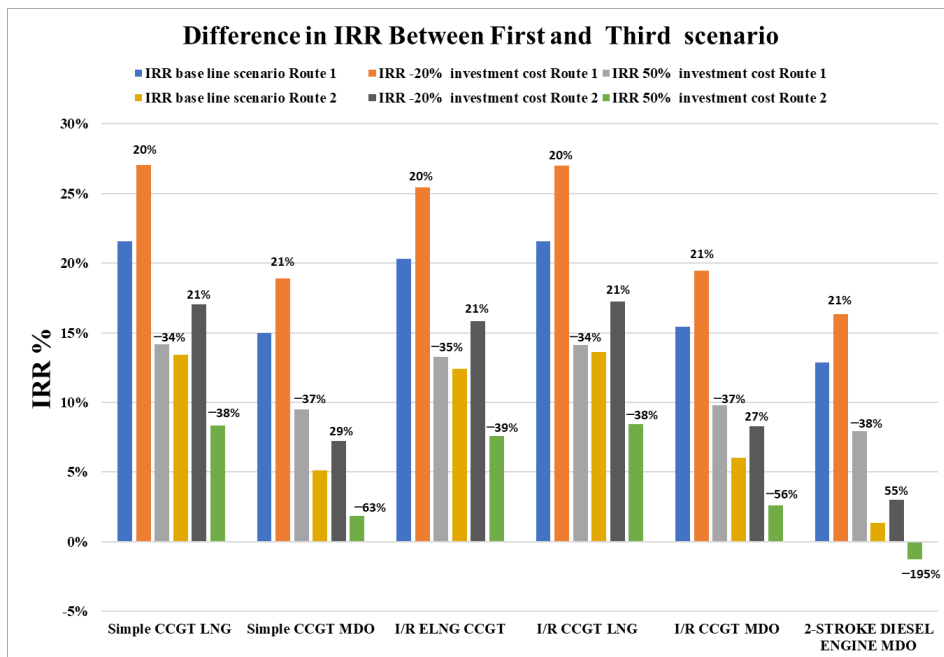


Figure 4-9 Difference in IRR between the first and third scenarios for Routes 1 and 2.

4.4.5 The Fourth Scenario

The hull fouling model uses the mean amplitude of the hull roughness as a variable. On average, it increases the hull resistance by approximately 2% for every 30 μm increase in the mean roughness amplitude [13]. The average hull

roughness amplitude was assumed to gradually increase by 30 μm every 15 y, with an initial clean hull roughness of 120 μm . The method was tested by simulating a large container ship with a hull roughness of 120–180 μm . The increased average hull roughness that was assumed in the fourth scenario increases the braking power of the vessel. The hull roughness also impacts the period of operation at reduced speeds and increases the fuel consumption. Figures 4-10 – 4-12 demonstrate the difference in NPV, PP, and IRR between the first and fourth scenarios for Routes 1 and 2.

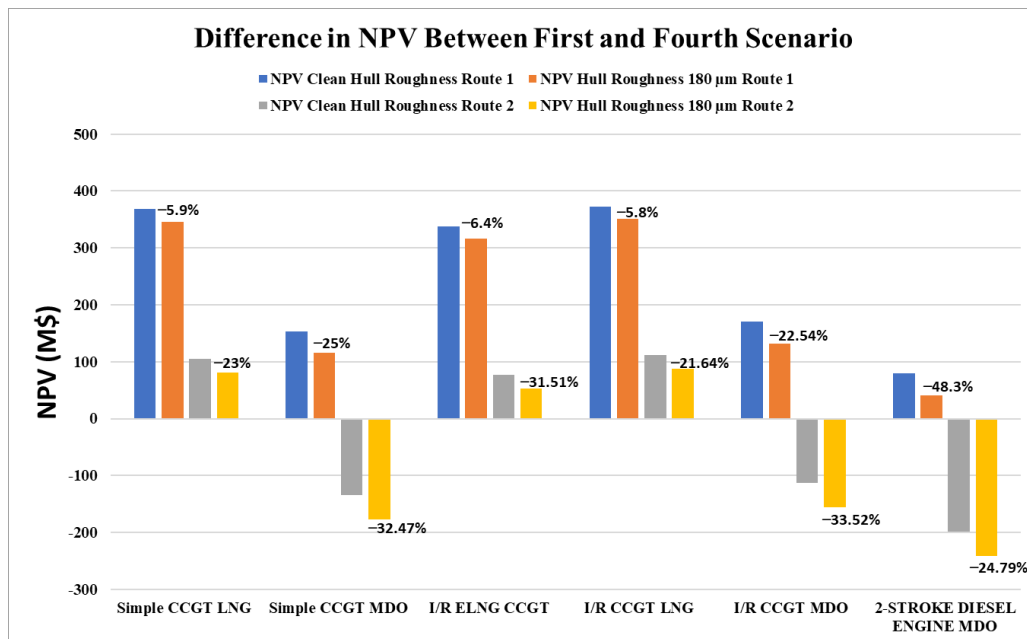


Figure 4-10 Difference in NPV between the first and fourth scenarios for Routes 1 and 2.

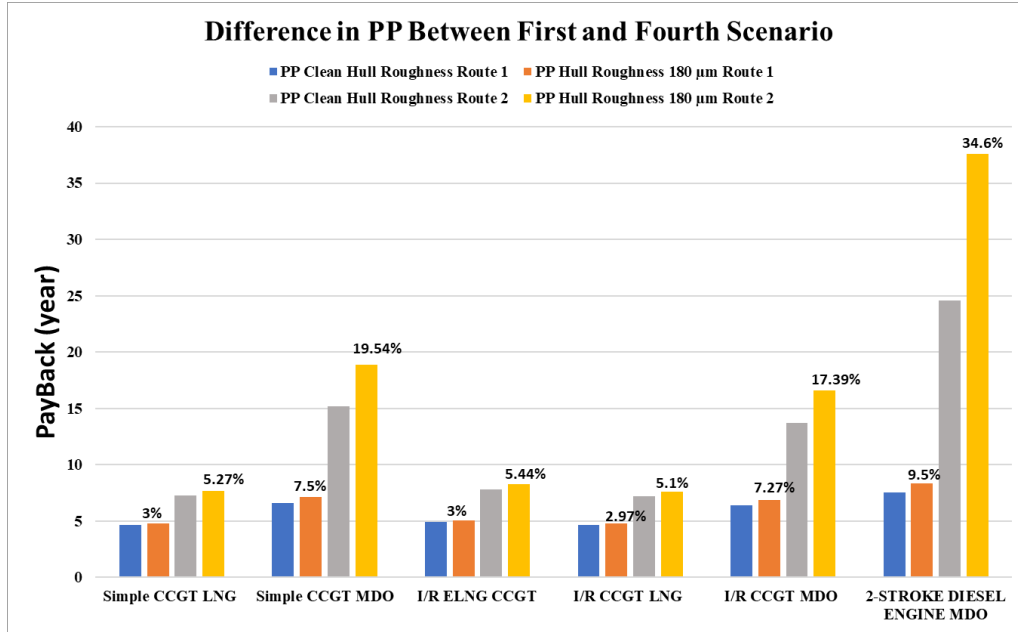


Figure 4-11 Difference in PP between the first and fourth scenarios for Routes 1 and 2.

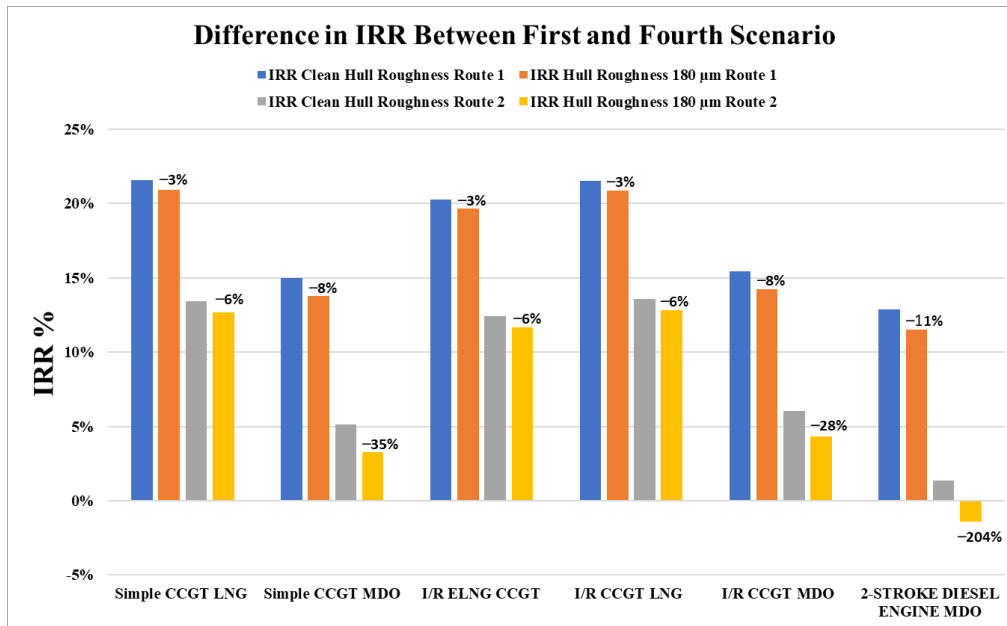


Figure 4-12 Difference in IRR between the first and fourth scenarios for Routes 1 and 2.

4.5 Conclusions

Techno-economic and risk analyses were performed to assess the economic benefits of using different CCGT cycles instead of a two-stroke diesel engine as the propulsion system in a large container ship. Accordingly, simple and I/R CCGTs that are fueled by LNG or MDO, an I/R ELNG CCGT, and a two-stroke

diesel engine that is fueled by MDO were analyzed. Several important findings were obtained considering various economic aspects, and the methodology that was used in the study was determined to be suitable for selecting an optimal propulsion system and the related decision-making processes. The key findings are summarized below.

- Various economic aspects were investigated considering two international shipping routes. The simulated routes were assumed to be direct routes and the stability of the ship was not considered in the analyses. The results indicated that the profitability of Route 1 depends significantly on fuel cost and consumption.
- CCGT cycles that are fueled by MDO are not desirable owing to the higher fuel costs and consumption compared to those that are fueled by LNG. The LNG-fueled CCGTs were more economically viable than the MDO-fueled two-stroke diesel engine as well. The I/R ELNG CCGT, and simple and I/R CCGTs that are fueled by LNG have significant potential as profitable low-risk investments.
- A sensitivity analysis and risk evaluation were performed to examine the effects of the fuel cost, capital cost, and hull fouling resistance on the economic analysis. A total of four scenarios were used to comprehensively analyze the profit and risk that is associated with each propulsion system. The first scenario represented the base-line scenario, with no changes in the fuel cost, capital cost, and hull fouling resistance; the second scenario examined the effect of changes in the fuel cost; the third scenario examined the effect of changes in the capital cost; and the fourth scenario examined the effect of changes in the hull fouling resistance. The results revealed that fuel and capital costs have a significant influence on the overall economic profit.

In summary, the assessment method that was developed in this study confirmed the importance of techno-economic and sensitivity analyses for comparing and choosing between multiple technological systems in the maritime sector.

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4.6 References

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5 TERA of Combined Cycles for Large Container Ship Propulsion

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5.1 Abstract

In recent years, the International Maritime Organization's (IMO) stringent regulations on air pollutants, associated with the increase in fuel costs, have encouraged the researcher to find fuels that are cleaner and technology that is more efficient than conventional propulsion systems. This paper defines and describes a Techno-economic environmental and risk assessment (TERA) method for assessing substitute fuels and technologies that could be utilised in the maritime sector to replace two-stroke diesel engines fuelled by heavy fuel oil (HFO). This method facilitates the comparative assessment of the functioning of advanced combined gas and steam cycles fuelled by liquified natural gas (LNG) and marine diesel oil (MDO), as well as a two-stroke diesel engine fuelled by MDO as a propulsion system in a large container ship based on different missions. This assessment was carried out for two different journeys. This paper shows the advantages of utilising advanced combined gas and steam cycles as a propulsion system in large container ships. Moreover, a sensitivity evaluation and risk assessment were also conducted to investigate the impact of increases and decreases in the container shipment price, discount rate and emission tax cost on the economic results. For the routes considered and when applied carbon dioxide tax, the two-stroke diesel engine fuelled by marine diesel oil, simple combined gas and steam cycle, and intercooler/reheat simple combined gas and steam cycle fuelled by marine diesel fuel results show higher reduction in net present value 217%, 135%, and 117%, respectively than the other technologies considered. Furthermore, the discount rate, and CO₂ tax risk assessment showed significantly impacted on the overall economic profit.

Keywords: Techno-economic environmental and risk assessment; combined gas and steam cycle; large container ship; propulsion system; liquefied natural gas; nitrogen oxide; carbon dioxide; net present value; payback period; internal rate of return; IMO.

5.2 Introduction

Marine transport is one of the most common forms of international transportation [1]. The marine transport growth from 2007 to 2017 was approximately 25.2% [2]. More than 90% of marine vessels are powered by diesel engines [3]. Marine transportation emits harmful emissions, such as sulfur oxides (SO_x), particulate matter (PM) and nitrogen oxides (NO_x) and produces 2.2% of the total carbon dioxide (CO₂) emissions [4]. Three types of ships—oil tankers, container ships and bulk carriers are responsible for most CO₂ emissions (Figure 5-1). Container ships have the highest impact on the total CO₂ emissions from marine vessels, being responsible for approximately 25.6% of these emissions [5].

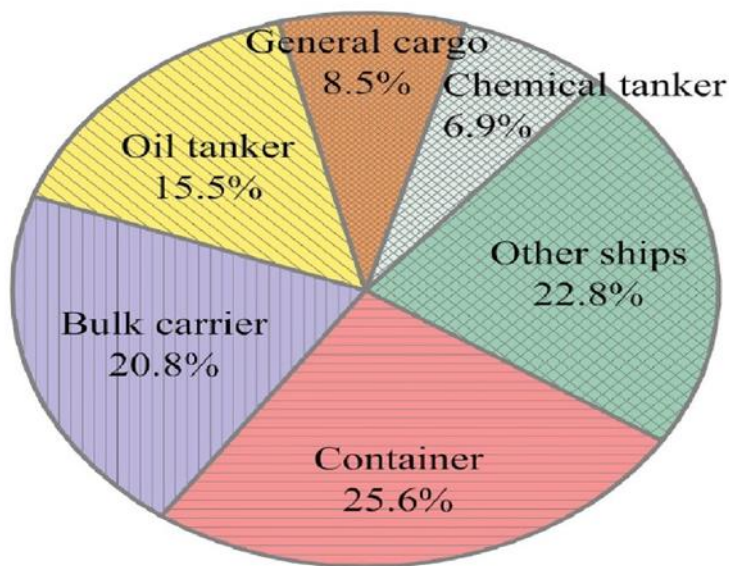


Figure 5-1 Percentage of CO₂ emissions by ship type in 2012 [6].

Taking these facts into consideration, the International Maritime Organization (IMO) established stringent regulations on air pollutants; it has also explored the possibility of introducing a tax on emissions to reduce the emissions from diesel engines fuelled by heavy fuel oil (HFO) [7]. In 2016 IMO Tier III, the NO_x

emissions were reduced by 75% compared to Tier II [8]. Similarly, in 2020 IMO, regarding air pollution (MARPOL), the sulphur content in the fuel was reduced from 3.50% to 0.50% [9]. The stringent regulations on harmful emissions have prompted the researcher to find marine fuel and technology alternatives that are cleaner than the conventional ones [10]. To reduce polluting emissions, there are two possible solutions: utilising a propulsion system with higher efficiency or using cleaner fuels [11]. With regard to this aim, the most promising marine fuel is liquified natural gas (LNG) [12]. Compared to HFO, LNG could reduce SO_x emissions by 100%, NO_x emissions by 85–95% and CO₂ emissions by 20% [2]. By 2050, ships powered by LNG are expected to comprise 32% of the shipping energy demand [7]. Higher-efficiency technology, such as gas and steam combined cycle technology (CCGT), is one promising technology that can be adopted in the marine sector [6]. Nevertheless, only a few ships with combined cycle propulsion were built; cost considerations may be the primary reason for this technology's low prevalence. However, the current situation is different due to increasing attention being directed at environmental issues and the potential performance gains attainable through CCGT. The literature studies of combined cycle power plants as propulsion systems for large ships were summarised in a previous study [13]. Techno–economic environmental evaluation and risk evaluation is a method that utilises a mathematical model to simulate and evaluate the technical performance of a individual or a set of propulsion systems. This method facilitates increased visibility of risks and can be used for various ship-type simulations with electrical or mechanical propulsion systems, as well as for different journey scenarios. The techno–environmental and techno–economic evaluations of advanced CCGT systems in comparison with two-stroke diesel engines for large container ships were performed in the authors' previous studies [13, 14, 15].

Few studies have addressed the TERA of an advanced combined gas and steam cycle for a large container ship. Therefore, by considering all the available evidence, this study contributes to the literature and achieves the following:

- The economic evaluation was conducted through a risk assessment of the effect of the container shipment cost and discount rate to assess the

CCGT cycles fuelled by LNG and MDO as well as a two-stroke diesel engine fuelled by MDO as a propulsion system in a large container ship based on two different international journeys.

- The risk assessment was also presented to examine the emission tax's impact on the economic analysis.

The economic model has been evaluated through different approaches, such as the net present value (NPV), payback period (PP) and internal rate of return (IRR). The rest of this paper is organised as follows: The first section described the methods used in this study. The results and discussion are described in the second section. The conclusion forms the final section.

5.3 Methodology

This study aimed to establish a method to evaluate the economic assessment and risk assessment of using a gas and steam combined cycle fuelled by LNG and MDO as a propulsion system in a large container ship, comparing it with the use of a two-stroke diesel engine fuelled by MDO; prior to this method establishment, a comprehensive analysis of the technical, environmental and economic aspects was carried out in the authors' previous studies [13] [14] [15]. To develop a possible and profitable solution for the propulsion system for ships, a technical, environmental, and economic model framework has been developed and described in detail in these studies [13] [14] [15]. The methodology of this study (Figure. 5-1) has a modular structure and includes two core models, which enable the simulation of the technical performance (Stage 1) of the detailed technology. The methodology is divided into four stages. Stage 1 describes the technical performance of the technologies evaluated. Stage 2 outlines the mission evaluations of the large container ship with different technologies and fuels regarding the technical and environmental aspects of two international journeys. These two stages are then linked to Stage 3, which describes the economic analysis of the technologies for the large container ship, considering each journey's ambient conditions and fuel consumption. The modules used in this work were defined in detail in a few previous studies [16,17,18].

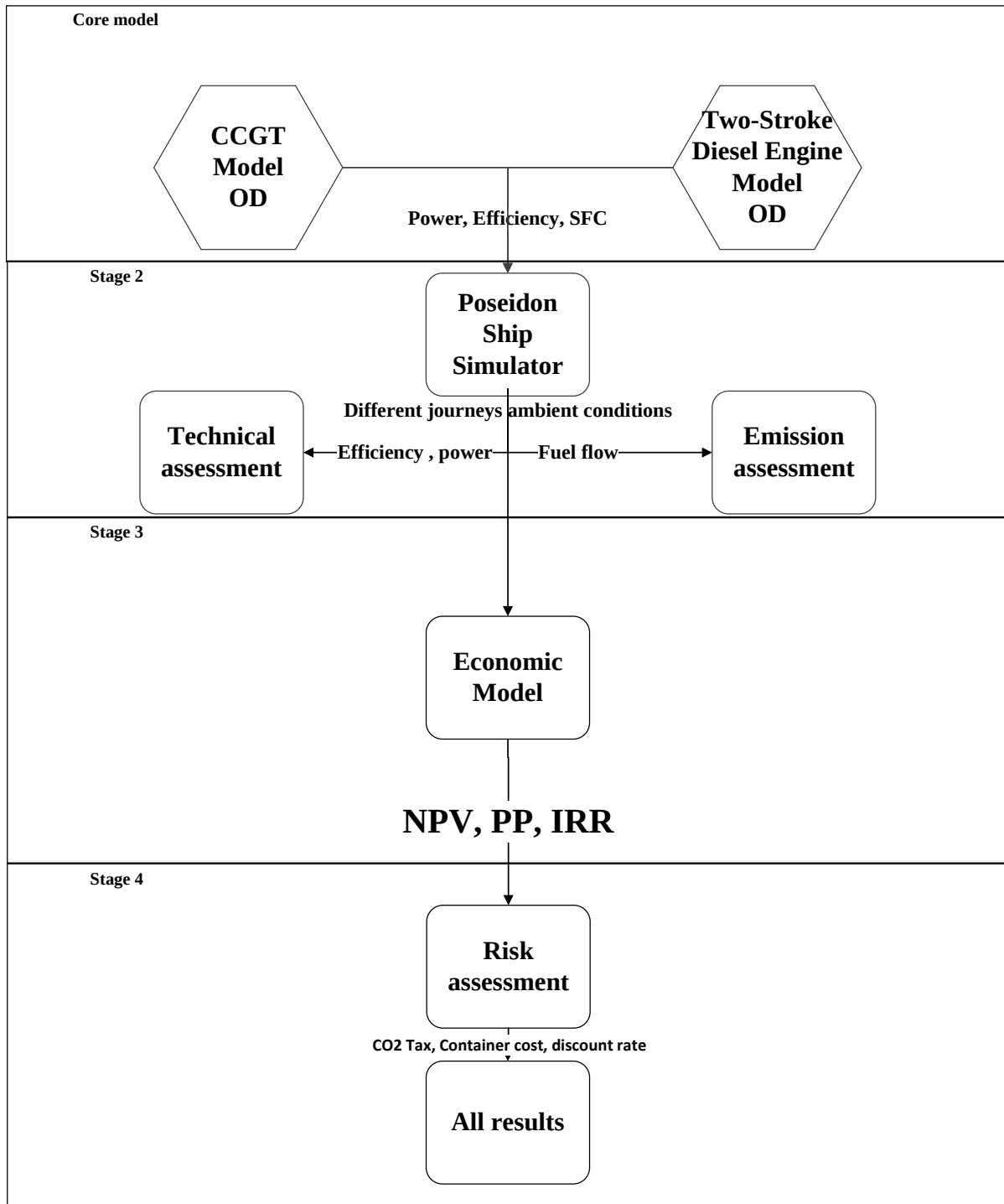


Figure 5-2 Methodology

5.3.1 Core models: Two-stroke diesel and CCGT engine models

The authors' previous studies described and evaluated the CCGT and two-stroke diesel engine models [13] [14]. The objective of these models was to evaluate the performance of the engine in an off-design point with different ambient

conditions to assess each technology with different fuels. Moreover, the unique cryogenic properties of LNG were used in CCGT to enhance the CCGT performance. The promising CCGT cycles were used in this study after carefully examining the thermal and environmental performance [13]. Table 1 shows several CCGT cycles with the different fuels used in each cycle.

Table 5-1 CCGT cycles with different fuels.

Engine	Fuel
Simple CCGT	LNG/MDO
Intercooler/reheater CCGT	LNG/MDO
ELNG intercooler/reheater CCGT	LNG

5.3.2 Stage 2 models: Poseidon ship simulator

The Poseidon ship simulator has been extensively described in previous research [14,16-18]. The objective of this model was to evaluate all the propulsion systems for a large container ship under different circumstances with aerodynamic and hydrodynamic resistance. The evaluations of the propulsion systems were conducted based on performance and environmental aspects. The results of the environmental model of the NO_x and CO₂ emissions from the CCGT cycles and the two-stroke diesel engine were outlined in detail previously [14].

5.3.3 Stage 3 model: Economic model

The objective of this model was to evaluate the economic aspect of each propulsion system with different fuels for a large container ship based on different international journeys. A previous study described the economic model in detail [15]. The focus was on an economic model that follows the NPV, IRR and PP approach:

- The investment cost considers the installation costs of all technologies.
- The operating and maintenance (O&M) costs take into account the fuel cost of the journey.

The NPV, IRR and PP formulas of the economic model were described in detail previously [15]. The results from this model were used as a baseline scenario for the different scenarios examined in Stage 4.

5.3.4 Stage 4: sensitivity and risk assessments

This stage aimed to conduct sensitivity and risk assessments of the economic model with different scenarios. The evaluation was based on various aspects of the economic assessment:

- The risk assessment of the emission tax on the economic analysis
- A risk assessment to examine the effect of the container shipment price and discount rate on the economic evaluation

This study examined four different scenarios for a comprehensive analysis of economic profit and the project's risk assessment of technology for a large container ship based on two different journeys. The baseline scenario was the first one, in which there was no change in the discount rate or container shipment price, and no emission tax was applied, as described in detail previously [15]. The second scenario investigated the risk and effect of the emission tax based on the economic aspect. The third scenario assessed the possibility of the container cost changing. The fourth scenario examined the impact of the discount rate.

5.4 Results and discussion

The capital and the O&M costs were examined and described in detail in previous research [15]. Table 5-2 shows the costs of all CCGT components and the two-stroke diesel engine. Reducing the size of the engine room and engine weight for the combined cycle would increase the ship's cargo capacity. Taking into account the weight reductions of the combined cycle propulsion system as compared to those of the diesel engine propulsion system considered in this study and described by the author in [13].

Table 5-2 Costs of CCGT components and two-stroke diesel engine.

Component	Diesel engine	Simple CCGT	I/R CCGT	I/R ELNG CCGT
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Diesel engine [\$/kW]	460	—	—	—
CCGT [\$/kW]	—	862.5	862.5	862.5
Gearbox [\$M]	—	1.5	1.5	1.5
Second combustor [\$/MW]	—	—	80000	80000
Intercooler [\$/MW]	—	—	20000	20000
Heat exchanger [\$/MW]	—	—	—	150000
Total capital cost \$ million	25.760	49.8	55.4	63.8
Installation cost	30%	30%	30%	30%
O&M costs	2.5%	4%	4%	4%
Ship cost \$ million	176.9	176.9	176.9	176.9
Total weight (t)	2500	619	692.28	812.39

The fuel costs are presented in this economic model. The LNG prices were taken from the Henry Hub markets and European Union (EU) [19]. A global price was considered for the MDO price [19,20]. The LNG and MDO prices considered in this paper are shown in Table 3.

Table 5-3 Average price of marine fuel.

Fuel	Price \$/tonne
LNG	500
MDO	887

The outflow and inflow for all propulsion systems have been previously described [15]. The cost of international transportation via ship for a container can vary widely, depending on several factors. The cost of transporting a 20-ft container via ship from one country to another was assumed to be 1390.01–6950.04 (\$) [21]. The first international journey was from Shanghai, China, to Los Angeles, USA, whereas the second was from Shanghai, China, to Hamburg, Germany. It was assumed that the first route had an average price of 4170 (\$) and that the second route had an average price of 6403.9 (\$); Route 1's distance was half that of Route 2. The outflow estimation was based on the O&M costs and fuel-

consumption costs. The emissions trading system recommended assessing CO₂ emission tax. The risk assessment considered the impact of the CO₂ emission tax. In the second scenario, the CO₂ emission tax was assumed to be the same for LNG and MDO to determine each propulsion system's advantage over the other. The regulation on CO₂ emissions was recommended by the emissions trading system, which is a keystone of the EU's policy for combating climate change. The carbon tax rates and years of implementation in European countries can be found in Table 5-4 [22-24]. The average rate of the CO₂ tax of all EU countries was considered the CO₂ tax in this study.

Table 5-4 Carbon tax rates and years of implementation in European countries.

Country	Carbon Tax Rate (\$/tonne CO₂)	Year of Implementation
Poland (PL)	0.08	1990
Finland (FI)	73.02	1990
Sweden (SE)	137	1991
Norway (NO)	69	1991
Denmark (DK)	28	1992
Slovenia (SI)	20.37	1996
Estonia (EE)	2.36	2000
Latvia (LV)	14.13	2004
Liechtenstein (LI)	101	2008
Switzerland (CH)	101	2008
Iceland (IS)	35	2010
Ireland (IE)	39.45	2010
Ukraine (UA)	0.3	2011
United Kingdom (GB)	21.23	2013
France (FR)	53	2014
Spain (ES)	17.67	2014
Portugal (PT)	28.26	2015
Luxembourg (LU)	23.55	2021
Netherlands (NL)	35.33	2021

Country	Carbon Tax Rate (\$/tonne CO ₂)	Year of Implementation
The average	42.09	

A sensitivity assessment presented the effect of the container price and discount rate on the economic analysis. In this study, the cost change was considered for the container cost; a higher cost was 50%, whereas a lower cost was -20%. In addition, the study considered a higher (18%) and a lower (4%) discount rate [25].

5.4.1 Assessment of the first and second scenarios

The second scenario addressed CO₂ emission taxes. The economic impact of the emission tax depended on the CO₂ emissions from the propulsion systems; therefore, a particular technology had an advantage over others when the emission tax was applied. Figure 5-3 shows the change in NPV between the first and second scenarios for the first and second routes.

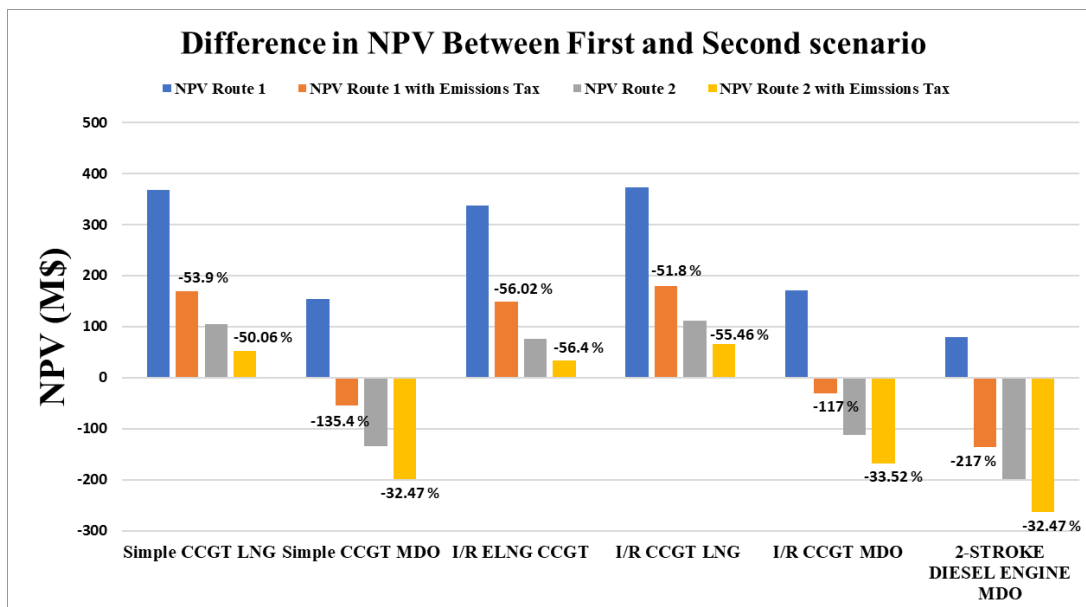


Figure 5-3 The NPV of all technologies.

However, when tax was applied, the results for the intercooler/reheated (I/R) enhanced liquefied natural gas (ELNG) CCGT cycle and CCGT cycles fuelled by LNG were shown to be more relevant than those of the other technologies

considered. The results for CCGT cycles fuelled by MDO and the two-stroke diesel engine exhibited high investment risk when CO₂ tax was applied. Figure 5-4 shows the change in PP between the first and second scenarios for the first and second routes. The highest period to return the investment was found for the CCGT cycles fuelled by MDO and the two-stroke diesel engine.

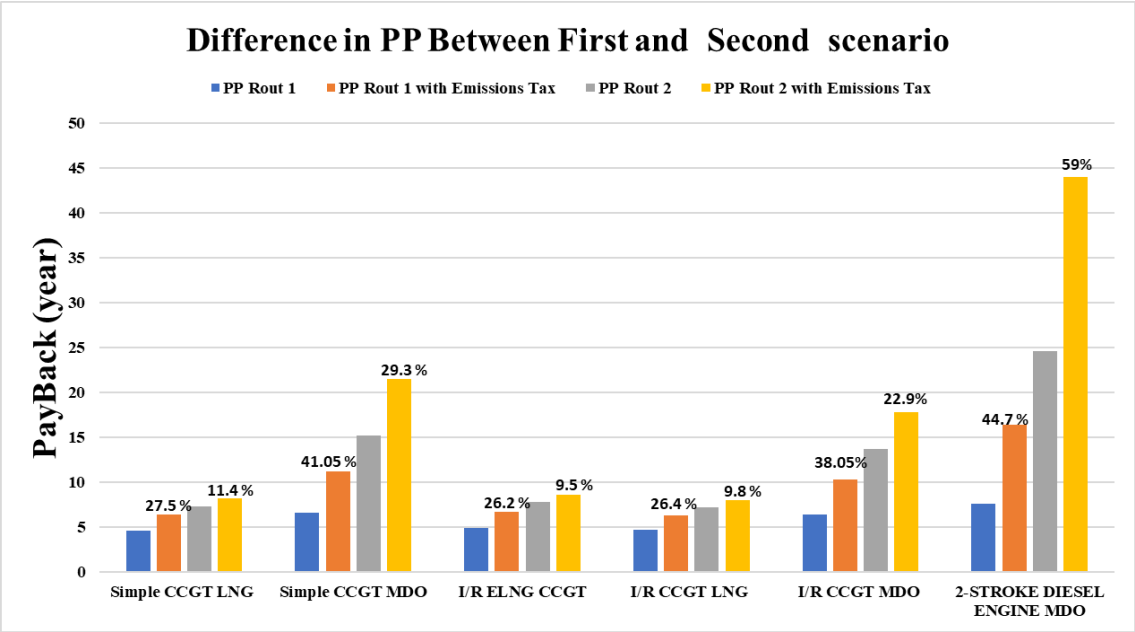


Figure 5-4 The PP of all technologies.

Figure 5-5 shows the difference in IRR between the first and second scenarios for the first and second routes. The I/R ELNG CCGT cycle and CCGT cycles fuelled by LNG showed a higher safe investment.

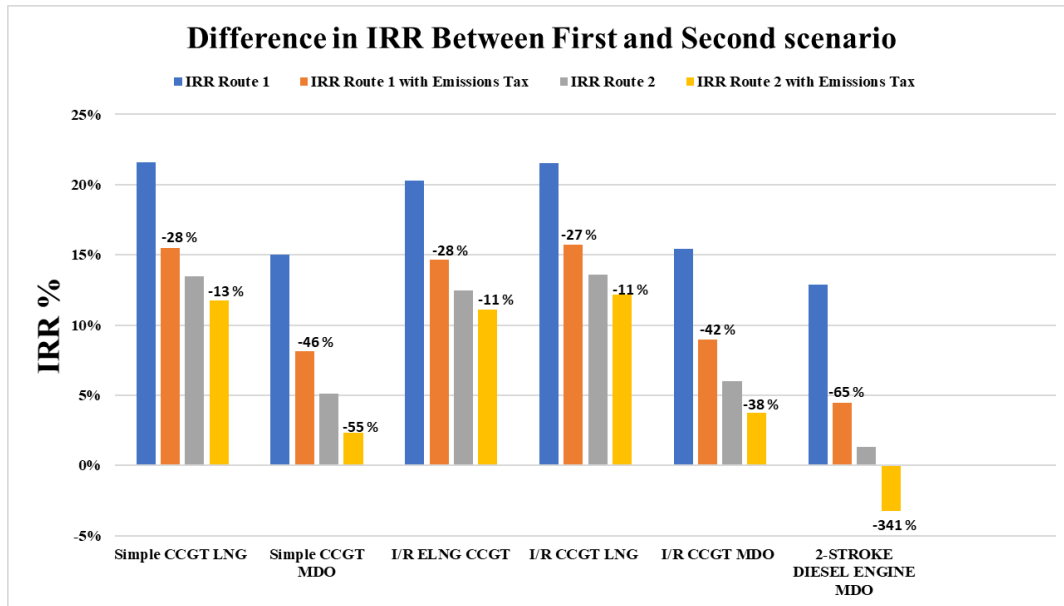


Figure 5-5 The IRR of all technologies.

5.4.2 Assessment of the third scenario

The third scenario analysed the impact of variations in the container cost (20% decrease and 50% increase). Figure 5-6 illustrates the difference in NPV between the first and second scenarios for Routes 1 and 2. When considering a 20% decrease in the container cost, the two-stroke diesel engine showed the highest reduction due to higher fuel consumption. When considering a 50% increase in the container cost, the CCGT fuelled by MDO and the two-stroke diesel engine had higher impacts on the container cost.

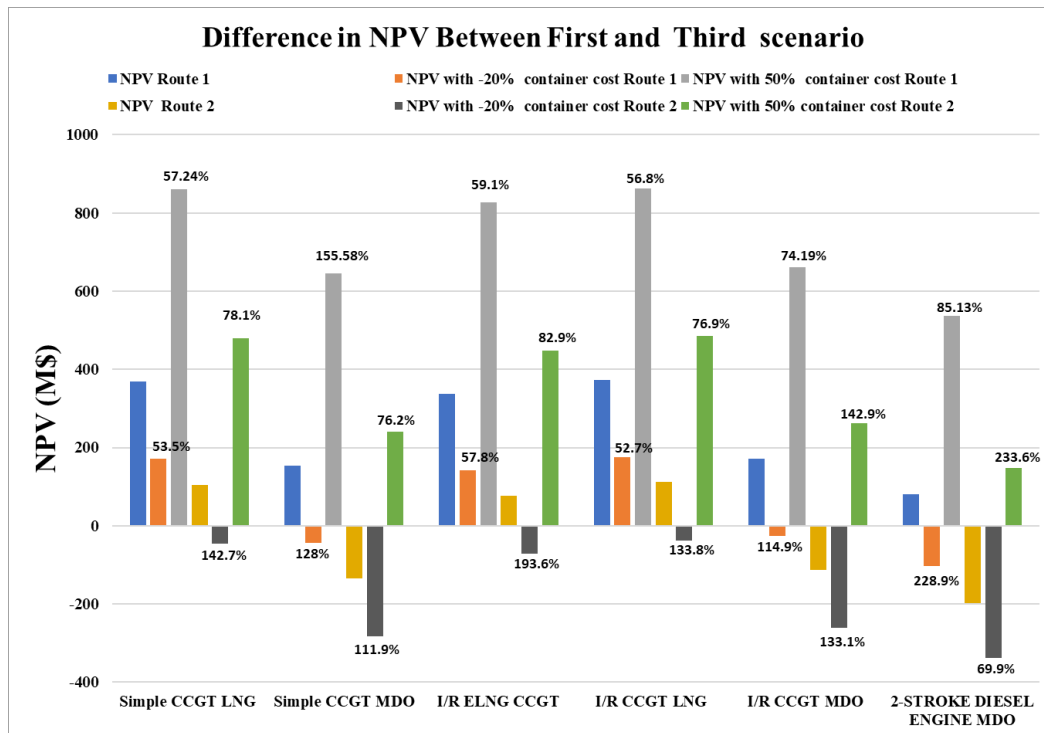


Figure 5-6 The NPV of all technologies.

Figure 5-7 shows the change in PP between the first and third scenarios for the first and second routes. The CCGT fuelled by MDO, and the two-stroke diesel engine had the highest period to return the investment. Moreover, the CCGT fuelled by MDO, and the two-stroke diesel engine results showed no desire to invest.

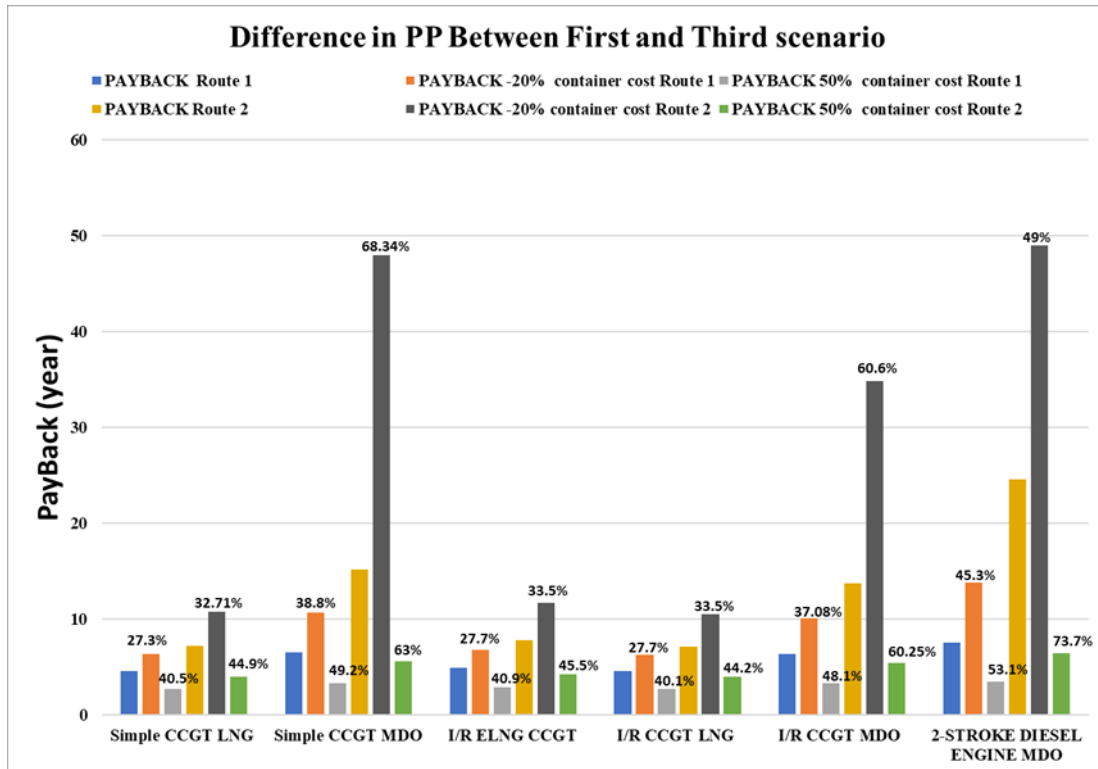


Figure 5-7 The PP of all technologies.

Figure 5-8 displays the IRR difference between the first and third scenarios for the first and second routes. Route 2 had a higher impact on fuel consumption. The CCGT fuelled by MDO, and the two-stroke diesel engine had the highest risk of the investment. Moreover, the container cost showed high impact on the economical results.

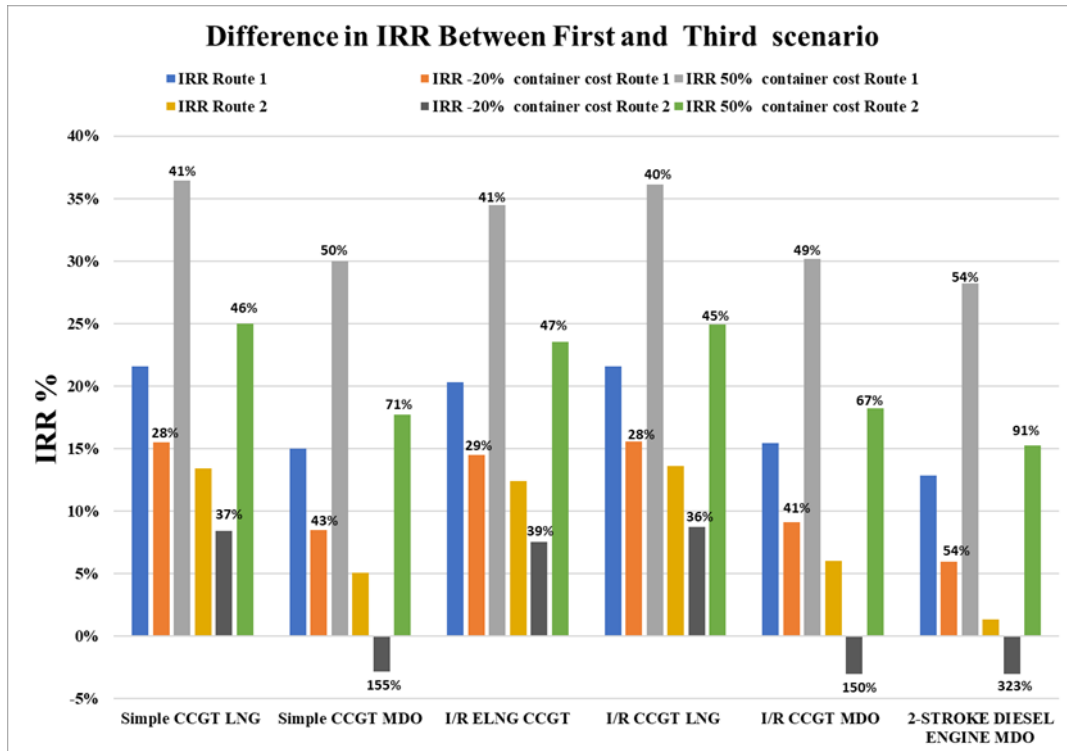


Figure 5-8 The IRR of all technologies.

5.4.3 Assessment of the fourth scenario

Figures 5-9 and 5-10 show the economic results (NPV) for Routes 1 and 2 with different discount rate values. For Route 1, the I/R ELNG, I/R and simple CCGT fuelled by LNG were found to be a low-risk investment and have considerably high potential as a substantial investment at all the discount rates examined. I/R, simple CCGT fuelled by MDO, and the two-stroke diesel engine were acceptable at 4% and 10% discount rates. For Route 2, the I/R ELNG, I/R and simple CCGT fuelled by LNG were acceptable at 4% and 10% discount rates. I/R, simple CCGT fuelled by MDO, and the two-stroke diesel engine were acceptable at a 4% discount rate. The two-stroke diesel engine was not acceptable at any of the discount rates examined.

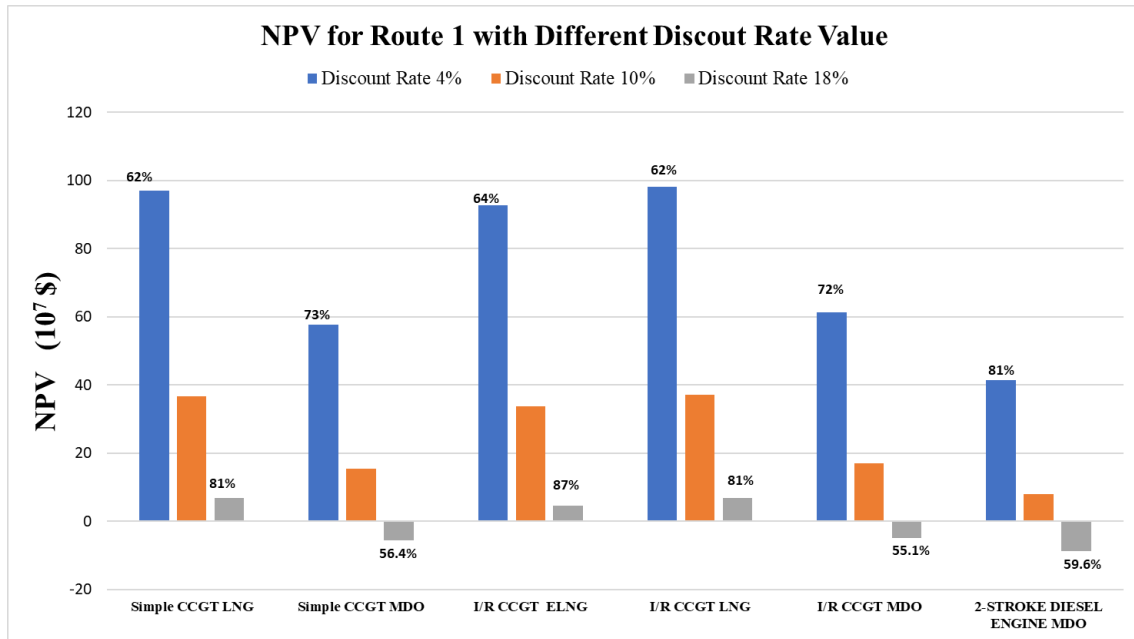


Figure 5-9 NPV for Route 1 with different discount rate values.

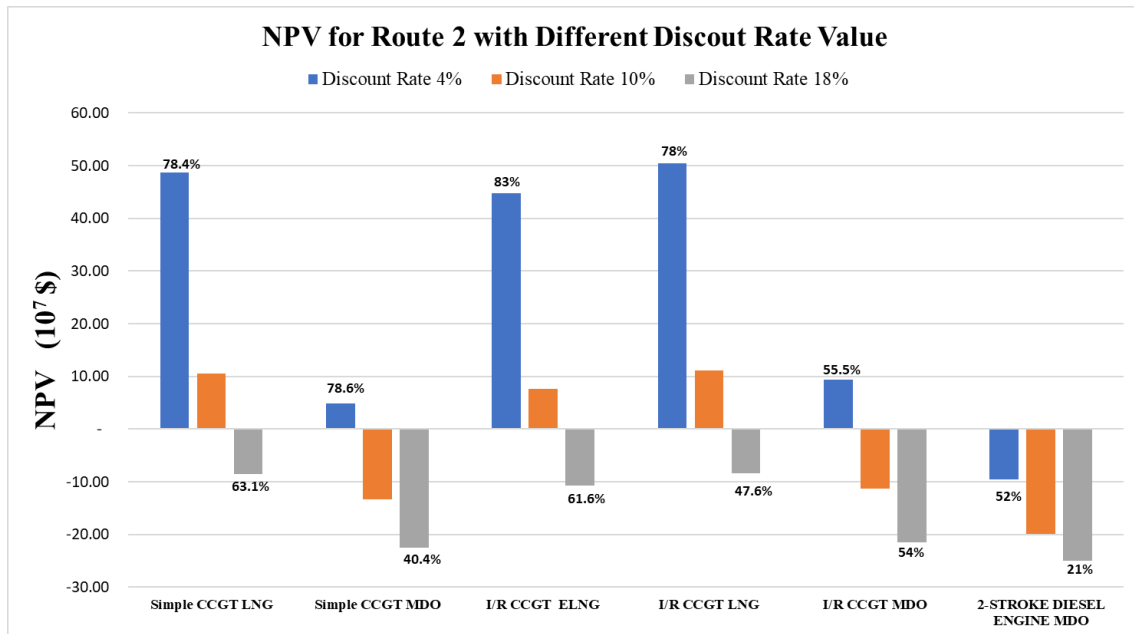


Figure 5-10 NPV for Route 2 with different discount rate values.

5.5 Conclusion

The TERA have been utilised to evaluate the economic benefits of using CCGT cycles, as an alternative to the conventional two-stroke diesel engine, as a propulsion system in large container ships. Simple and I/R CCGT fuelled by LNG and MDO, I/R ELNG CCGT and two-stroke diesel engine propulsion systems

fuelled by MDO were examined. The results were encouraging in terms of the economic aspects, and the methodology used was confirmed to be beneficial for the engine chosen and the decision-making process. This study's main findings can be summarised as follows:

- The economic aspects were evaluated based on different international routes. when the simulated routes were assumed to be direct routes, ship stability was not considered. The study showed that economic profitability depends significantly on fuel consumption.
- The study showed that the CCGT cycles fuelled by MDO were not attractive due to the fuel cost and consumption. The LNG-fuelled CCGT cycles were more economically viable than the MDO-fuelled two-stroke diesel engine. The I/R ELNG, I/R and simple CCGT fuelled by LNG had considerably high potential as a substantial, low-risk investment.
- The economic assessments considered the effects of introducing a CO₂ tax, the container shipment price and discount rate on the economic analysis. This research examined four different scenarios for a comprehensive analysis of the economic profit and the risk of each scenario's project. The first scenario was the baseline scenario, which had no change in fuel cost, capital cost or hull fouling resistance. The second scenario examined the CO₂ tax. The third scenario investigated the change in the container shipment price. The fourth scenario examined the change in the discount rate. The CO₂ tax and container shipment price had notable impacts on the profit.

Ultimately, this study confirms that the assessment of TERA used in the maritime sector is an essential tool for comparing and choosing between various propulsion systems.

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Conflicts of Interest: The authors declare no conflicts of interest.

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6 Overall Discussion

6.1 Implementation of the work

The techno-economic environmental and risk assessment established in this study to assess the efficacy of different technologies for large container ships under various circumstances. Though the results achieved were of great relevance, the primary value of this study was the methodology applied. The most important outcome was the establishment of a model for assessing the feasibility of the employment of cleaner fuel and more efficient propulsion systems in the marine sector.

To evaluate the technical aspects of utilizing more efficient technologies with cleaner fuel, such as using CCGT with LNG and MDO, it was necessary to model these technologies with a numerical model (Turbomatch and MATLAB software) to simulate performance under different conditions, both design point and off design. This modelling also examined the cryogenic properties unique of LNG, which could increase the efficiency of CCGT. When considering the size and weight of the technologies, the decrease in size of the engine room and the decreased engine weights can allow for increased cargo capacity of the ship. This study has been evaluated in paper one.

To evaluate and simulate the performance of conventional propulsion systems (two-stroke diesel engines) fuelled by MDO, and more efficient technology (in this case CCGT) fuelled by LNG and MDO, improvements were made to “Poseidon” simulator software that makes it possible to study the new technologies, as well as encourage further refinement of the software itself. A Poseidon ship simulator was used with different routes to produce more realistic results. Although the simulated journeys were assumed to be direct routes, ship stability was not taken into account. To assess the NO_x and CO₂ exhaust emissions a mathematical model was used that was adapted to handle all propulsion systems with different fuels. This techno-environmental study has been evaluated in paper two.

To study the economic and risk assessment of all propulsion systems for large container ships, it was necessary to develop an economic model through different

formulas such as NPV, PP, and IRR. The risk assessment has been examined include fuel cost, capital cost, and hull fouling resistance. This study has been done in paper 3.

Further investigations into the economic viability and risk assessment of advanced CCGT propulsion, in contrast to that of two-stroke diesel engines, were undertaken by simulating different scenarios. These included the effect of the container shipment cost and discount rate on the economic viability, and the potential implementation of emission taxes on economic viability. This study has been described in paper 4.

6.1.1 Overall technical assessment

A technical assessment has been carried out on CCGT cycles when fueled with MDO and LNG and used as propulsion systems for large container ships. The cycles studied were a simple, reheat, and intercooler/reheat combined gas steam turbine with a single heat recovery steam generator. The probability to place the intercooler and reheater were evaluated as it can significantly affect engine performance and efficiency. The objective of the technical assessment is to identify the propulsion system with the highest efficiency. For the reheat cycle, the best position for the reheater between the high-pressure turbine and the low-pressure turbine in the gas turbine cycle must be chosen. The efficiency of the reheat gas turbine cycle increases by about 4% when the reheater is positioned between the HPT and LPT, rather than between the LPT and PT. This can be attributed to the fact that the expansion process occurred in two stages, resulting in a reduction in waste heat when the reheat between the HPT and LPT. However, when the reheat between the LPT and P.T., the additional work cannot be extracted by the P.T., leading to increased waste heat. The results demonstrate that enhanced combined cycles are the most efficient, with up to 1.6% more efficiency than the other assessed cycles. In terms of performance, the I/R CCGT fuelled by LNG and MDO was more efficient than a reheat CCGT with the same fuel. The CCGT was more efficient burning LNG than burning MDO. The higher calorific value of liquified natural gas compared to marine diesel fuel decreases the amount of fuel required to produce the same power; therefore,

the fuel efficiency of liquified natural gas is better than that of marine diesel fuel in all CCGT cycles. The efficiency of all CCGT cycles fuelled by liquified natural gas was about 1% higher than that of CCGT cycles fuelled by marine diesel fuel.

The results obtained showed that the implementation of ELNG and CCGT fuelled by LNG on large container ships could improve efficiency by about 11% and 7% respectively, compared to the two-stroke diesel engine fuelled by MDO. For both simulated journeys analysed, the validity of the implementation of CCGT with LNG over a two-stroke diesel engine with MDO was confirmed. Efficiency was highest during the winter season due to higher air mass flow. In the summer season, the warmer air requires more energy to compress, which increases internal energy losses. Another aspect to consider when assessing the feasibility of this solution is the weight of the propulsion systems. The weight of CCGT, I/R CCGT, and ELNG CCGT, systems was respectively 75%, 72%, and 67.5% lower than that of a two-stroke diesel engine. Reducing the size and weight of the engine for CCGT systems allows a ship to have increased cargo capacity.

6.1.2 Environmental assessment

As already mentioned, only NO_x and CO₂ emissions were considered in this study. The most significant data emerging from all simulated voyages was fuel consumption. Higher CO₂ emissions occurred through the use of the two-stroke diesel engine, due to its lower efficiency when compared to CCGT. In terms of NO_x emissions, the two-stroke diesel engine was significantly higher than CCGT cycles, as CCGT runs at lower and more homogeneous temperatures. Certainly, CCGT cycles utilise a steady combustion process that allows for better NO_x emission control than that of a two-stroke diesel engine, where the peak temperatures produced during the discontinuous process trigger the formation of thermal NO_x species. The results show that the NO_x emissions of the I/R ELNG CCGT were approximately 76.3% lower than the two-stroke diesel engine. Moreover, the simple and I/R CCGT fuelled by LNG NO_x emissions were lower than two-stroke diesel engines around 31.5% and 73.6% respectively. Also, the simple and I/R CCGT fuelled by MDO NO_x emissions were lower two-stroke diesel engines around 10.5 % and 68.4 % respectively. Furthermore, the I/R ELNG CCGT NO_x emissions were lower than the simple and I/R CCGT fuelled by LNG around 57.6% and 3.3% respectively. Ultimately, the I/R ELNG CCGT NO_x emissions were lower than the simple and I/R CCGT fuelled by MDO around 67.3% and 8.4 respectively. In terms of CO₂ emissions, the I/R ELNG CCGT was about 44.7% lower than the two-stroke diesel engine due to higher efficiency. Moreover, the simple and I/R CCGT fuelled by LNG CO₂ emissions were lower than two-stroke diesel engines around 35.4 % and 43.7% respectively. Also, the simple and I/R CCGT fuelled by MDO CO₂ emissions were lower two-stroke diesel engines around 12.5 % and 25 % respectively. Furthermore, the I/R ELNG CCGT CO₂ emissions were lower than the simple and I/R CCGT fuelled by LNG around 14.5% and 2% respectively. the I/R ELNG CCGT CO₂ emissions were lower than the simple and I/R CCGT fuelled by MDO around 36.9% and 26.3 respectively.

6.1.3 Economical assessment

The objective of this model was to evaluate the economic viability of each technology for a large container ship when using different fuels and different international journeys. Therefore, the net present value, payback period, and internal rate of return were applied to assess the performance of several technologies. Several scenarios were assessed to achieve a comprehensive understanding of the economic benefits and risks associated with each technology with different journeys. The baseline scenario was the first scenario, with no change in any parameter value of the economic model. The second scenario investigated the impact of fuel cost. The third scenario estimated the effect of capital cost. The fourth scenario examined the impact of hull fouling resistance. The fifth scenario investigates the economic risks and effects of a potential emissions tax. The sixth scenario assessed the possibility of container cost changes. The seventh scenario examines the impact of the discount rate on NPV. For the routes that were considered, the first scenario shows the NPV of the simple CCGT fuelled with LNG, I/R CCGT fuelled with LNG, and I/R ELNG increased about 78.3%, 78.5%, and 76.4%, respectively compared with two-stroke diesel engine. At the same time, the PP was reduced by 38.8%, 38.9%, and 35%, respectively. The highest reduction in NPV among all scenarios were two-stroke diesel engine fuelled by MDO, simple CCGT fuelled by MDO, and I/R CCGT fuelled by MDO, respectively due to lower efficiency and higher fuel consumption. The discount rate, container price, capital cost, emissions tax, and fuel cost scenarios show the highest impact on economic results compared with the other scenarios for all technologies.

6.2 Overall research potential impact

- 1.The project suggests solutions to produce higher-efficiency prime movers for container ships than the current standard of diesel engines, with a relatively low level of emissions.
- 2.Significant economic and environmental improvements were produced for large container ships travelling 5000 to 11000 Nm, which would have global impacts.
- 3.The project offers a good method for researchers to evaluate the propulsion systems of container ships, taking into account performance, emissions and technology costs.
- 4.The project uses risk assessments for different scenarios to clarify the benefits of each technology.
- 5.The project assists and follows the International Maritime Organisation's regulations and future standards plan.
- 6.The project creates an avenue to assess if the current circumstances regarding legislation for two-stroke diesel engine with HFO allow for the use of CCGT at marine sector

7 Conclusion

This study investigated the potential of CCGT propulsion systems for large container ships using numerical simulation to reduce ship emissions. Mathematical modelling and simulation of the ship propulsion systems were accomplished. This allowed for a comprehensive investigation of different propulsion systems, including advanced CCGT cycles, to assess the effectiveness and compare it to conventional diesel systems using a TERA method. Furthermore, the developed ship simulator, Poseidon, was used to study different propulsion systems for large container ships and to compare them. The proposed advanced CCGT propulsion systems clearly demonstrated their ability as alternative propulsion systems for traditional prime mover diesel engines for large container ships. This study's main findings are summarised as follows:

- Simple, reheat, intercooler/reheat, and ELNG CCGT cycles were analysed., The intercooler/reheat ELNG was the most efficient cycle. Regarding the technology weight, the CCGT propulsion systems were approximately 24.7% lighter than the original diesel engine propulsion system.
- Two different routes were assessed. The simulation results of large container ship routes showed that the utilisation of CCGT cycles burning LNG was generally favourable when compared to a two-stroke diesel engine burning MDO. The I/R ELNG CCGT cycle on large container ships could increase the fuel efficiency by 11% compared with that of the MDO-fuelled two-stroke diesel engine.
- Regarding environmental impacts, the I/R ELNG, I/R, and simple CCGT cycles fuelled with LNG could reduce NOx approximately 76.3%, 75%, and 71%, respectively, compared to the two-stroke diesel engine. The I/R ELNG, I/R, and simple CCGT cycles fuelled with LNG reduced the CO2 emissions approximately 44.7%, 42%, and 30.7%, respectively, compared to the two-stroke diesel engine.
- The economic analysis showed the benefit of utilising CCGT propulsion systems for large container ships. In terms of NPV, the I/R ELNG, I/R, and

simple CCGT demonstrated an increase of about 76.4%, 78.3%, and 78.4%, respectively, compared to the two-stroke diesel engine. Regarding the PP, the I/R ELNG, I/R, and simple CCGT showed a reduction in the period of approximately 35%, 38.9%, and 38.8%, respectively, compared to the two-stroke diesel engine. Additionally, the IRR showed a low-risk investment with significant potential benefits of CCGT cycles fuelled with LNG.

- A sensitivity and risk analysis for different scenarios was performed, which showed that the discount rate, container price, capital cost, emissions tax, and fuel cost scenarios had the highest impact on economic results compared with the other scenarios for all technologies.

Finally, this study confirmed that the use of TERA assessments in the maritime sector is an essential tool to evaluate different propulsion systems.

8 Future work

One of the most challenging tasks of a study is to limit the level of detail taken into account and the number of examined cases that must be included in the study. As potential ideas and solutions may be countless at the beginning of a study, a thorough refinement of examined topics must be undertaken. Due to time constraints, not all possible features have been assessed. Some of these are listed below as recommendations for future areas of research.

- The performance degradation of gas turbine components could be included in more comprehensive CCGT performance and exhaust emission models.
- The simulation of a steam turbines based on a dual pressure HRSG and triple pressure HRSG is strongly recommended to provide further information through which to assess and enhance an advanced CCGT system.
- Studying renewable energy technologies, such as a solar power system, wind turbines, and electric propulsion systems, and implementing them in the Poseidon code would increase the number of comparative cases and strengthen the utility of comparative results.
- Other fuels such as hydrogen and biofuels may further decrease emissions and fuel consumption, which is important when comparing the pros and cons of the different solutions.
- A study to assess the volume needed to store LNG or liquified hydrogen fuel in large container ships, and therefore the feasibility of such solutions for short and long journeys.
- Larger or comparable studies assessing various kinds of vessels and different journeys, to obtain more information about the optimal circumstances for the installation of CCGT and renewable energy propulsion technologies.
- Simulating CCGTs of different sizes could provide an opportunity to study docking and undocking procedures, and port manoeuvres, which were not taken into account in this study.

- Further investigation can be undertaken into the ELNG cycle in the ships and how it will fit such as; a cryogenic energy storage system, also the possibility of the ELNG tank that could be integrated into the hull structure or independent of it, and the thermal cycling issue are going to be associated with the systems.
- The impact of propeller cavitation could also be taken into account in further work. Furthermore, the ship route in this study was considered a straight route; several simulation routes could be examined to better reflect real shipping circumstances.

APPENDICES

Appendix A Turbomatch input file

Industrial gas turbine simple simulation

////

OD SI GM VA FP

-1

-1

INTAKE S1,2 D1-6 R300

COMPRES S2,3 D7-18 R301 V7 V8

PREMAS S3,4,14 D19-22

PREMAS S14,15,16 D80-83

COMPRES S4,5 D23-34 R302 V23 V24

BURNER S5,6 D35-42 R303

MIXEES S6,15,7

TURBIN S7,8 D43-58 V44

DUCTER S8,9 D100-104 R304

MIXEES S9,16,10

TURBIN S10,11 D63-78 V64

TURBIN S11,12 D79-94 V79 V80

NOZCON S12,13,1 D109,110 R305

PERFOR S1,0,0 D79,73-75,305,300,303,0,0,0,0

CODEND

DATA ITEMS////

!-----

!INTAKE

!-----

1 0.0 ! INTAKE: Altitude

2 0.0 ! Deviation from ISA temperature

3 0.0 ! Mach number

4 -1 ! Pressure recovery

5 0.0 ! Deviation from ISA pressure [atm]

6 60.0 ! Relative humidity [%]
!-----
!-----
! LP COMPRESSOR
5!-----
7 -1. ! AXIAL - COMPRESSOR: Z
8 1. ! DP Relative rotational speed PCN
9 4.6368 ! DP Pressure ratio
10 0.889 ! DP isentropic efficiency
11 0.0 ! Error selection
12 3.0 ! Compressor Map Number
13 1. ! Shaft number
14 1. ! Scaling Factor of Pressure Ratio - Degradation factor
15 1. ! Scaling Factor of Non-D Mass Flow - Degradation factor
16 1. ! Scaling Factor of Isentropic Efficiency - Degradation factor
17 -1 ! Effective component volume [m^3]
18 0. ! Stator angle (VSV) relative to DP

!-----
!BLEED VALVE 1
!-----
19 0.902183 !Accessories bleed
20 0. ! DELTA W
21 1. ! LAMBDA P
22 0.0 ! DELTA P
!-----
! SPLIT COOLING COOLING BLEED FOR TURBINE 1 AND 2

80 0.76 ! Lambda (W) = Wout1/Win
81 0.0 ! Delta (W)
82 1.0 ! Lambda (P)
83 0.0 ! Delta (P)
!-----

! HP COMPRESSOR

- 23 -1. ! AXIAL - COMPRESSOR: Z
- 24 1. ! DP Relative rotational speed PCN
- 25 4.6368 ! DP Pressure ratio
- 26 0.889 ! DP isentropic efficiency
- 27 0.0 ! Error selection
- 28 3.0 ! Compressor Map Number
- 29 2. ! Shaft number
- 30 1. ! Scaling Factor of Pressure Ratio - Degradation factor
- 31 1. ! Scaling Factor of Non-D Mass Flow - Degradation factor
- 32 1. ! Scaling Factor of Isentropic Efficiency - Degradation factor
- 33 -1 ! Effective component volume [m³]
- 34 0. ! Stator angle (VSV) relative to DP

! BURNER

!-----

! BURNER

!-----

- 35 0.05 ! COMBUSTOR: Pressure loss
- 36 0.99 ! Combustion efficiency
- 37 -1. ! Fuel flow (If -1. TET must be determined in SV)
- 38 0.0 ! (>0) Water flow [kg s⁻¹ or lb s⁻¹] or (<0) Water to air ratio
- 39 288. ! Temperature of water stream [K]
- 40 0. ! Phase of water (0=liquid, 1=vapour)
- 41 1. ! Scaling factor of ETAb – Degradation factor
- 42 -1 ! Effective component volume [m³]

! HP TURBINE

- 43 0 ! HP TURBINE: Auxiliary or power output [W]
- 44 -1 ! DP Relative non-dimensional ZT (if = -1, value 0.8 is invoked)
- 45 -1 ! DP Relative non-dimensional speed CN (if = -1, value 0.6 is invoked)
- 46 0.88 ! DP isentropic efficiency

47 -1. ! DP Relative non-dimensional speed PCN (= -1 for compressor turbine)
 48 2. ! Shaft Number (for power turbine, the value "0." is used)
 49 5. ! Turbine map number
 50 -1. ! Power law index "n" (POWER = PCN^n)
 51 1. ! Scaling factor of TF – Degradation factor
 52 1. ! Scaling factor of DH – Degradation factor
 53 1. ! Scaling factor of ETAc – Degradation factor
 54 -1. ! DP Rotor rotational speed [RPS]
 55 -1. ! Rotor moment of inertia [kg.m^2]
 56 -1. ! Effective component volume [m^3]
 57 -1.
 58 0. ! NGV angle, relative to D.P.

 ! DUCTER (REH)

 100 0. ! REHEAT
 101 0.0 ! PRESSURE LOSS
 102 0.0 ! COMBUSTION EFFICIENCY
 103 100000 ! FUEL FLOW
 104 -1

 ! LP TURBINE

 63 0 ! HP TURBINE: Auxiliary or power output [W]
 64 -1 ! DP Relative non-dimensional ZT (if = -1, value 0.8 is invoked)
 65 -1 ! DP Relative non-rimensional speed CN (if = -1, value 0.6 is invoked)
 66 0.88 ! DP isentropic efficiency
 67 -1. ! DP Relative non-dimensional speed PCN (= -1 for compressor turbine)
 68 1. ! Shaft Number (for power turbine, the value "0." is used)
 69 5. ! Turbine map number
 70 -1. ! Power law index "n" (POWER = PCN^n)
 71 1. ! Scaling factor of TF – Degradation factor
 72 1. ! Scaling factor of DH – Degradation factor

73 1. ! Scaling factor of ETAc – Degradation factor
 74 -1. ! DP Rotor rotational speed [RPS]
 75 -1. ! Rotor moment of inertia [kg.m²]
 76 -1. ! Effective component volume [m³]
 77 -1.
 78 0. ! NGV angle, relative to D.P.
 ! POWER TURBINE
 79 40750000! POWER REQUIRED
 80 -1. ! DP Relative non-dimensional ZT (if = -1, value 0.8 is invoked)
 81 -1. ! DP Relative non-dimensional speed CN (if = -1, value 0.6 is invoked)
 82 0.88 ! DP isentropic efficiency
 83 1. ! DP Relative non-dimensional speed PCN
 84 0. ! Shaft Number
 85 5. ! Turbine map number
 86 -1 ! Power law index "n"
 87 1. ! Scaling factor of TF – Degradation factor
 88 1. ! Scaling factor of DH – Degradation factor
 89 1. ! Scaling factor of ETAc – Degradation factor
 90 -1. ! DP Rotor rotational speed [RPS]
 91 -1. ! Rotor moment of inertia [kg.m²]
 92 -1. ! Effective component volume [m³]
 93 -1.0
 94 0. ! NGV angle, relative to D.P.
 !-----
 !NOZCON
 109 -1.0 ! CONVERGENT NOZZLE
 110 -1.
 !PERFOR
 95 1.0
 96 1.0 ! PROPELLER EFFICIENCY
 97 0.0 ! SCALING INDEX(NO SCALING)
 98 0.0 ! Required thrust
 -1

1 2 106 ! INLET MASS FLOW

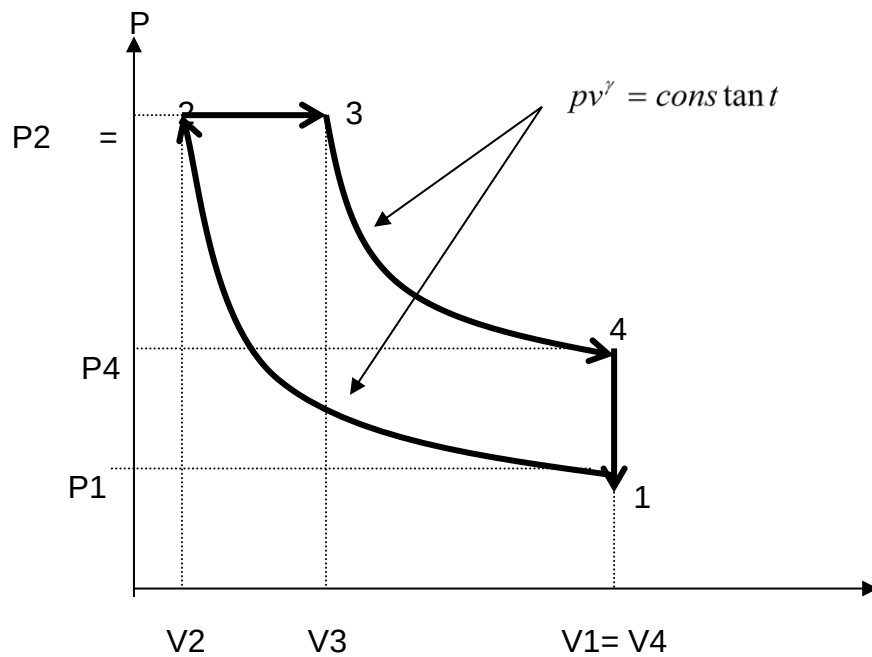
6 6 1600 ! FIRST COMBUSTOR OUTLET TEMPERATURE

-1

Appendix B 2-stroke diesel engine model

The Diesel Engine Cycle:

In a diesel engine, the heat is supplied at constant pressure and rejected at constant volume. There are four processes inside the main cycle listed as the following and shown in the figure.



Process 1: From 1 to 2 is isentropic compression

Process 2: From 2 to 3 is reversible constant pressure heating.

Process 3: From 3 to 4 is isentropic expansion.

Process 4: From 4 to 1 is reversible constant volume heat rejected.

1. Thermal Cycle one cylinder Calculations:

$$\text{Compression ratio} = \frac{\text{Displacement Volume} + \text{clearance volume}}{\text{clearance volume}} \quad (1)$$

$$M_{air} = \frac{P_1 * V_1}{R * T_1} \quad (8)$$

$$AF = \frac{M_{air}}{M_{fuel}} \quad (3)$$

$$M_T = M_{air} + M_{fuel} \quad (4)$$

$$Q_{in} = M_m * C_p * (T_3 - T_2) \quad (5)$$

Net Indicated Work for One Cylinder During One Cycle (kJ)

$$W_i = W_{1-2} + W_{2-3} + W_{3-4} \quad (6)$$

Net Brake Work for One Cylinder During One Cycle (kJ)

$$W_b = \eta_m * W_i \quad (7)$$

Where η_m is mechanical efficiency

2.Overall Engine Performance

$$W_{brake} = W_b * N * \left(\frac{n}{60 * 2} \right) \quad (8)$$

Where N= number of cylinders n= speed engine rpm

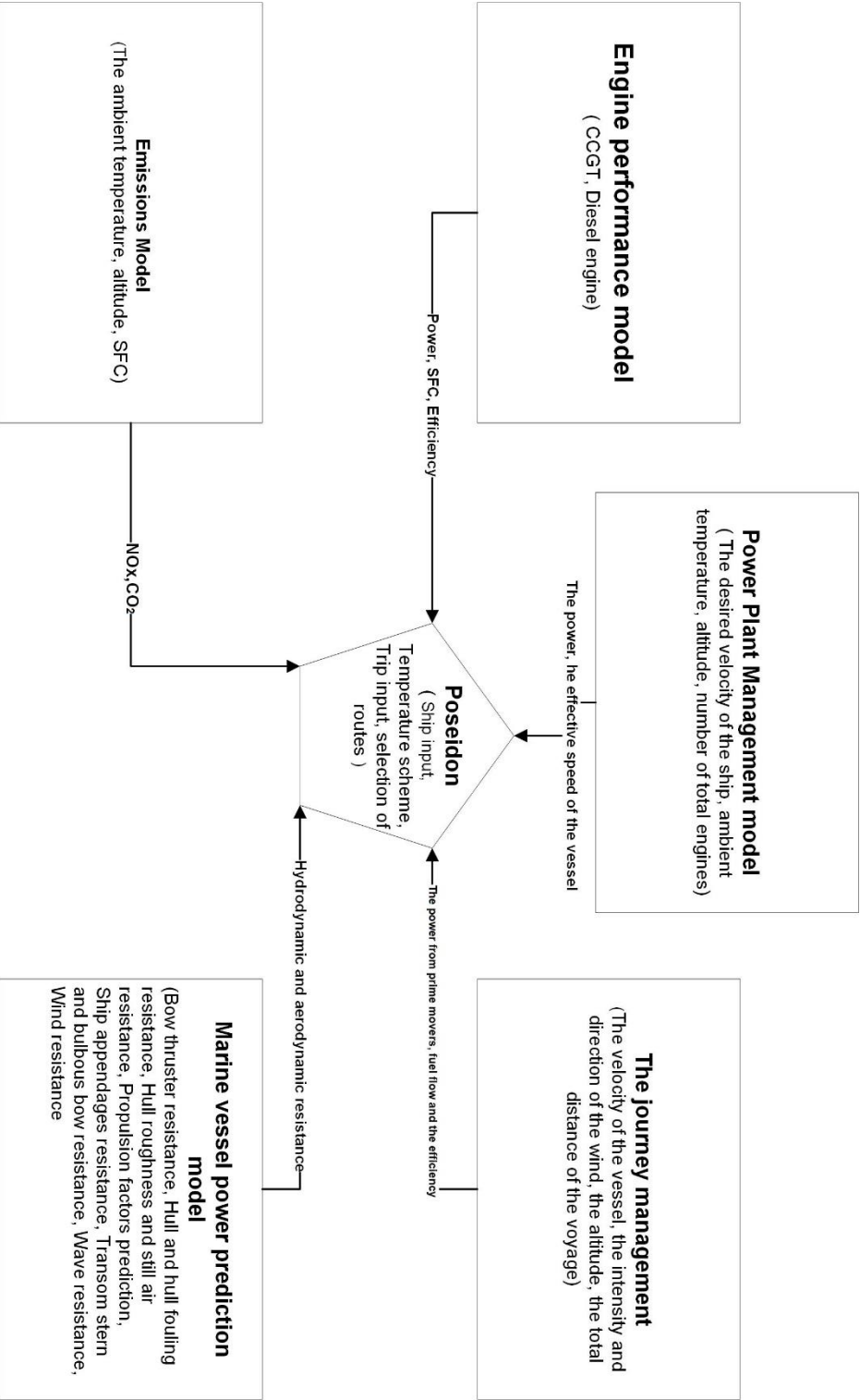
Brake Specific Fuel Consumption

$$sfc = \left(\frac{M_{fuel}}{W_{brake}} \right) \quad (9)$$

Brake Thermal Efficiency

$$\eta_t = \frac{1}{SFC * Q_{hv}} \quad (10)$$

Appendix C Poseidon Simulator Model



Appendix D A guide of main form coefficients and elements of the hull shape

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Table 17—Variation of Form Coefficients and Elements of Hull Shape, Based on Lindblad (1961) and Todd (1945)

Type of ship	Slow speed cargo ship	Medium speed cargo ship	Cargo liners	Passenger and cargo, fruit ships	High-speed passenger liners, ferries, etc.	Fast passenger liners, tugs	Cross-channel ships	Destroyers
C_p	0.80	0.75	0.70	0.65	0.60	0.55	0.54–0.52	0.46–0.54
C_m	0.99–0.995	0.985–0.99	0.98	0.98	0.97	0.93	0.915–0.905	0.76–0.85
C_{wp}	0.809–0.805	0.762–0.758	0.715	0.664	0.62	0.59	0.59–0.575	0.56–0.64
F_n	0.88	0.84	0.81	0.78	0.71	0.69	0.69–0.675	0.68–0.76
F_n	0.15–0.18	0.18–0.19	0.21	0.24	0.24–0.30	0.24–0.36	0.36–0.45	0.45 and above
L_p percent	35	25	12	5	0	0	0	0
L_p/L_R	0.7	0.8	0.9	1.0	1.0–1.1	1.1–1.2	1.2	0.55
LCB percent L_{pp} from PP	1.5–2.5 fwd	1.0–2.0 fwd	0–1.0 aft	1.0–2.0 aft	1.5–2.0 aft	2.0–2.8 aft	2.0–3.0 aft	0.5–2.0 aft
Sectional area curve shape	Fwd Straight with U sections, slightly convex with V sections and raked stem	Straight with slight hollow at extreme fore end	Straight with some hollow forward giving S-shape	S-Shape—fine entrance essential with pronounced hollow forward	S-Shape for $F_n = 0.24$, becoming straight above this value, with addition of bulb	S-Shape at $F_n = 0.24$ straight above $F_n = 0.27$	S-Shape with hollow forward at $F_n = 0.36$ becoming straighter for 0.45	Maximum area aft of midships. Straight or slightly convex area curve forward
	Aft Straight or slightly convex with easy shoulder	Straight or slightly convex	Straight except at extreme aft end	Straight except at extreme aft end	Straight except at extreme aft end	S-Shape	Straight with hollow at extreme aft end	Good buttock lines aft and transom stern
LWL shape	Fwd Slightly convex through-out	Slightly convex or straight	Slightly hollow forward, or straight with longer entrance	S-Shaped, hollow forward	Fine W_L , almost straight with slight hollow	Fine W_L , S-shaped below $F_n = 0.30$ straight above this value	Up to $F_n = 0.30$ fine W_L with hollow, above $F_n = 0.3$, W_L endings fuller and straight, or hollow with bulb	Maximum beam aft of midships. Waterline forward quite straight or even a little convex
	Aft Slightly convex. If possible the slope should not exceed 20 deg	Slightly convex	Slightly convex	Slightly convex	Full W_L , nearly straight	Full, straight or convex	Full W_L , convex	W_L aft very full to suit transom stern and cover screws
Half-angle of entrance on LWL (θ)	35 deg	27 deg	12 deg with hollow LWL , 16 deg if LWL is straight	10 deg	6 deg	8½–10 deg	6–7 deg below $F_n = 0.30$. Above this speed, 9 deg with straight W_L , 6 deg with hollow and bulb	4–11 deg

PRINCIPLES OF NAVAL ARCHITECTURE

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Appendix E Journeys Route and Midpoint city

ROUTE mid point	FROM	TO	Distance Nm
Midway island	Shanghai ,china	Los Angeles ,USA	5708
Vietnam	Shanghai ,china	Malacca, Malaysia	2359
Srilanka	Malacca, Malaysia	Gulf of Aden, Yemen	3504
Crete island (Greek)	Gulf of Aden, Yemen	Gibraltar	3307
Ushant island (France)	Gibraltar	Hamburg ,Germany	1618

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