

Article

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

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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



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1. 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 liquefied 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

2. 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 2-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, or calm seas.
- 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 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].

2.1. Core Models

2.1.1. 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 liquefied 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 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 2 shows the heat balance in the air precooling heat exchanger between the LNG and the inlet air in the ELNG cycle.

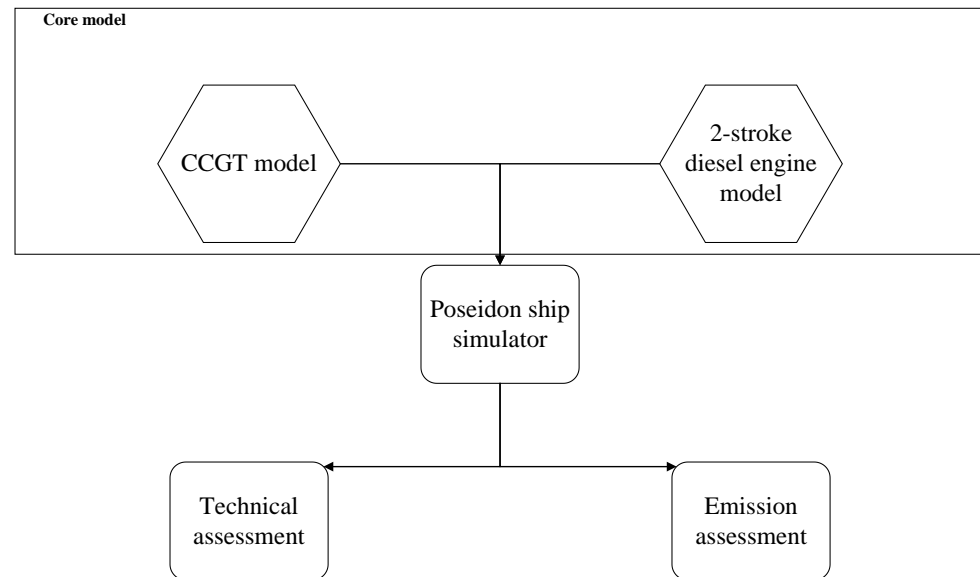


Figure 1. Flow diagram of the methodology used in this study. CCGT: gas and steam combined cycle.

Table 1. CCGT engines with different fuels.

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

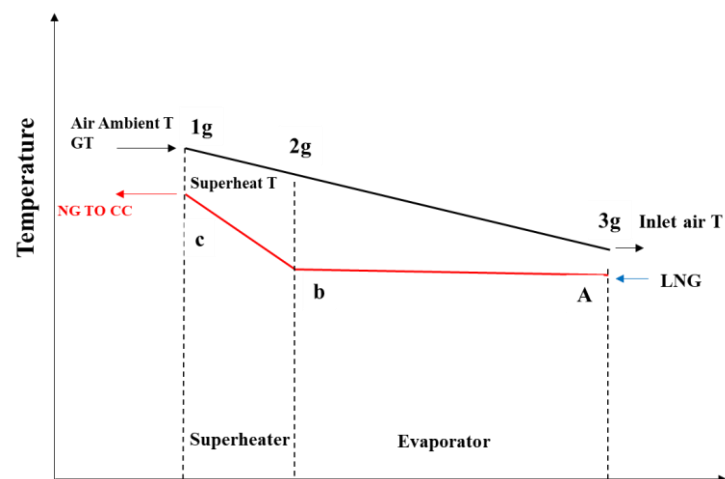


Figure 2. Heat balance in heat exchanger between the inlet air and LNG. 1g: inlet air mass flow temperature to heat exchanger; 2g: outlet air mass flow temperature from superheater stagnation to evaporator; 3g: outlet air mass flow temperature from heat exchanger to gas turbine; A: inlet LNG mass flow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

2.1.2. 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 2-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.

2.2. 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 (Figure 3A,B) [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 d, the midseason had 165 d, and the day in each season contained 24 h. 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.

2.3. 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

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

where E is the total emission (tonnes/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]

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

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 CO_2 emission per kilogram of fuel, the following equation was applied [21]

$$kg \ CO_2 = \left(\frac{44}{12} \times C_m \right) \quad (3)$$

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

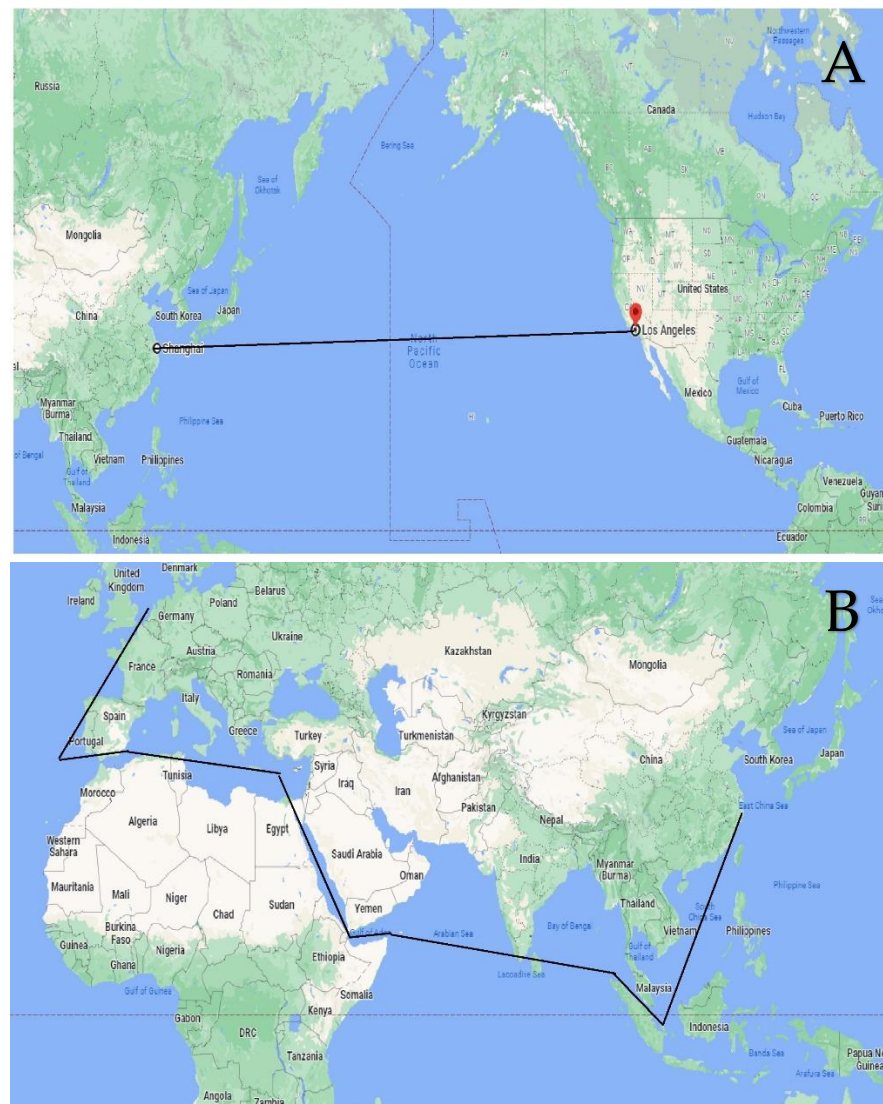


Figure 3. (A) The first journey route Shanghai, China, to Los Angeles, USA; (B) the second journey was from Shanghai, China, to Hamburg, Germany.

3. Results

3.1. 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 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.

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 [14].

Table 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

Table 3. Two-stroke diesel engine parameters.

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

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

Table 4. Simulation data and actual parameters of the 2-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

3.2. 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 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 d; the midseason had 165 d. 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 5.

Table 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 4 and 5, respectively.

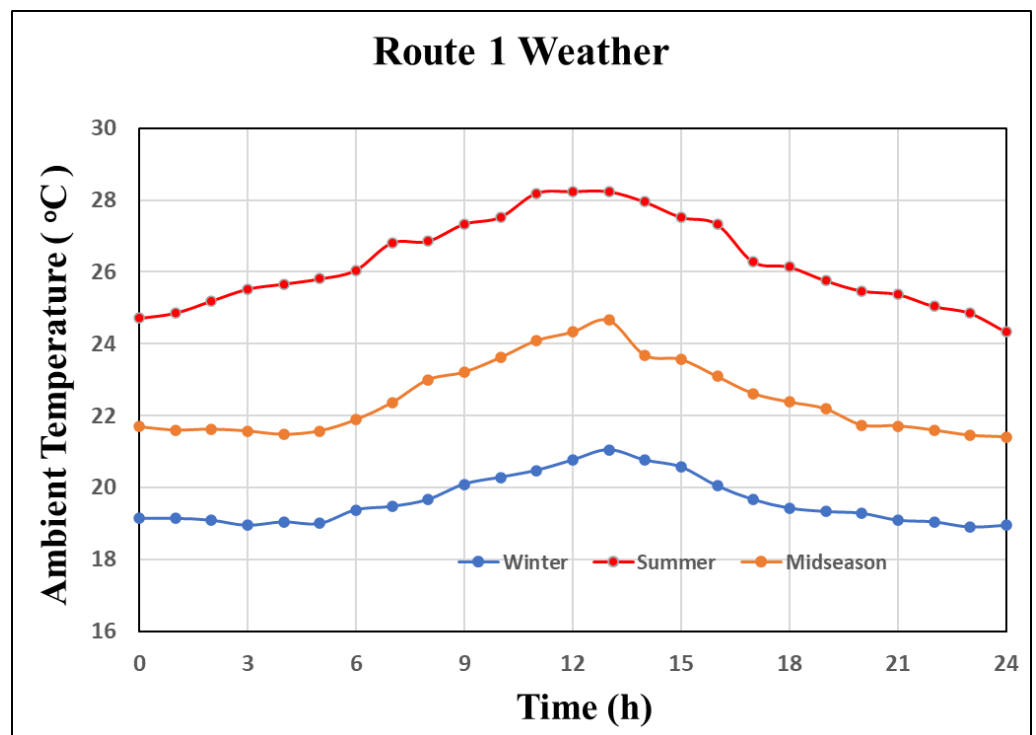


Figure 4. Ambient temperature of all seasons for the first journey route Shanghai, China, to Los Angeles, USA.

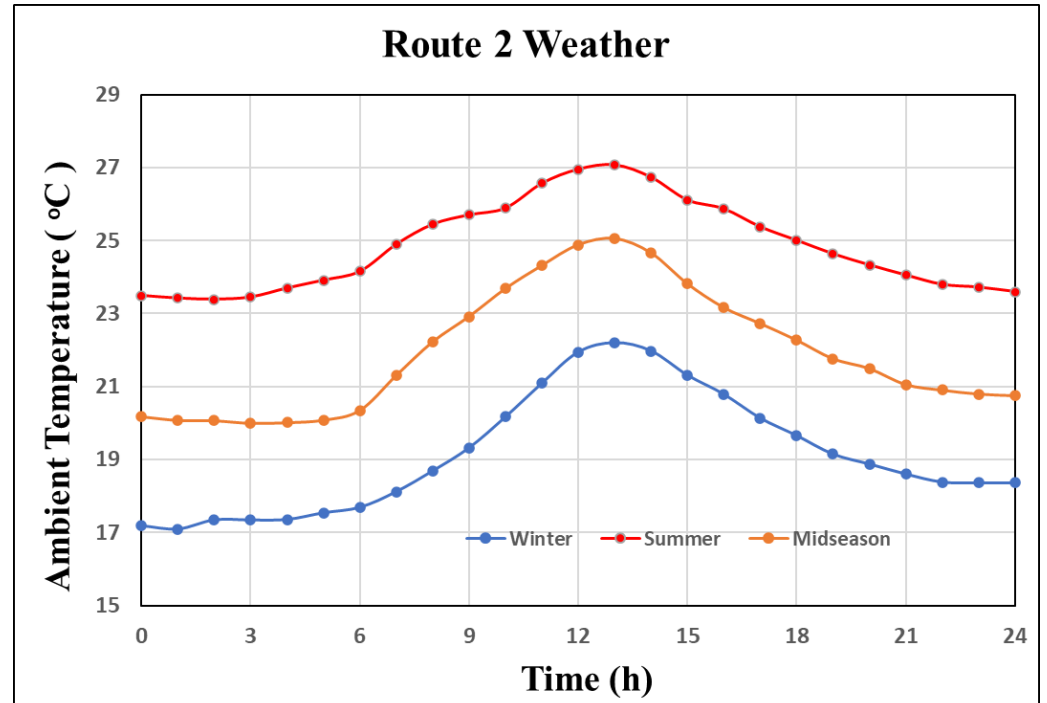


Figure 5. Ambient temperature of all seasons for the second journey from Shanghai, China, to Hamburg, Germany.

3.3. Technical Evaluation

Figures 6 and 7 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.

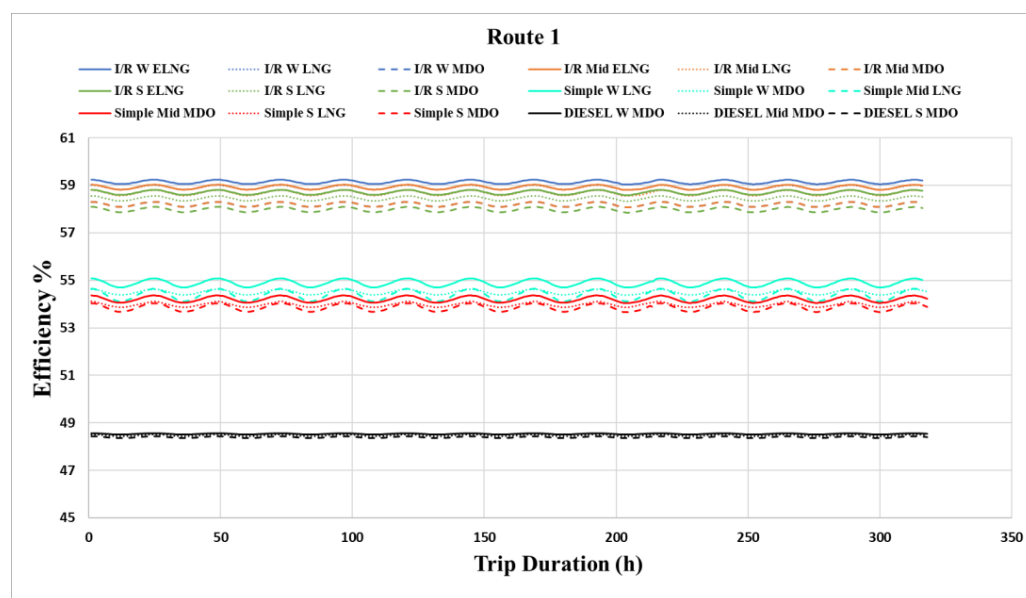


Figure 6. Performance of various propulsion systems of the large container ship travelling between Shanghai and Los Angeles. I/R: intercooler/reheater CCGT; S: simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer season; ELNG: enhanced liquified natural gas; MDO: marine diesel fuel; LNG: liquified natural gas.

3.4. Environmental Results

As mentioned earlier, only CO_2 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 CO_2 emissions depend on the fuel consumption and carbon concentration in the fuel. The CO_2 fuel content was obtained from [34]. Table 6 show the theoretical parameters of each fuel.

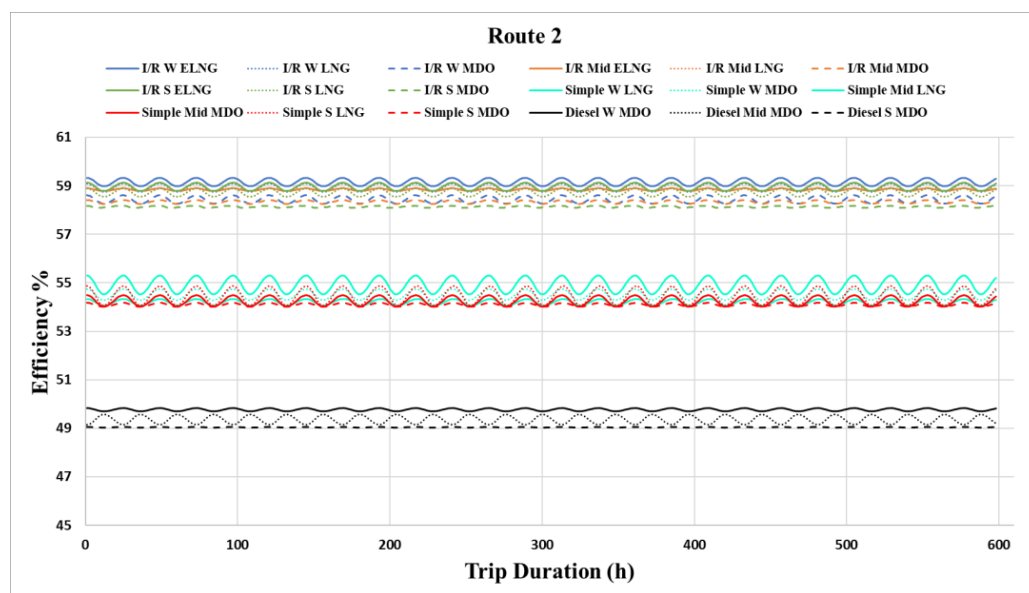


Figure 7. Performance of various propulsion systems of the large container ship travelling between Shanghai and Hamburg. I/R: intercooler/reheater CCGT; S: simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer season; ELNG: enhanced liquified natural gas; MDO: marine diesel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

Table 6. Theoretical parameters of different propulsion systems and fuels.

Fuel	ELNG	LNG	MDO
NO _x concentration in the gas turbine (ppm)	17.4	25	156
Molecular weight (g/mol)	16.04	16.04	198–202

Figures 8–11 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 8 and 9, 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.

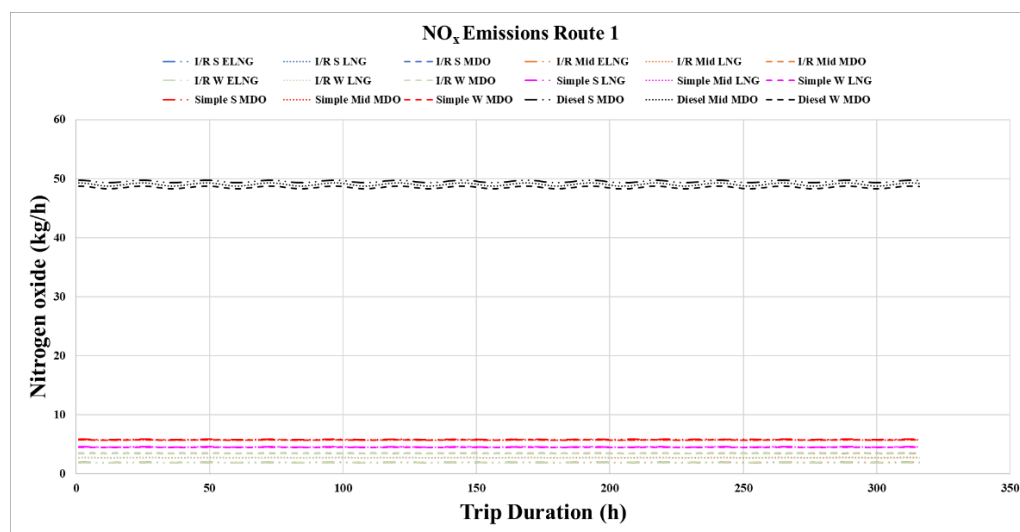


Figure 8. NO_x emissions of various propulsion systems of the large container ship travelling between Shanghai and Los Angeles. I/R: intercooler/reheater CCGT; R: reheater CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

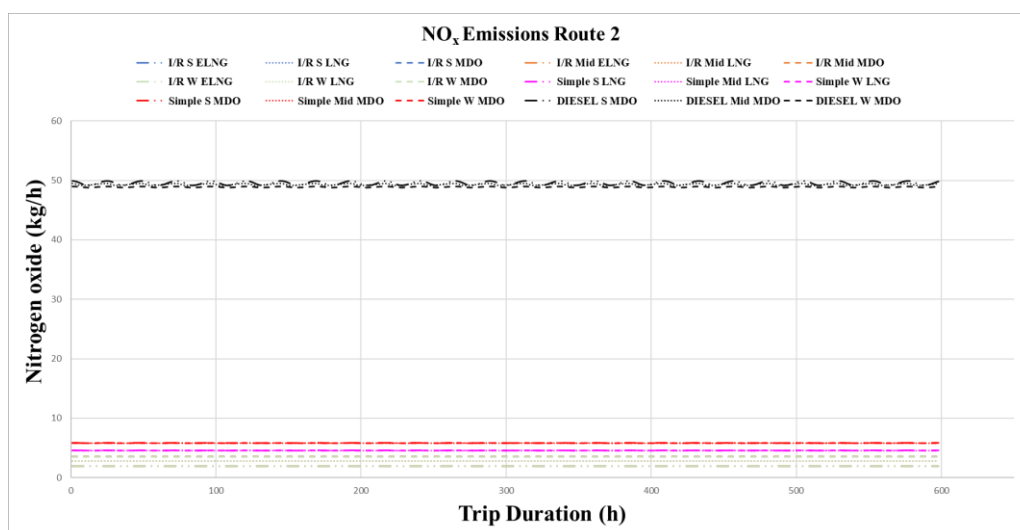


Figure 9. NO_x emissions of various propulsion systems of the large container ship travelling between Shanghai and Hamburg. I/R: intercooler/reheater CCGT; R: reheater CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

Figures 10 and 11 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.

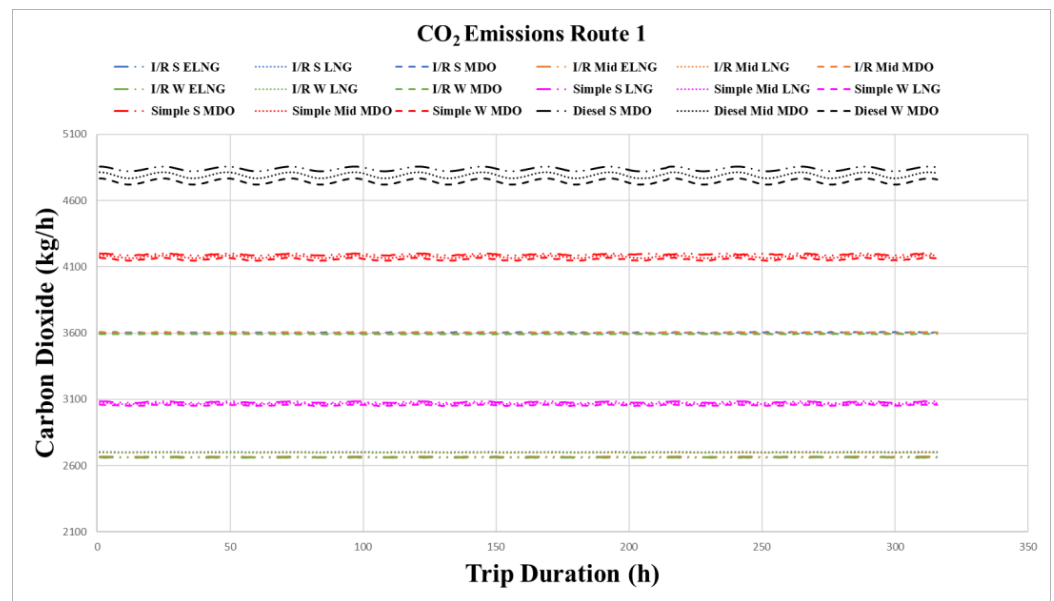


Figure 10. CO₂ emissions of various propulsion systems of the large container ship travelling between Shanghai and Los Angeles. I/R: intercooler/reheater CCGT; R: reheater CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

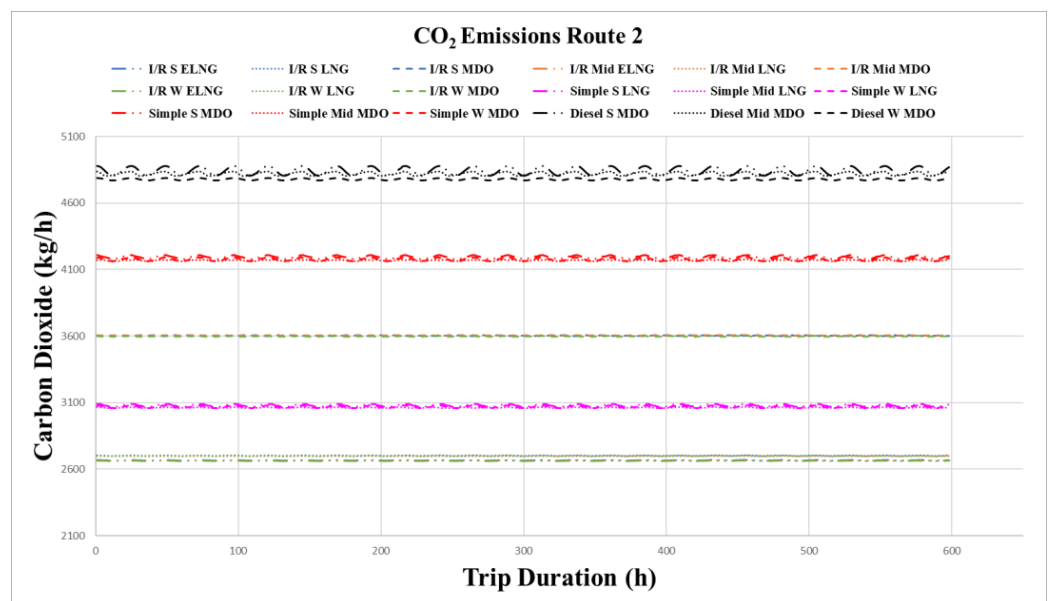


Figure 11. CO₂ emissions of various propulsion systems of the large container ship travelling between Shanghai and Hamburg. I/R: intercooler/reheater CCGT; R: reheater CCGT; S simple CCGT; Diesel: two-stroke diesel engine; W: winter; Mid: midseason; S: summer.

4. 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.

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